Astron. Astrophys. 330, 145–154 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Hipparcos photometry of Herbig Ae/Be stars*

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Received 8 August 1997 / Accepted 12 September 1997

Abstract. The photometric behaviour of a sample of 44 Herbig Ae/Be (HAeBe) candidate stars was studied using a uniform set of optical photometry obtained by the Hipparcos mission. Astrophysical parameters (distance, temperature, luminosity, mass, age) of this sample of stars were derived as well by combining the astrometric data provided by Hipparcos with data from literature. Our main conclusions can be summarized as follows: (1) More than 65% of all HAeBe stars show photometric variations with an amplitude larger than $0\overset{\mathrm{m}}{.}05$; (2) HAeBes with a spectral type earlier than A0 only show moderate (amplitude $< 0\overset{\mathrm{m}}{.}5$) variations, whereas those of later spectral type can (but not necessarily have to) show variations of more than $2\overset{\mathrm{m}}{.}5$. We explain this behaviour as being due to the fact that stars with lower masses become optically visible, and hence recognizable as Herbig Ae stars, while still contracting towards the zero-age main sequence (ZAMS), whereas their more massive counterparts only become optically visible after having reached the ZAMS; (3) The Herbig stars with the smallest infrared excesses do not show large photometric variations. This can be understood by identifying the stars with lower infrared excesses with the more evolved objects in our sample; (4) No correlation between the level of photometric variability and the stellar $v \sin i$ could be found. If the large photometric variations are due to variable amounts of extinction by dust clouds in the equatorial plane of the system, the evolutionary effects probably disturb the expected correlation between the two.

Key words: circumstellar matter – stars: distances – HR diagram – stars: pre-main sequence – stars: variables

1. Introduction

Lately, the group of Herbig Ae/Be (HAeBe) stars, objects which are believed to be intermediate-mass (2–10 $M_\odot$) stars still in their phase of pre-main sequence (PMS) contraction, has received a great deal of interest. In his original paper, Herbig (1960a) selected a sample of candidate intermediate-mass young stellar objects with the following properties: (1) spectral type earlier than F0; (2) presence of emission lines; (3) location in an obscured region; (4) association with a fairly bright reflection nebula. Later, these criteria were extended to include less massive stars, as well as stars which are situated in more isolated regions. Nowadays, some authors also include stars without strong emission lines in samples of HAeBe stars (Malfait et al. 1997), making the distinction with the Vega-type stars somewhat vague. In this paper, we will adopt the following criteria for inclusion of stars in our sample: (1) spectral type B, A or F; (2) luminosity class III–V; (3) emission component(s) in Hα; (4) presence of infrared emission due to circumstellar dust. The first two criteria will eliminate most confusion with evolved objects, the third characteristic will eliminate confusion with Vega-type stars, and the last criterion will exclude the classical Be stars from our sample. Yet these criteria may still select a small fraction of evolved massive stars, so one has to be careful in identifying HAeBe stars with PMS objects.

One of the best studied characteristics of the group of HAeBe stars is their photometric behaviour. A significant fraction of HAeBes show usually irregular variations up to several magnitudes in the visual. These have been explained using several models. The large ($> 0\overset{\mathrm{m}}{.}5$) irregular variations in brightness seen in the UXOR subgroup (named after their prototype UX Ori) of the Herbig stars, with a typical time scale of weeks, can be explained as being due to variable amounts of extinction by, presumably circumstellar, dust of the starlight (e.g. Bibo & Thé 1991). Superimposed on this, variations on the $0\overset{\mathrm{m}}{.}1$ level, with a time scale from hours to days, can be explained as due to clumpy accretion (Pérez et al. 1992) or as due to chromospheric activity (star spots; Catala et al. 1993). More regular variations at the millimagnitude level have been explained as caused by stellar pulsations when a PMS star is in the same instability strip in the Hertzsprung-Russell diagram (HRD) as the evolved δ Scuti objects (Kurtz & Marang 1995).

In a recent *letter* (van den Ancker et al. 1997b, Paper I), we studied fundamental astrophysical parameters of a small sample of HAeBe stars using Hipparcos data, released to the P.I. prior

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* Based on data from the Hipparcos astrometry satellite.

