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Geneva photometry of the open cluster NGC 2451 and its exceptional Be star HR 2968*,**

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Abstract. During many years, several authors discussed whether NGC 2451 was a real open star cluster or not. By using parallaxes and proper motions from HIPPARCOS satellite, and Geneva multicolour photometric measurements of 64 stars, the existence of two clusters A and B is confirmed. Distances and Geneva colour excesses $E[B-V]$ are respectively 197 pc, 0.01 and 358 pc, 0.12 for NGC 2451 A and B. The two clusters have the same age ($\log t = 7.7$).

A unique Be star, HR 2968, which belongs to cluster B, has been monitored from 1978 to 1998 in Geneva photometry and from November 1989 to March 1993 by the HIPPARCOS satellite. This star shows exceptional luminosity variations: i) The mean luminosity, which has been stable since 1978 (normal B-star phase), increased from 1990 to 1995 (Be phase), and then decreased until 1998; ii) Also, in 1990 started a periodic light variation with a period of 371 d. Five periods of this mid-term light variation were observed. HIPPARCOS and Geneva photometries are in perfect agreement.

A model is proposed to explain this periodic variability: the Be star is the main component of a binary system having an eccentric orbit of period 371 d; from 1990, the Be star was surrounded by matter expelled in its equatorial plane and, at each periastron passage, the companion star interacts gravitationally and/or radiatively with the disk. The physical parameters of the Be star and its companion (most probably a main sequence star) are determined by using their belonging to NGC 2451 B and by calculating an approximate orbit from published radial velocities.

Key words: techniques: photometric – stars: emission-line, Be – stars: individual: HR 2968 – galaxy: open clusters and associations: individual: NGC 2451

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* Based on observations collected at the Swiss 40 cm and 70 cm telescopes at the European Southern Observatory (La Silla, Chile) and on data from the ESA HIPPARCOS satellite.

** The mean values of the photometric data are only available in electronic form at the CDS via anonymous ftp to cdsarc.u.strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

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1. Introduction

NGC 2451 is a young open cluster located in Puppis at galactic coordinates $l = 252.4$, $b = -6.7$. Previous photometric works have been done by Williams (1966, 1967a and 1967b), Feinstein (1966) and Pastoriza & Röpke (1983), who found a distance of 330 pc, 260 pc and 353 pc respectively. Several authors wondered if NGC 2451 was a real cluster. Eggen (1983) concluded that it was not a cluster, but in a later investigation (Eggen, 1986) found a concentration of stars at less than 250 pc. Maitzen & Catalano (1986) were the first to divide NGC 2451 into a near and a far cluster. Röser & Bastian (1994), on the basis of proper motions from the PPM Catalogue, found a first cluster at 220 pc and possibly another cluster at a distance of about 400 pc. Also, on the basis of proper motion measurements (Yale/San Juan Southern Proper Motion Program), Platais et al. (1996) affirmed the existence of two clusters, A and B.

HR 2968 (HD 61925, NGC 2451–187, 146 G Pup) is a quite unique Be-type star belonging to cluster B. The star is classified B6IVe in SIMBAD (Centre de Données Stellaires de Strasbourg, CDS). The Be characteristic was found by Neubauer (1930), who detected H_β emission. Since then, weak emissions in H_α (Jaschek et al, 1964) or H_β (Jaschek et al, 1965), or no emission at all (Morris, 1961; Slettebak, 1982) were observed.

HR 2968 was observed in UBV photometry by Stagg (1987), in the framework of a vast statistical survey of Be star variability. No photometric variation was found in HR 2968, but the star had been measured only 4 times. HR 2968 was used as a standard star in Geneva photometry from 1978 to 1991. During this long time interval, the star remained stable in luminosity and colours. Afterwards, the star became variable, exhibiting a very interesting new kind of photometric variation.

In this paper, the two clusters NGC 2451 A and B will be examined on the basis of the parallaxes and proper motions from HIPPARCOS satellite and of Geneva multicolour photometric measurements. On the other hand, the variability of HR 2968 will be described by using the photometric data resulting from the surveys in the Geneva system from 1978 to 1998 and by the HIPPARCOS satellite from November 1989 to March 1993.

2. Observations

From 1974 to 1998, 64 stars of NGC 2451 have been measured in the Geneva photometric system (Golay, 1980) with the photoelectric photometer P7 (Burnet & Rufener, 1979) installed on the 40 cm and 70 cm Swiss telescopes in La Silla (ESO, Chile). The photometric reduction procedure is described by Rufener (1964, 1985); the photometric data in the Geneva system are collected in the General Catalogue (Rufener, 1988) and its up-to-date database (Burki, 1998). An amount of 1615 measurements have been obtained on these 64 stars. Three stars have a great amount of measurements: respectively 358, 817 and 146 for the Be star NGC 2451–187 (HR 2968), the standard stars NGC 2451–163 (HR 2955) and NGC 2451–239 (HD 62803). The mean values of the photometric data for these 64 stars are available in electronic form at the CDS via anonymous ftp to cdsarc.u.strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html. Clear evidence of variability is detected only for HR 2968, which has $\sigma_V = 0.032$ (see Sect. 5). Therefore, only the measurements during its stable phase are used to discuss its cluster membership.

3. Cluster membership

The membership criteria used in this paper are based on parallaxes, proper motions and Geneva photometric analysis. The stars are identified by the numeration of Williams (1967a).

3.1. Proper motions

Among the 64 stars shown in Table 1, 47 have proper motions in the PPM Catalogue (Bastian et al, 1993), 30 of them having also proper motions from HIPPARCOS (ESA, 1997). The mean difference between the two databases in the vicinity of NGC 2451 has been revealed by using these 30 stars in common. We found:

$$(\mu_\alpha \cos\delta)_{\rm HIP} = (\mu_\alpha \cos\delta)_{\rm PPM} - 1.16 \qquad (\sigma = 2.39)$$
$$(\mu_\delta)_{\rm HIP} = (\mu_\delta)_{\rm PPM} + 10.25 \qquad (\sigma = 2.64)$$

with μ and σ in mas/yr. As noted by Platais et al. (1996) there are two groups of stars, noted A and B, in the μ_δ versus $\mu_\alpha \cos\delta$ plane (see Fig. 1). They correspond to the two clusters superimposed on the line of sight (Maitzen & Catalano, 1986; Röser & Bastian, 1994). These two groups, one centered at $\mu_\alpha \cos\delta$ = -21.5 and μ_δ = 15.4 and the other at $\mu_\alpha \cos\delta$ = -8.9 and μ_δ = 6.0, correspond to the near (A) and distant (B) clusters respectively. According to the criterion based on proper motions, 21 stars belong to cluster A, 21 to cluster B and 5 are non-members (#154, 163, 193, 281, 297).

3.2. Parallaxes

Thirty stars have a precise parallax from HIPPARCOS. The two groups A and B are also clearly shown up by the distribution of these parallaxes (see Fig. 1). Average parallaxes of 5.37 mas (σ = 0.33) and 2.72 mas (σ = 0.44) are respectively derived for the clusters A and B, using an iterative method selecting the

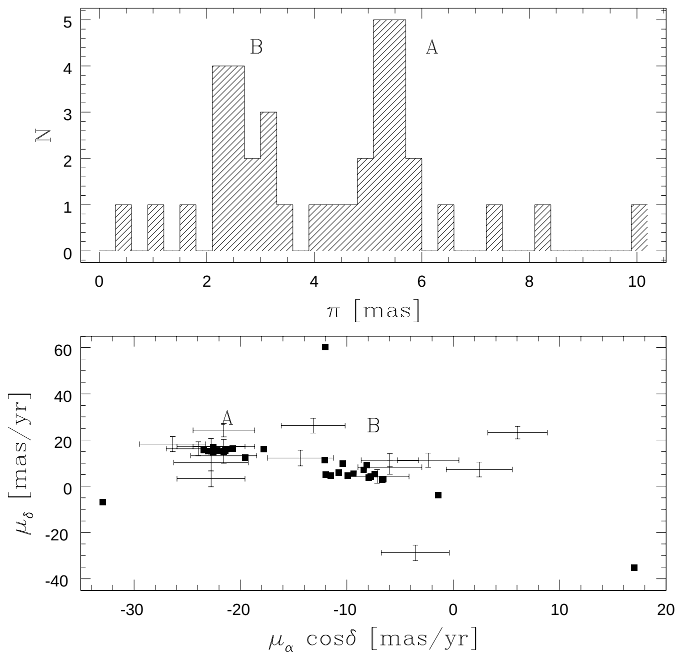

Fig. 1. Evidence of the existence of the two clusters A and B. *Top*: Distribution of the parallaxes for the 38 stars of NGC 2451 measured by HIPPARCOS. Among those stars, thirty have Geneva photometry. *Bottom*: Proper motions plane. HIPPARCOS data are identified with squares (the square size represents the errors) and PPM data with error bars. The PPM proper motion values have been corrected according to the analysis of Sect. 3.1.

stars at less than two sigmas of the mean. However, only four stars are excluded at one sigma of NGC 2451 A or B by the parallaxes: #141, 163, 188 and 268. According to this criterion, 15 stars belong to cluster A and 11 to cluster B. Star #131 is member of cluster A according to its parallax and of cluster B from its proper motions; this star will therefore be considered as a non-member (see Sect. 3.4.).

3.3. Photometry

By using the properties of various photometric diagrams, it is possible to identify the back– and foreground stars. This classical photometric method is based on the fact that magnitudes are sensitive to distance and reddening effects, colour indices to reddening only and the so-called reddening free parameters to neither of them. In the seven-colour Geneva photometric system, many colour indices and several parameters can be used for this purpose (Golay, 1980; Rufener, 1988). In the case of the young cluster NGC 2451, having a great amount of B- and A-type members, the V magnitude, the colour indices $[B_2 - V_1]$ and $[U - B_2]$ and the parameters X and Y are well adapted.

The relation between the Geneva colour indices and $T_{\rm eff}$, spectral type and luminosity class are described by Golay (1980), Meylan & Hauck (1981), Hauck (1994) and Künzli et al. (1997). The properties of X and Y parameters, in particular their calibration in terms of $T_{\rm eff}$, $\log g$ and spectral type, have been described by Cramer & Maeder (1979), North & Nicolet

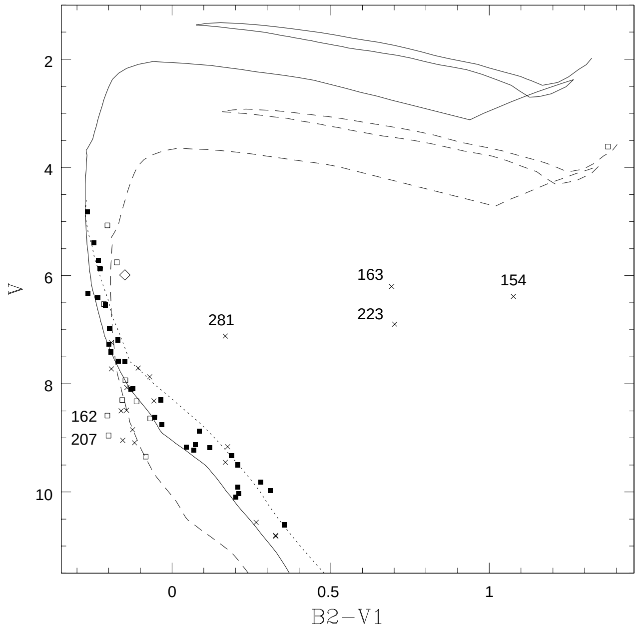

Fig. 2. Colour-magnitude diagram of the stars in Table 1. Members of the near cluster (A) are identified with filled symbols, members of the distant cluster (B) with open symbols and non-members with crosses. HR 2968 is indicated as a diamond. The isochrone at $\log t = 7.7$ (solid line) is displayed for cluster A, together with the theoretical envelope of equal mass binaries (dotted line), as well as the isochrone at the same age for the cluster B (dashed line).

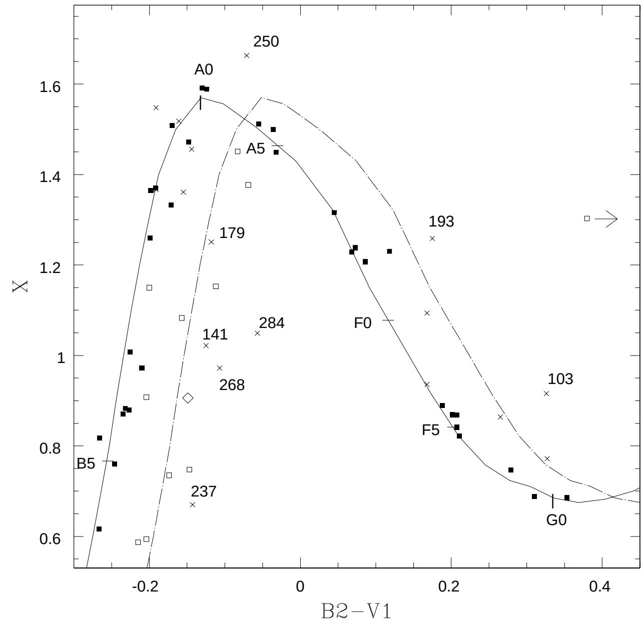

Fig. 3. Colour-parameter diagram for the same stars as in Fig. 2. The Zero-Age Main Sequence (ZAMS) for cluster A (solid line) and B (dot-dashed line) are displayed. The arrow refers to the supergiant #254, which has a value $[B_2 - V_1]$ = 1.374.