Table 1. Astrophysical parameters of programme stars. Numbers in parenthesis indicate error estimates in the same units as the corresponding quantities

Probable Herbig Ae/Be candidates

(1) HIP	(2) Name	(3) π [mas]	(4) $f_{\rm rej}$ [%]	(5) d [pc]	(6)	(7) Association	(8)	(9) $d_{\rm lit}$ [pc]	(10) Ref.	(11) $H_{\rm p,min.}$ [$^{\rm m}$]	(12) δH_p [$^{\rm m}$]	(13) n_H	(14) Var.	(15) Sp. Type	(16) Ref.	(17) Hα	(18) Ref.	(19) $v \sin i$ [km s^{-1}]	(20) Ref.	(21) A_V [$^{\rm m}$]	(22) $\log T_{\rm eff}$	(23) $\log L_\star/L_\odot$	(24) M [M$_\odot$]	(25) log(Age) [yr]	(26) Remarks
					D.C.	B.N.	S.A.																		
3401	V594 Cas	3.3(1.6)	0	> 120	L1302	NGC 225	RSF1 Cas	650	(1)	10.45	0.36	167	●	B8eq	(20)	P	(46)	55(5)	(46)	2.14	4.08	> 1.13			
16243	BD+30°549	2.6(1.9)	2	> 120	L1450,L1452	NGC 1333	Per R1	350	(2)	10.48	0.13	83		B8Vpe	(21)					1.89	4.08	> 0.93			
17890	XY Per	8.3(3.5)	17	–	L1442,L1449	Anon.	RSF Per B	350	(2)	9.23	0.38	99	●	A2II+B6e	(22)	D	(46)	95+130	(62)	2.26	4.15	–			vis. bin.
22910	AB Aur	6.9(1.0)	0	144^{+23}_{-17}	L1519,(L1517)	Anon.	Tau R2	140	(3)	7.06	0.06	40	●	A0Ve+sh	(23)	P	(46)	80(5)	(46)	0.50	3.98	$1.68^{+0.13}_{-0.11}$	2.4(2)	6.3(2)	
23143	HD 31648	7.6(1.2)	0	131^{+24}_{-18}						7.75	0.11	44	●	A3ep+sh	(24)	P	(47)			0.25	3.94	$1.51^{+0.15}_{-0.13}$	2.2(3)	6.4(2)	
23602	UX Ori	0.6(2.5)	0	> 130	(L1616)	Anon.				10.12	1.21	73	●	A3IIIe	(25)	D	(48)	70(6)	(46)	0.37	3.93	> 0.40			
24552	HD 34282	6.1(1.6)	2	160^{+60}_{-40}						9.87	0.77	79	●	A0e	(26)					0.59	3.98	$0.68^{+0.27}_{-0.21}$	–	–	
25253	HD 35187	6.7(2.5)	7	–						7.85	0.21	68	●	A2–3IV/Ve	(27)	D	(27)	105(9)	(46)	0.65	3.95	–			vis. bin.
25299	V346 Ori	1.6(2.0)	0	> 130		(Anon.)	Ori OB1 a	400	(4)	10.21	0.14	141	●	A5III:e	(28)	S	(49)			0.43	3.91	> 0.21			
25540	CO Ori	−1.8(2.8)	0	> 120		C54				10.47	1.28	66	●	F9:e	(29)	P	(50)			1.83	3.79	> 0.53			vis. bin.
25546	HD 35929	0.9(0.9)	2	> 360	(L1641)		Ori OB1 c	430	(4)	8.19	0.05	85		F0IIIe	(29)	S	(51)	150(30)	(49)	0.40	3.86	> 1.92			
25793	HD 36112	4.9(1.2)	0	200^{+60}_{-40}						8.33	0.06	77		A5IVe	(30)	S	(52)			0.22	3.91	$1.35^{+0.24}_{-0.18}$	2.0(3)	6.5(3)	
26327	V380 Ori	3.7(5.5)	8	–	L1641	NGC 1999	Ori OB1 c	430	(4)	10.26	0.33	98	●	A1:e	(22)	S	(50)			1.43	3.97	–			IR bin.
26403	BF Ori	−0.7(1.8)	0	> 210	L1641	NGC 1980	Ori OB1 c	430	(4)	9.70	2.49	92	●	A5–6IIIe	(29)	D	(49)	100(10)	(46)	0.26	3.90	> 0.56			
26752	HD 37806	1.1(1.1)	0	> 230	L1630	(Anon.)	Ori OB1 b1	500	(4)	7.91	0.07	128	●	A2Vpe	(31)	D	(53)	120(30)	(46)	0.03	3.95	> 1.51			
27059	V351 Ori	3.5(1.6)	2	> 210	L1630		Ori OB1 b1	500	(4)	8.91	0.14	62	●	A7 IIIe	(32)	D	(32)			0.50	3.88	> 1.14			
28582	HD 250550	1.7(1.5)	0	> 160	L1586,L1587		Gem OB1	280	(5)	9.49	0.10	77		B4–5IIIe	(29)	P	(54)	110(9)	(46)	0.71	4.20	> 1.33			
31042	HD 46060	4.6(2.5)	10	–		Anon.	Mon R2	760	(6)	8.85	0.15	176	●	B3ne	(21)					1.61	4.27	–			
31235	HD 259431	3.5(1.4)	0	> 130	L1605	NGC 2247	Mon R1	800	(7)	8.67	0.08	58		B1Ve	(29)	D	(55)	90(8)	(46)	1.61	4.41	> 2.37			
34042	Z CMa	−0.9(2.2)	0	> 180	L1657	S295	CMa R1	1150	(7)	9.56	0.47	78	●	F6IIIe	(29)	P	(50)	< 130:	(63)	2.42	3.80	> 1.72			IR bin.
35488	NX Pup	2.0(2.4)	33	–	DC256.2-14.4	Anon.		450	(8)	9.55	1.18	107	●	A9–F0Ve	(20)	D	(49)	120(10)	(46)	0.59	3.87	–			vis. bin.