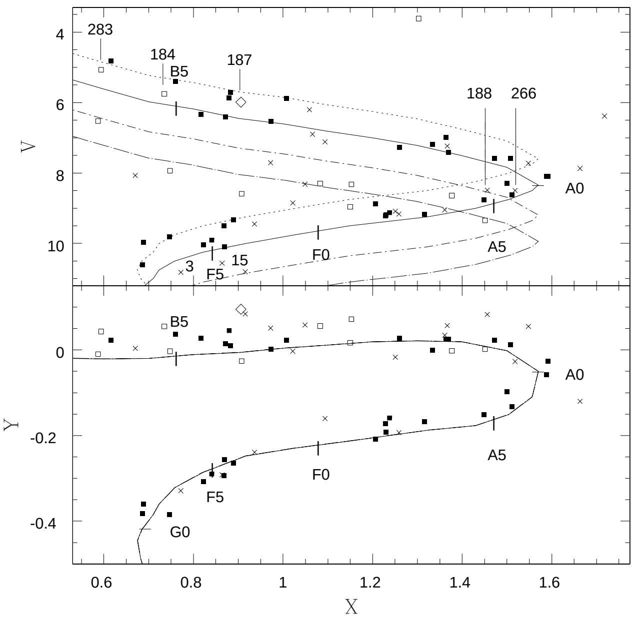

Fig. 4. *Top*: Parameter-magnitude diagram for the same stars as in Fig. 2. The ZAMS for the two clusters are shown: solid line for cluster A and dot-long dashed line for cluster B, dotted and dot-dashed lines for the envelopes of equal mass binaries of clusters A and B. *Bottom*: Parameter-parameter diagram with the same stars.

(1990), Cramer (1994a) and Raboud et al. (1997). The effect of the interstellar extinction on the colour indices has been given by Cramer (1994b). The evolutionary effects on these photometric indices and parameters are described by an age and mass calibration established by North & Cramer (1981).

The following diagrams have been used (see Figs. 2 to 5): i) V vs $[B_2 - V_1]$, the observational HR diagram, useful to compare the cluster sequences with the evolutionary tracks; ii) $[U - B_2]$ vs $[B_2 - V_1]$, the colour-colour diagram equivalent to the classical $(U - B)$ vs $(B - V)$ diagram; iii) X vs $[B_2 - V_1]$, similar to the colour-colour diagram but without reddening effect on X; iv) V vs X, in which the distance and reddening affect only the ordinate; v) Y vs X, the diagram of parameters, which allows a good classification of the stars as well as the determination of their evolutionary status.

Moreover, the extinction was assumed uniform in front of the clusters. This was tested by calculating $E[B - V]$ with the calibration of Cramer (1993) for the B stars in this region. No differential reddening was found: it is not possible to show a linear trend in α and δ for $E[B - V]$. Furthermore, the F-test does not reject, with regard to a linear trend in α and δ, the hypothesis of a constant excess, which is 0.01 and 0.12 for the clusters A and B respectively.

The result of the photometric analysis is given in Table 1. Star #148 is too blue by 0.04 mag with respect to cluster B sequence. Stars #184, 187 and 283 are a little too bright with respect to cluster B sequence in the V vs X diagram (see Fig. 4), but we kept them as cluster members: their V and X values are affected by evolutionary effects and, moreover star #187 is a variable Be star (see Sect. 5). Stars #162 and 207 are bluer than the main sequence (see Fig. 2), nevertheless they belong to cluster B: indeed, they are Bp-Ap stars according to Maitzen & Catalano (1986) and these stars have bluer temperature indices

Table 1. Membership of the stars of NGC 2451 measured in Geneva photometry. The parallax π is from the HIPPARCOS Catalogue (ESA, 1997), the proper motions $\mu_\alpha \cos\delta$ and μ_δ are from the HIPPARCOS Catalogue (stars having also a parallax measurement) or from the PPM Catalogue (Bastian et al, 1993), and the spectral types from the SIMBAD database. The last four columns indicate the conclusion of the membership analysis: A for "cluster A", B for "cluster B", non for "non-member", bcgd for "background", frgd for "foreground", btwn for "between A and B", red for "too reddened", ev for "too evolved".

No	π [mas]	$\mu_\alpha \cos\delta$ [mas/yr]	μ_δ [mas/yr]	Sp	$\mu_{\alpha,\delta}$ criterion	π criterion	Photometry criterion	Membership
003	–	–	–	–	–	–	btwn	–
015	–	–	–	–	–	–	btwn	–
022	–	–	–	B9V	–	–	B	B
036	–	–	–	A0Vp	–	–	B	B
047	–	–	–	A3V	–	–	A	A
050	–	–	–	–	–	–	A	A
057	–	–	–	–	–	–	A	A
073	–	–	–	–	–	–	A	A
089	–	–	–	–	–	–	A	A
094	–	–	–	–	–	–	A	A
097	–	–	–	–	–	–	A	A
103	–	–	–	–	–	–	red, bcgd	–
115	–	–	–	–	–	–	A	A
131	4.04 ± 0.60	-8.41 ± 0.44	7.13 ± 0.54	B9V	B	A	A	–
141	1.10 ± 0.82	-6.57 ± 0.74	3.10 ± 0.75	B9III-IV	B	bcgd	bcgd, red	–
145	–	-20.4 ± 3.1	3.0 ± 3.3	B9.5V	A	–	A	A
148	–	-6.0 ± 3.0	-6.0 ± 3.0	B8/B9V	B	–	B?	B?
154	5.76 ± 0.54	-12.05 ± 0.45	60.26 ± 0.46	K4III	non	A	older	–
161	–	-20.4 ± 2.9	7.0 ± 3.0	A0V	A	–	A	A
162	–	-4.8 ± 2.7	1.0 ± 2.8	B9	B	–	B	B
163	8.29 ± 0.55	17.02 ± 0.50	-35.32 ± 0.48	G8III	non	frgd	frgd, ev	–
175	5.68 ± 0.46	-21.35 ± 0.41	16.03 ± 0.42	B2.5V	A	A	A	A
179	–	-13.2 ± 3.1	2.0 ± 3.4	B9:V	B	–	bcgd	–
182	5.33 ± 0.53	-22.54 ± 0.50	16.90 ± 0.49	B5Vn	A	A	A	A
184	2.92 ± 0.49	-10.37 ± 0.46	9.71 ± 0.44	B2.5V	B	B	B	B
186	2.13 ± 0.70	-7.39 ± 0.62	5.32 ± 0.67	B7V	B	B	B	B
187	2.41 ± 0.49	-1.41 ± 0.40	-3.89 ± 0.46	B6IVe	B	B	B	B
188	1.66 ± 0.74	-6.67 ± 0.56	3.00 ± 0.68	B9V	B	bcgd	btwn	–
193	–	-2.4 ± 3.2	-39.0 ± 3.3	F0V:	non	–	ev, older	–
202	3.15 ± 0.65	-8.16 ± 0.56	9.09 ± 0.65	B9V	B	B	A	–
203	5.28 ± 0.50	-20.74 ± 0.47	16.34 ± 0.47	B5V	A	A	A	A
207	–	-4.8 ± 3.0	-2.0 ± 3.1	B9p	B	–	B	B
209	5.01 ± 0.56	-17.80 ± 0.53	16.15 ± 0.70	B7V	A	A	A	A
214	–	-22.8 ± 3.0	6.0 ± 3.0	A7V:	A	–	A	A
218	4.87 ± 0.61	-22.57 ± 0.53	14.77 ± 0.61	B9V	A	A	A	A
223	2.81 ± 0.60	-11.50 ± 0.53	4.61 ± 0.65	G6/G8III	B	B	older	–
228	–	–	–	A0Vn	–	–	A	A
233	5.62 ± 0.57	-21.41 ± 0.50	15.59 ± 0.67	B9Vsp	A	A	A	A
237	2.22 ± 0.77	-7.73 ± 0.65	4.22 ± 0.87	B8III	B	B	bcgd, red	–
239	5.96 ± 0.63	-23.00 ± 0.55	15.31 ± 0.66	B9V	A	A	A	A
243	2.62 ± 0.79	-9.37 ± 0.65	5.45 ± 0.88	B8V	B	B	B	B
244	–	-21.6 ± 3.2	7.0 ± 3.4	A3V	A	–	A	A
245	–	–	–	A5	–	–	A	A
246	5.36 ± 0.57	-22.23 ± 0.45	15.72 ± 0.62	B7V	A	A	A	A
248	–	-21.6 ± 3.5	0.0 ± 3.7	A0V	A	–	A	A
249	–	–	–	A0V	–	–	A	A
250	–	3.6 ± 3.1	-3.0 ± 3.2	A7IIIp	B	–	ev, older	–
251	3.54 ± 0.64	-11.98 ± 0.62	5.13 ± 0.73	B3IV	B	B	B	B
254	2.35 ± 0.55	-10.77 ± 0.45	5.97 ± 0.58	K2.5Ib-II	B	B	B	B
255	4.21 ± 0.57	-21.58 ± 0.49	14.97 ± 0.60	A0IV	A	A	A	A
256	5.27 ± 0.61	-23.45 ± 0.49	15.65 ± 0.68	B9V	A	A	A	A