36068	HD 58647	3.6(0.8)	1	280^{+80}_{-50}						6.85	0.03	97		B9IVe	(26)	D	(49)	280(50)	(49)	0.50	4.03	$2.48^{+0.22}_{-0.17}$	4.2(6)	5.2(4)	
48269	HD 85567	1.0(0.7)	1	> 480	(DC281.7-4.4)					8.54	0.06	133	●	B7–8Ve	(29)	P	(51)			0.81	4.10	> 2.54			
54413	HD 97048	5.7(0.8)	0	180^{+30}_{-20}	DC297.2-15.6	S135	CED 111	160	(9)	8.50	0.05	106		B9–A0ep+sh	(33)	P	(51)	140(20)	(46)	1.24	4.00	$1.61^{+0.13}_{-0.10}$	2.5(2)	> 6.3	
55537	HD 98922	1.0(0.6)	0	> 540	(DC288.3+7.3)					6.77	0.04	165	●	B9Ve	(34)	P	(51)			0.34	4.02	> 2.96			Sp. bin.
56379	HD 100546	9.7(0.6)	0	103^{+7}_{-6}	(DC296.2-7.9)			170	(10)	6.68	0.19	131	●	B9Vne	(35)	D	(49)	250(50)	(49)	0.28	4.02	$1.51^{+0.06}_{-0.05}$	2.4(1)	> 7.0	
58520	HD 104237	8.6(0.5)	0	116^{+8}_{-7}			Cha III	84	(10)	6.59	0.11	134	●	A4IVe+sh	(29)	D	(51)			0.31	3.93	$1.55^{+0.06}_{-0.05}$	2.3(1)	6.3(1)	
77542	HD 141569	10.1(0.8)	2	99^{+9}_{-8}	(L169)	Anon.				7.14	0.03	91		B9.5Ve	(36)	D	(56)	236(9)	(27)	0.47	4.00	$1.35^{+0.08}_{-0.07}$	2.3(1)	> 7.0	IR bin.
78092	HD 142527	5.0(1.2)	0	200^{+60}_{-40}		Anon.				8.42	0.09	91	●	F7IIIe	(29)	S	(51)			1.49	3.80	$1.84^{+0.23}_{-0.19}$	3.5(6)	5.0(5)	
78943	HD 144432	4.0(1.5)	0	> 200			Sco R1			8.24	0.05	102		A5Ve	(29)	D	(57)	74(2)	(27)	0.56	3.91	> 1.48			
79080	HR 5999	4.8(0.9)	0	210^{+50}_{-30}	DC339.7+9.2	S14	Lupus 3	270	(11)	6.87	1.02	126	●	A5–7III/IVe+sh	(37)	D	(58)	180(20)	(19)	0.47	3.90	$1.93^{+0.19}_{-0.14}$	3.2(5)	5.7(3)	vis. bin.
81624	HD 150193	6.7(1.7)	3	150^{+50}_{-30}	L1729		Sco R1	160	(12)	8.91	0.05	94		A1Ve	(38)	D	(51)	100(30)	(20)	1.61	3.97	$1.47^{+0.25}_{-0.19}$	2.3(2)	> 6.3	vis. bin.
82747	AK Sco	6.9(1.4)	0	150^{+40}_{-30}	DC348.0+3.7			200	(13)	9.01	0.60	55	●	F5+F5IVe	(13)	C	(51)	19(1)	(13)	0.62	3.81	$0.88^{+0.20}_{-0.16}$	–	–	Sp. bin.
85755	51 Oph	7.7(0.9)	0	131^{+17}_{-13}						4.79	0.02	66		B9.5Vne	(39)	D	(51)	267(5)	(27)	0.15	4.00	$2.39^{+0.11}_{-0.09}$	4.0(3)	5.5(2)	
87819	HD 163296	8.2(1.0)	0	122^{+17}_{-13}						6.88	0.07	95	●	A1Ve	(38)	D	(59)	120(30)	(20)	0.25	3.97	$1.48^{+0.12}_{-0.10}$	2.3(1)	6.6(4)	
90617	V431 Sct	−2.1(4.2)	6	–	(L481)					11.41	0.60	35		B1e	(40)					–	4.05	–			
93449	R CrA	122(68)	5	–	DC359.9-17.9	NGC 6729		130	(14)	10.63	1.67	69	●	A1e–F7e var	(29)	D	(50)			1.64	3.93	–			Sp. var.
94260	HD 179218	4.1(0.9)	0	240^{+70}_{-40}	(L693)					7.41	0.03	77		B9e	(41)			60(6)	(64)	1.27	4.02	$2.50^{+0.22}_{-0.17}$	4.3(5)	5.0(6)	
98719	V1295 Aql	0.2(1.1)	2	> 290						7.85	0.05	100	●	A2IIIe	(42)	P	(42)			0.19	3.95	> 1.80			
100289	BD+40°4124	9.3(2.2)	18	–	L888/L895	NGC 6910	Cyg R1	980	(15)	10.47	0.26	129	●	B2Ve	(43)	C	(60)	180(20)	(20)	3.16	4.34	–			IR bin.
103763	HD 200775	2.3(0.6)	0	430^{+160}_{-90}	L1174	NGC 7023	Cep R2	440	(16)	7.39	0.04	108	●	B2.5IVe	(44)	D	(61)	40(4)	(46)	1.92	4.31	$3.89^{+0.26}_{-0.21}$	10(2)	4.2(3)	IR bin.
107207	V361 Cep	3.0(6.1)	0	> 50		NGC 7129		1250	(17)	10.85	0.13	49		B3ne	(20)	D	(46)	180(50)	(46)	1.89	4.27	> 0.71			
107983	BD+46°3471	−0.8(1.5)	0	> 280	L1055	S125	(IC 5146)	900	(18)	10.17	0.11	110		A4e+sh	(20)	P	(46)	150(12)	(46)	0.90	3.93	> 1.17			
114995	MWC 1080	−7.0(3.3)	6	–	L1238	S158		2200	(19)	11.31	0.39	104	●	B0e	(45)	P	(60)	100(30)	(62)	5.27	4.48	–			vis. bin.