Table 1. (continued)

No	π [mas]	$\mu_\alpha \cos\delta$ [mas/yr]	μ_δ [mas/yr]	Sp	$\mu_{\alpha,\delta}$ criterion	π criterion	Photometry criterion	Membership
259	–	–	–	F0IV-V:	–	–	A	A
260	–	-20.4 ± 2.9	14.0 ± 2.9	A8/A9V	A	–	A	A
266	–	-21.6 ± 3.2	-7.0 ± 3.4	A0IV	A	–	btwn	–
267	5.16 ± 0.53	-19.53 ± 0.45	12.37 ± 0.54	B7V	A	A	A	A
268	0.54 ± 1.03	-7.94 ± 0.91	3.77 ± 1.10	B8V	B	bcgd	ev, bcgd	–
277	4.76 ± 0.55	-22.17 ± 0.48	15.50 ± 0.52	B8III	A	A	A	A
281	5.46 ± 0.56	-32.95 ± 0.50	-6.95 ± 0.56	F3IV	non	A	ev, older	–
283	2.63 ± 0.53	-9.94 ± 0.50	4.69 ± 0.58	B2.5III	B	B	B	B
284	2.22 ± 0.84	-12.08 ± 0.70	11.24 ± 0.86	B9Vn	B	B	bcgd, ev	–
285	–	-25.2 ± 3.1	8.0 ± 3.3	A3V	A	–	A	A
291	–	-1.2 ± 2.9	1.0 ± 3.1	B8/B9V	B	–	B	B
297	–	7.2 ± 2.8	13.0 ± 2.7	F2/F3V	non	–	A	–
305	–	-12.0 ± 3.0	16.0 ± 3.2	F0V	A	–	A	A

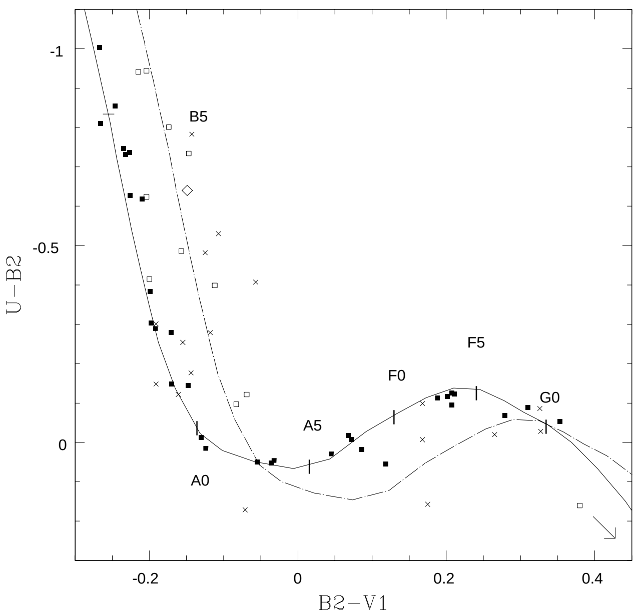

Fig. 5. Colour-colour diagram for the same stars as in Fig. 2. The ZAMS for cluster A (solid line) and B (dot-dashed line) are displayed. The arrow refers to the supergiant #254, which has values $[U-B_2]$ = 1.948 and $[B_2-V_1]$ = 1.374.

like $[B_2-V_1]$ or X than normal stars (Hauck & North 1993), due to the blanketing effect (Gerbaldi et al, 1974). This results from the blocking effect in the wavelength region of the V_1 filter, around 5400 Å. The non-member stars are the following:

1. Foreground star: #163. This star is too bright with respect to its spectral type. This cannot be explained by an evolutionary effect only, and therefore the star must lie in front of cluster A.
2. Stars between clusters A and B: #3, 15, 188 and 266. These stars are located between the Zero-Age Main Sequences of clusters A and B in the diagrams V vs X and X vs $[B_2-V_1]$.
3. Background stars: #103, 141, 179, 237, 268 and 284. These stars are too faint and have a too important colour excess $E[B_2-V_1]$. In addition, stars #268 and 284 have a correct luminosity with respect to cluster B, thus they are older than the cluster members.
4. Too evolved stars: #154, 193, 223, 250 and 281. These stars could be members of clusters A or B but, with respect to the sequences and isochrones for the age of NGC 2451, they are too old.

Table 2. Global parameters for clusters A and B of NGC 2451. Other colour excesses can be derived from the Geneva excess: $E[B_2-V_1] = 0.758E[B-V]$ and $E(B-V) = 0.885E[B-V]$, where $E(B-V)$ is the UBV colour excess. The distances, in the first line, are derived from the adjustment of an isochrone, whereas in the second line they are calculated from the parallaxes (see Sect. 3.2).

	Cluster A	Cluster B
distance [pc]	197 ± 12	358 ± 22
distance (π) [pc]	186^{+12}_{-11}	368^{+72}_{-52}
$E[B-V]$	0.01	0.12
$\log(age)$ [yr]	7.7 ± 0.1	7.7 ± 0.1

3.4. Conclusion on the membership

The conclusions on the membership to cluster A or B, based on the proper motions, parallaxes and photometry analysis, are given in the last column of Table 1. If one of the three criteria is not satisfied, the star is considered as non-member. Among the 64 stars measured in Geneva photometry, 32 belong to cluster A, 13 (12 without star #148) belong to cluster B and 19 are not members of these clusters.