Table 1. (Continued)

Low-mass young stellar objects

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
HIP	Name	π	$f_{\rm rej}$	d	Association			$d_{\rm lit}$	Ref.	$H_{\rm p,min.}$	δH_p	n_H	Var.	Sp. Type	Ref.	Hα	Ref.	$v \sin i$	Ref.	A_V	$\log T_{\rm eff}$	$\log L_\star/L_\odot$	M	log(Age)	Remarks
		[mas]	[%]	[pc]	D.C.	B.N.	S.A.	[pc]		[$^{\rm m}$]	[$^{\rm m}$]							[km s^{-1}]		[$^{\rm m}$]			[M$_\odot$]	[yr]	
24855	HD 34700	0.9(1.8)	0	> 180						9.29	0.05	74	●	G0Ve	(26)	S	(52)			0.68	3.78	> 1.23			
26295	CQ Tau	10.1(2.0)	0	100^{+25}_{-17}			Tau T4	130	(65)	9.96	1.07	90	●	A1–F5IVe	(66)	D	(46)	110(20)	(46)	0.96	3.84	$-0.21^{+0.19}_{-0.16}$	–	–	
58285	T Cha	15.1(3.3)	0	66^{+19}_{-12}	DC300.2-16.9		Cha I	160	(9)	10.73	2.69	91	●	G2:e	(29)	P	(67)	48(10)	(68)	1.64	3.77	$0.13^{+0.22}_{-0.17}$	1.1(2)	> 7.1	