4. Cluster distance and age

In order to determine the distance and reddening of clusters A and B, Zero-Age Main Sequence (Mermilliod, 1981) and isochrones (Schaller et al, 1992) have been adjusted in various photometric diagrams (see Figs. 2 to 5). By using also the relation $A_V = 2.75E[B-V]$ by Cramer (1994b), the values in Table 2 are derived. These distances are in agreement with the

Table 3. Weighted mean value and rms for the 7 Geneva magnitudes of HR 2968, calculated with the 92 measurements obtained in the time interval PJ = 5 000–8 000 (period of constant luminosity). The rms is also given for two standard stars of similar spectral type, one in NGC 2451, #239 (HD 62803), and one analyzed by Kienzle et al. (1998).

		Filter λ_0 [Å]	U 3464	$B1$ 4015	B 4227	$B2$ 4476	$V1$ 5395	V 5488	G 5807
HR 2968	B6IVe	Mean mag.	5.9447	5.8185	5.0000	6.5556	6.7086	6.0133	7.1978
		rms (σ)	0.0075	0.0072	0.0065	0.0072	0.0061	0.0058	0.0067
HD 62803	B9V	rms (σ)	0.0080	0.0063	0.0063	0.0058	0.0060	0.0042	0.0069
HD 93540	B6VI	rms (σ)	0.0070	0.0061	0.0057	0.0058	0.0050	0.0043	0.0048

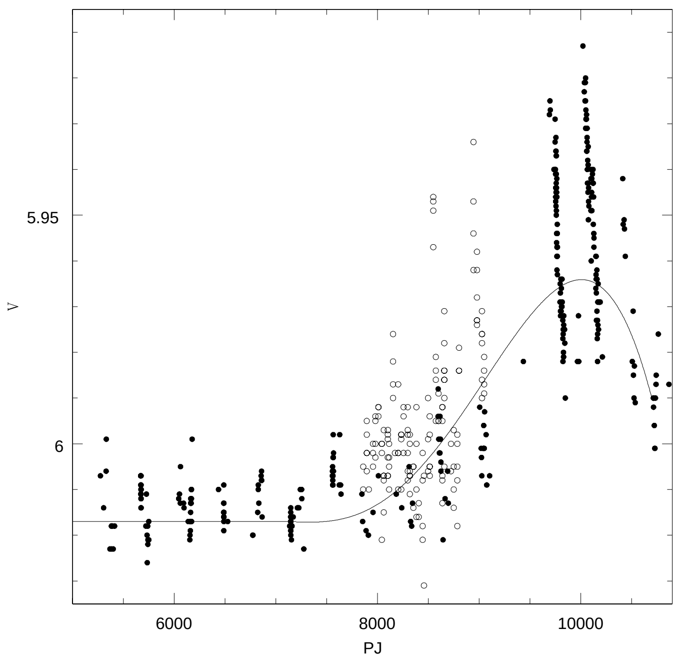

Fig. 6. V magnitude measurements of HR 2968. Corrected Hp magnitudes are identified by open dots and V magnitudes from Geneva photometry by filled dots. The mean luminosity curve is drawn: it represents the long-term variability.

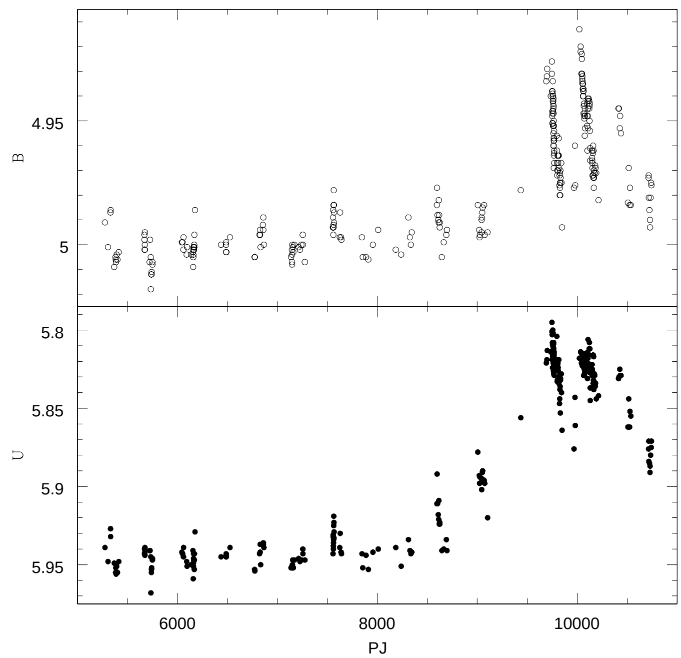

Fig. 7. U and B magnitude measurements of HR 2968.

values derived from the parallaxes (see Sect. 3.2. and Table 2). Note that the best fitted isochrones are essentially constrained by the five brightest stars for cluster A (#175, 182, 203, 246 and 267), and the two stars (#184 and 283) at the top of the sequence and the supergiant #254 for cluster B.

5. The unique Be star HR 2968

As described by Moujtahid et al. (1998), Be stars are known to exhibit several types of photometric variations: i) short-term (multi-)periodic variations with time scales of the order of 0.4 to 3 d, interpreted as due to non-radial pulsations and/or spots on the stellar surfaces; ii) mid-term periodic variations with time scales from days to hundreds of days, observed in binary Be stars; iii) long-term variations with characteristic times from months to decades, related to stellar and/or envelope evolution. In this context, HR 2968 shows a quite exceptional behaviour.

In addition to the 358 observations of HR 2968 in Geneva photometry, the 147 photometric measurements obtained by the HIPPARCOS satellite have been used. To compare the magnitude Hp from HIPPARCOS with V, the following relation of Cramer (1998) for the B stars has been used:

$$V - Hp = 0.0241[B-V]^4 + 0.0238[B-V]^3 + 0.1169[B-V]^2 - 0.0172[B-V] - 0.1408 \quad (1)$$

From this relation, we adopted for HR 2968 the mean correction:

$$V = Hp - 0.004 \quad (2)$$

with a maximum error of ± 0.002 on V induced by the observed colour variations.

Figs. 6 and 7 show that **HR 2968 is a new variable star** exhibiting globally two types of variations, probably related one to the other:

1. A luminosity increase in U, B, V since PJ $\simeq 8\,000$ (long-term variation).
2. An oscillation around the mean light curve since the start of the luminosity increase (mid-term variation).

Table 4. Physical parameters for HR 2968. The results in the first and second lines come from the cluster analysis and the isochrone by Schaller et al. (1992). In addition, the parameters in the first line take account of the duplicity of the star (see Sects. 6 and 7). Those in the third line come from the HIPPARCOS parallaxes, the stellar atmosphere models (Kurucz, 1994) and the calibrations by Cramer (1994b) without taking account of the presence of a companion. Thus the second and the third lines are directly comparable. From the cluster analysis, the temperature is obtained using only the dereddened $[B_2 - V_1]$ index.