Isolated B[e] stars

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
HIP	Name	π	$f_{\rm rej}$	d	Association			$d_{\rm lit}$	Ref.	$H_{\rm p,min.}$	δH_p	n_H	Var.	Sp. Type	Ref.	Hα	Ref.	$v \sin i$	Ref.	A_V	$\log T_{\rm eff}$	$\log L_\star/L_\odot$	M	log(Age)	Remarks
		[mas]	[%]	[pc]	D.C.	B.N.	S.A.	[pc]		[$^{\rm m}$]	[$^{\rm m}$]							[km s^{-1}]		[$^{\rm m}$]			[M$_\odot$]	[yr]	
30800	HD 45677	2.8(1.1)	0	> 300						7.89	0.46	116	●	B2III–V[e]	(69)	D	(71)	70(20)	(73)	0.87	4.33	> 2.60			
32923	HD 50138	3.5(0.8)	0	290^{+90}_{-50}						6.55	0.10	82	●	B5V[e]	(29)	D	(72)	150	(74)	0.59	4.19	$2.85^{+0.23}_{-0.18}$	5.0(1.0)	5.0(5)	
53444	GG Car	−1.8(1.7)	2	> 200						8.59	0.42	124	●	B0–2[e]+K3:	(70)	D	(51)			2.57	4.41	> 3.17			vis. bin.
63547	CD−48°7859	−1.6(2.3)	3	> 140						10.52	0.18	161	●	B6:III[e]	(29)	S	(51)			0.74	4.15	> 0.72			
87136	HD 316285	−0.1(1.5)	0	> 220	L34					8.93	0.13	61	●	B0[e]+sh	(70)					6.29	4.48	> 4.74			vis. bin.

Stars lacking evidence for circumstellar dust

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)
HIP	Name	π	$f_{\rm rej}$	d	Association			$d_{\rm lit}$	Ref.	$H_{\rm p,min.}$	δH_p	n_H	Var.	Sp. Type	Ref.	Hα	Ref.	$v \sin i$	Ref.	A_V	$\log T_{\rm eff}$	$\log L_\star/L_\odot$	M	log(Age)	Remarks
		[mas]	[%]	[pc]	D.C.	B.N.	S.A.	[pc]		[$^{\rm m}$]	[$^{\rm m}$]							[km s^{-1}]		[$^{\rm m}$]			[M$_\odot$]	[yr]	
21768	HD 283817	2.5(1.8)	0	> 180	L1538		Tau R2	140	(3)	10.46	0.16	74	●	A3e	(79)					3.41	3.94	> 1.72			Sp. bin.
26594	ω Ori	2.0(0.9)	2	> 210		DG 70	Ori OB1 a	400	(4)	4.44	0.09	76	●	B3IIIe	(80)	D	(22)	160(20)	(20)	0.28	4.23	> 3.42			
28816	17 Lep	3.1(0.7)	0	330^{+90}_{-60}		Anon.		44	(75)	4.96	0.05	195	●	A1Ve+sh+M3III	(81)	P	(81)	105(30)	(39)	0.20	3.97	$3.21^{+0.21}_{-0.17}$	–	–	Sp. bin.
25950	HD 36408	2.9(1.6)	7	–						5.49	0.07	95	●	B7III+B7IV	(82)	S	(84)	60+300	(82)	0.28	4.12	–			vis. bin.
29988	MWC 137	−4.5(4.5)	0	> 110	(L1586,L1587)	S266		1100	(76)	11.78	0.17	59		Bep	(83)	S	(22)			4.53	4.48	> 2.25			
33868	GU CMa	1.1(1.7)	10	–	L1657	S293	CMa R1	1150	(7)	6.52	0.22	81	●	B2Vne	(22)	D	(58)	400(40)	(20)	0.87	4.34	–			vis. bin.
34116	HD 53367	4.1(1.4)	8	–	L1657	S292	CMa R1	1150	(7)	7.03	0.24	78	●	B0IVe	(20)	S	(22)	30(15)		2.23	4.50	–			vis. bin.
43792	HD 76534	2.4(1.3)	1	> 160	DC264.3+1.5	Anon.	Vela R2	830	(77)	8.04	0.08	120	●	B2ne	(20)	D	(85)	110(40)	(20)	1.21	4.34	> 2.48			vis. bin.
72616	HD 130437	−0.6(1.9)	0	> 180	DC318.2-0.6					9.91	0.15	140	●	O8–B0ep	(29)					3.22	4.52	> 3.04			
100628	BD+41°3731	0.4(1.2)	3	> 260	L895	NGC 6914	Cyg R1	980	(15)	9.87	0.09	112		B2ne	(20)	S	(60)	300(20)	(20)	1.02	4.34	> 2.01			IR bin.
113017	IL Cep	1.2(1.7)	1	> 160	L1216	DG188	Cep OB3	690	(78)	9.28	0.08	112	●	B3e	(20)	D	(46)	190(15)	(46)	2.88	4.27	> 2.53			vis. bin.