	$\log T_{eff}$ $[K]$	$\log g$ $[cgs]$	R $[R_\odot]$	M $[M_\odot]$	$\log L/L_\odot$	M_V	$Distance$ $[pc]$	$\log t$ $[yr]$
Cluster (comp. A)	4.09 ± 0.02	3.8 ± 0.1	5.1 ± 0.6	5.9 ± 0.5	3.22 ± 0.11	−1.76 ± 0.27	358 ± 22	7.7 ± 0.1
Cluster (comp. A+B)	4.12 ± 0.01	3.7 ± 0.1	5.7 ± 0.6	6.2 ± 0.2	3.31 ± 0.04	−2.06 ± 0.10	358 ± 22	7.7 ± 0.1
Individual (comp. A+B)	4.11 ± 0.01	3.7 ± 0.1					433 ± 87	

In the following, the quantity PJ = HJD - 2 440 000 will be used instead of HJD.

5.1. Long-term variation

The mean curve drawn in Fig. 6 represents this long-term variability. During many years, at least from PJ $\simeq$ 5 000 to 8 000, this star has been constant in the optical bands: Table 3 shows that no variability was apparent, except perhaps in the V band (the value $\sigma = 0.0058$ is a bit too large, taken into account the quality of the La Silla site, the performance of our installation and the brightness of the star).

The mean luminosity started to increase in 1990 (PJ $\simeq$ 8 000); this brightening continued until 1995 (PJ $\simeq$ 10 000), then the mean luminosity decreased until now (i.e. 1998). The maximum brightening was 0.12, 0.05 and 0.06 mag for the mean U, B and V light curves respectively. The variation in colour was especially important in those indices containing the U passband, as e.g. $[U - B]$. The mean curve of $[U - B]$ reached an amplitude of variation of about 0.07 mag.

This brightening indicates probably a so-called "phase change" from a normal B to a Be star. Phase changes characterize some well-known Be stars: i) HD 200120 shows three periods of variation (Underhill & Doazan, 1982) from 1904 to the present alternating B-, Be- and Be shell-phases. ii) Pleione behaved as a normal B star from 1905 to 1938. Then, it alternated Be-shell (1938 and 1972) and Be phases (Hirata & Kogure, 1976; Gulliver, 1977). Unfortunately, the spectroscopic data available for HR 2968 are previous to April 1972 (Houk, 1982). It is then impossible to describe this B to Be phase change by analysing spectroscopically the strength of the emission in hydrogen lines. However, some quite clear conclusions can be obtained by comparing the photometric curves of HR 2968 with those described by Harmanec (1994): the mean luminosity variation of HR 2968 corresponds to the "positive correlation" case, i.e. the transition from B to Be phases is accompanied by a luminosity increase and an apparent change of the luminosity class from V-IV to II-I. This change is due to physical properties of the circumstellar envelope but not to variations of the central star (Divan, 1979). Indeed, these characteristics are observed in HR 2968.

The B to Be phase change is analyzed in Fig. 8: the star moves from a position corresponding to $\log g \sim 4$ (normal B star near the main sequence) to a position occupied by the supergiants ($\log g \sim 3$). From this analysis, we postulate that **a B to Be phase change occured at about PJ = 8 000**. The fact that a Be star becomes bluer in $(U - B)$ (i.e. $(U - B)$ more negative) when it brightens, is statistically known (Nordh & Olofsson, 1977; Mennickent et al, 1994). Note in addition that, according to Harmanec's qualitative description, HR 2968 would not be seen equator-on. Indeed, more than 80% of all Be stars rotate in the interval 0.6 $< v/v_c <$ 1.0 (Porter, 1996). The critical equatorial velocity can be deduced from the HR 2968 parameters listed in Table 4: $v_c \sim$ 385 km s^{-1}. It follows, for the measured $v \sin i$ (see Sect. 5.3), than the corresponding aspect angle should be in the interval 30° $< i <$ 60°.

This long-term variability of HR 2968 is very similar to the case of X Persei (Roche et al, 1997; Telting et al, 1998). Two luminosity increases have been observed in 1986-1988 and 1993-1995, with a V amplitude of about 0.6 mag. Between these long-term luminosity increases, the star was stable during about 1 500 d in V magnitude: it was then in an "extended low state" (ELS) according to Roche et al. (1997). In this period no marked signs of emission in H_α were found: the star was discless. In addition, X Persei exhibited the same behaviour as HR 2968 in the diagram $(U - B)$ vs $(B - V)$ (see Fig. 8), interpreted as phase changes B–Be–B. Moreover, X Persei is the optical companion of the X-ray binary pulsar 4U 0352+30. The X-ray source is a neutron star with a spin period of ~836 s (Nagase, 1989; Haberl, 1994). The previous claims for a period of 580 d in X Persei (Hutchings, 1977; Kemp & Barbour, 1983) have not been subsequently confirmed by later studies (Larionov & Larionova, 1989; Reynolds et al, 1992; Roche et al, 1993) and the orbital period of this system remains an unsolved problem.

Another similar case is the star γ CAS (Doazan et al, 1983; Horaguchi et al, 1994). This star exhibits three types of spectra: Be, Be-shell and quasi-normal B. The Be-shell and B phases last only a few years, whereas the Be phase can last more than fifty years. During the Be phase, the V magnitude becomes brighter and the $(B - V)$ color index becomes larger. The whole amplitude of the light variation is approximately 1.5 mag. Moreover, γ CAS behaves as HR 2968 and X Persei in the diagram $(U - B)$

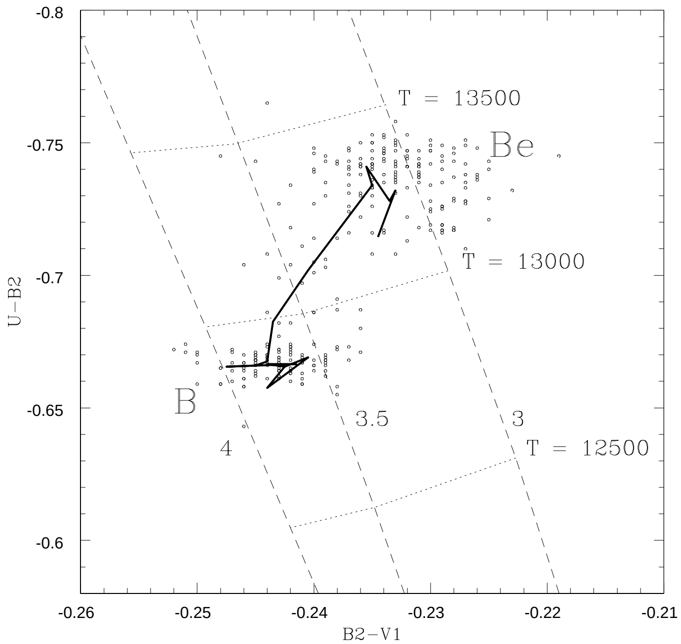

Fig. 8. The B to Be phase change in the $[U-B_2]$ vs $[B_2-V_1]$ diagram. This evolution is due to the circumstellar envelope variations, while the central star remains in the same state. The bold line connects the annual means of the photometric measurements. Curves of iso–$\log g$ and iso-$T_{\rm eff}$ are identified by dashed and dotted lines, according to stellar atmosphere models (Kurucz, 1994) and calibrations by Cramer (1994b).

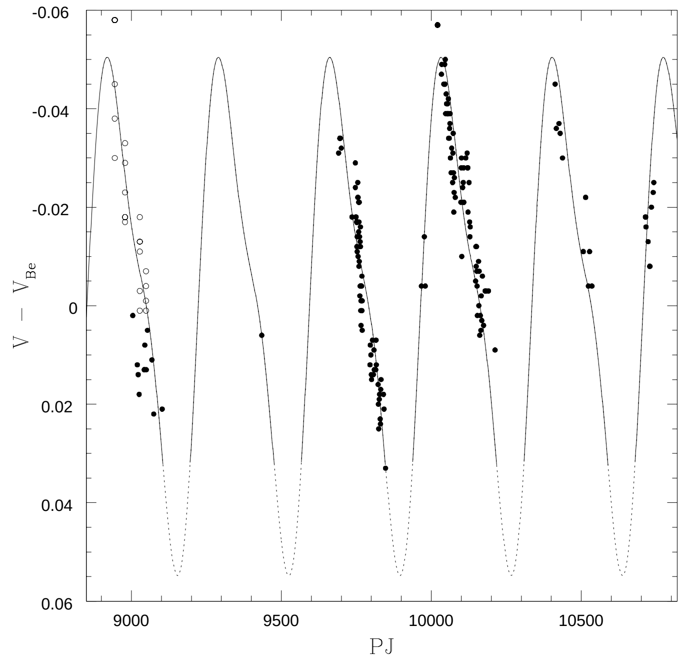

Fig. 9. The mid-term variation in V magnitude. The period of the light curve is 371 d. The corrected Hp magnitudes are identified by open dots and the Geneva V magnitudes by filled dots.

vs $(B-V)$ (see Fig. 8). Another similarity with X Persei, and certainly with HR 2968, is its binarity. Indeed, γ CAS is the optical companion of the X-ray source MX 0053+604 which is either a white dwarf (Murakami et al, 1986) or a neutron star (Frontera et al, 1987).

5.2. Mid-term variation

The start of the increase of the mean luminosity at PJ $\simeq 8\,000$ described in Sect. 5.1. corresponds to the beginning of a periodic luminosity variation. These two facts are certainly related one with the other. From PJ $\simeq 8\,000$ to about PJ $\simeq 8\,500$, the star undergoes a transition from a non periodic to a periodic behaviour. Indeed, the periodic pattern of the variation before PJ $\simeq 8\,000$, whose total amplitude is of the order of $\Delta V \sim 0.028$ mag, is not observed. The amplitude of the periodic variation is enhanced during the long-term brightening. After this phase, the amplitude of the variation seems to remain constant during about 5 periods, and then probably fades near PJ $\simeq 10\,500$.

The period of this oscillation is of course a key parameter to understand its physical origin. There are two difficulties to determine properly this period: i) the star was not observed between July and November; ii) the photometric data must be corrected for the mean long-term variation. In spite of these difficulties, a clear period has been found. The corresponding light curve is shown in Fig. 9. The following comments are to be made:

– The period is 371 d.
– Geneva and HIPPARCOS magnitudes are in perfect agreement.
– Five periods are covered by the monitoring. This brings a strong support to our description.
– The amplitude of the V magnitude variation is enhanced during the long-term brightening and then seems to have been constant during the five periods; the peak-to-peak value is about 0.08 to 0.10 mag in V.
– The fit of a light curve with two harmonics is mathematicaly correct but the exact shape of this light curve could be significantly different than the drawn one.

The period deduced from the V measurements is in agreement with the variations observed in B and U. The amplitude in B was also roughly constant during the observed four periods (there was no HIPPARCOS measurement for B), with a peak-to-peak value of 0.07 to 0.08 mag. On the contrary, the amplitude in U was variable. In particular, as shown by Fig. 7, the peak just after PJ $=10\,000$ was badly defined and has a smaller amplitude.

Periodic or quasi-periodic photometric variations on time scales of some hundred of days have been detected in several Be stars. For example, a photometric period of 138 days and a total amplitude of 0.07 mag have been discovered for HR 3642 (ESA, 1997). These variations are often superimposed to long-term variations (as in HR 2968), see for example HR 3237 (Hubert & Floquet, 1998). However, the case of HR 2968 is quite remarkable because the periodic variability with $P \sim 371$ d appeared when the mean luminosity increased.

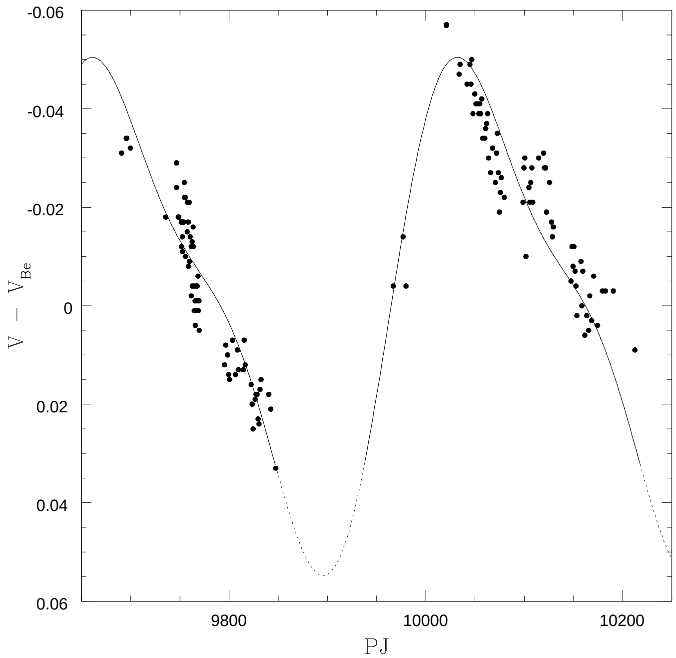

Fig. 10. A detailed vue of the light curve shape in V magnitude. The light variations along the fitted curve are not regular.

5.3. Short-term variation

Many Be stars show short-term variations, with characteristic times or periods of the order of 0.4 to 3.0 days (Barrera et al, 1991), which are often related to their rotation period. In the case of HR 2968, the rotation period is of the order of 1.3 d, this value being deduced from the value of $v \sin i$ = 200 km s^{-1} (Slettebak, 1982) and the star radius R= 5.1 R$_\odot$ (see Sect. 6 and Table 4). Using a sample of 86 bright Be stars south of declination $-20°$, Stagg (1987) estimated that short-term variability seems to occur in about half of the Be stars and found HR 2968 stable, but on the basis of only 4 measurements. From our monitoring, **no short-term variation was found in the period range of a few days**.

5.4. Light curve shape

A careful examination of Fig. 9 reveals that the light variations are not perfectly regular along the fitted curves. This characteristics is clearly shown up by Fig. 10. The high precision of the measurements and the good continuity of the monitoring allow to put into evidence the existence of "steps" or "jumps" during the light decrease and to suspect that these characteristics do not appear at the same phase at each cycle.

6. Physical parameters of HR 2968

Only the photometric data prior to PJ = 8 000 (when the star had no noticeable long-term photometric variations) are used to determine the physical parameters of the star. According to its cluster membership, a precise mass can be obtained. The adjustment of the theoretical isochrone of Schaller et al. (1992) to the data points of the members of NGC 2451 B in the various photometric diagrams allows the determination of the physical parameters of HR 2968 given in Table 4. Moreover, this determination takes account of the duplicity of the star (see Sect. 7): the companion affects the V magnitude (by about $\Delta V \sim 0.13$ to 0.75 mag). The values of $\log T_{\rm eff}$ and $\log g$ can be compared to those obtained according to stellar atmosphere models (Kurucz, 1994) and calibrations by Cramer (1994b) (see Table 4 and Fig. 8, the parameters of this figure are not corrected from the duplicity). The individual distance of HR 2968 from the HIPPARCOS parallax is also given in Table 4. Its value is slightly larger than those stemming from the photometric analysis and from the mean parallax of the cluster. However, these three distances are compatible within one sigma.

7. A model for HR 2968

The observational facts which must be explained by a model of HR 2968 are the following:

- The star is a Be-type of 5.9 M$_\odot$.
- After at least 8 years of constant luminosity, the star had exhibited (since 1990) a progressive increase of its mean luminosity during about 2 000 d, followed by a decrease apparently steeper. At the maximum of the mean luminosity, the increase was ~0.06 mag in V.
- The photometric characteristics of this mean luminosity variation are similar to those of other Be stars during their B to Be phase changes.
- Related to this mean luminosity variation, a periodic light variation was observed with a period of 371 d and a peak-to-peak amplitude in V magnitude of 0.08 to 0.10 mag. This kind of periodic variation was present during the entire phase of the mean luminosity increase (at least 5 periods have been well described).

The model we propose for HR 2968 is qualitatively the following:

- The Be star is the main component of a binary system having an eccentric orbit of period 371 d.
- In 1990, the rapidly rotating Be star was temporarily surrounded by matter expelled in its equatorial plane (development of the Be phase).
- At each periastron passage, the companion star interacts gravitationally and/or radiatively with the disk around the Be star. This interaction induces a periodic modulation of the luminosity of the system (stars and disk).
- Besides, due to a large separation of both components, the orbital axis is not necessarily aligned with the Be rotation axis which could be seen rather pole-on (see Sect. 5.1). Therefore, the luminosity variation, with a period of 371 d, could be reinforced by a reflecting effect on the disk. This could also be the cause of the "steps" observed during the light decrease (see Fig. 10).

A crucial element is of course to know whether HR 2968 is member of a binary system or not. Five radial velocity measure-

Table 5. Radial velocities for HR 2968 according to Evans (1967), Buscombe et al. (1965) and Wilson (1953).

HJD -2400000	V_r $(km\,s^{-1})$
24993.5	1.
25259.7	29.
25602.6	39.
36621.9	$-19.$
37661.0	28.

Table 6. Orbital parameters deduced for the binary system.

P [days]	e	$V_\circ$ [km s^{-1}]	K_1 [km s^{-1}]	$a_1 \sin i$ 10^6 [km]	$f_1(M)$ M$_\odot$	σ(O−C) [km s^{-1}]
371	0.7	21.3	50	190	1.5	4.0
± 6	± 0.1	± 4.0	± 12	± 35	± 0.9	

ments have been found in the literature (Evans, 1967; Buscombe et al, 1965; Wilson, 1953). They are listed in Table 5. With the hypotheses that none of these values is aberrant and that their uncertainties are a few km s^{-1}, the variability of HR 2968 in radial velocity is quite clear and is in favour of an orbital motion. Let us mention that this star is declared "SB" in the Bright Star Catalogue (Hoffleit, 1982), and that Morris (1961), in a study of the spectral types of the stars in Scorpio-Centaurus association, postulated that HR 2968 would be a binary star.

Several orbital parameters are listed in Table 6. The orbital period is deduced from the light curve analysis. The isochrone adjusted to cluster B gives an estimation of the mass of the primary. The system velocity is obtained by calculating the mean of the radial velocities of stars #184 and 254 (Campbell et al, 1911; Campbell & Moore, 1928; Neubauer, 1930; Sowell, 1987). These two stars are members of cluster B and their radial velocities can be considered as constant. With the values of P and V_0 fixed, the orbital elements given in Table 6 have been derived. It is especially noteworthy that a good orbital solution can be found. The eccentricity $e \cong 0.7 \pm 0.1$ is in perfect agreement with our model. The mass function $f_1(M) = (a_1 \sin i)^3/P^2 = (M_2 \sin i)^3/(M_1 + M_2)^2$ gives a lower limit for the secondary mass: $M_2 \gtrsim 5.5 \pm 2$ M$_\odot$. With this mass, the secondary cannot be a white dwarf nor a neutron star. If, in addition, we exclude the hypothesis that the secondary is a black hole, this component must be a main sequence star of mass lower than the primary mass ($M_2 \lesssim 5.9$ M$_\odot$). In consequence, we have $3.5 \lesssim M_2 \lesssim 5.9$ M$_\odot$. The semimajor axis, deduced from the third Kepler law, is $a = a_1 + a_2 = 480 \pm 20$ R$_\odot$. Besides, the distances between both components at the periastron and at the apastron are respectively: 145 ± 50 R$_\odot$ and 815 ± 60 R$_\odot$. Finally, the inclination i can be estimated: $i = 70 \pm 20°$. This result confirms the hypothesis that the orbital and the Be rotation axes would not be aligned.

Our model presents some similarities with the schematic model for transient Be/X-ray binary systems (van den Heuvel & Rappaport, 1987). In these systems, a neutron star moves in a moderatly eccentric orbit around a Be star, which is much smaller than its own critical equipotential lobe. The rapidly rotating Be star is temporarily surrounded by matter expelled in its equatorial plane. Near its periastron passage, the neutron star enters this circumstellar matter and the resultant accretion produces an X-ray outburst lasting several days to weeks. Some of the X-ray/Be systems are of a particular interest for our purpose:

- V0332+53/BQ Cam is a system with an orbital period of 34.25 d and a spin period of 4.37 s. X-ray flares have been observed simultaneously to maxima in the infrared light curves, i.e. when the amount of circumstellar material around the Be star is supposed to be maximum (Coe et al, 1993).
- A0535+26/HDE 245770 is a system with an orbital period of ∼110 d and an X-ray pulsed period of ∼104 s (Giovannelli et al, 1985). An optical photometric variability with a period equal to the orbital period (110 d) seems to have been detected by Guarnieri et al. (1985).

In the case of HR 2968, the X-ray luminosity measured by the ROSAT satellite was $10^{30.07}$ ergs s^{-1} (Berghöfer et al, 1996). This value is in agreement with the X-ray luminosity of stars of same spectral type (Meurs et al, 1992) and is thus not exceptional. This could be a confirmation that the secondary component is a main sequence star. However, it must be noted that at the moment of the X-ray measurement (1990) the circumstellar shell around the Be star was probably not important.

8. Conclusion

The main results of this study can be found in the Abstract. One of the most exciting results is the discovery of a periodicity in the light variability of HR 2968. Thus, a mid-term radial velocity survey is to be done to confirm the existence of a companion with an orbital period of 371 days. The study of this Be star is a good example to illustrate the absolute necessity of long-term monitorings in order to describe completely the complex behaviour of such stars.

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