S: Single Peak Hα profile; D: Double-peaked; P: P-Cygni or inverse P-Cygni profile; C: Complex Hα profile.

References to Table 1: (1) Hagen (1970); (2) Herbertz et al. (1991); (3) Elias (1978); (4) Warren & Hesser (1978); (5) Cantó et al. (1984); (6) Kutner et al. (1980); (7) Herbst et al. (1982); (8) Brandt et al. (1971); (9) Whittet et al. (1997); (10) Hu et al. (1989); (11) Thé & Tjin A Djie (1978); (12) Whittet (1974); (13) Andersen et al. (1989); (14) Marraco & Rydgren (1981); (15) Shevchenko et al. (1991); (16) Whitcomb et al. (1981); (17) Shevchenko & Yabukov (1989); (18) Dobashi et al. (1994); (19) Levreault (1988); (20) Finkenzeller (1985); (21) Racine (1968); (22) Finkenzeller & Mundt (1984); (23) Böhm & Catala (1993); (24) Jaschek et al. (1991); (25) Timoshenko (1985); (26) Cannon & Mayall (1949); (27) Dunkin et al. (1997); (28) Herbig (1960b); (29) de Winter, D., personal communication; (30) Houk, N. 1995, personal communication with B. Zuckerman; (31) Guetter (1981); (32) van den Ancker et al. (1996); (33) Whittet et al. (1987); (34) Houk (1978); (35) Houk & Cowley (1975); (36) Jaschek & Jaschek (1992); (37) Tjin A Djie et al. (1989); (38) Houk & Smith-Moore (1988); (39) Abt & Morrell (1995); (40) Kukarkin (1974); (41) Slettebak (1966); (42) Ringuelet et al. (1987); (43) Hillenbrand et al. (1995); (44) Rogers et al. (1995); (45) Cohen & Kuhi (1979); (46) Böhm & Catala (1995); (47) Morrison, N.D. private communication; (48) Grinin et al. (1994); (49) Grady et al. (1996); (50) Reipurth et al. (1996); (51) van den Ancker, M.E., unpublished spectra Coudé Auxiliary Telescope, La Silla; (52) Zuckerman (1994); (53) Pogodin (1986); (54) Hamann & Persson (1992); (55) Vieira & Cunha (1994); (56) Andrillat et al. (1990); (57) Pérez et al. (1997); (58) Praderie et al. (1991); (59) Pogodin (1994); (60) Férnandez et al. (1995); (61) Beskrovnaya et al. (1994); (62) Herbig & Bell (1988); (63) Davis et al. (1983); (64) Bernacca & Perinotto (1970); (65) Artyukhina (1959); (66) Koval' chuk & Pugach (1992); (67) Alcalá et al. (1994); (68) Chavarria et al. (1989); (69) Feinstein et al. (1976); (70) Lopes et al. (1992); (71) de Winter & van den Ancker (1997); (72) Pogodin (1997); (73) Israelian & Musaev (1997); (74) Houziaux (1960); (75) Jenkins (1952); (76) Cahn et al. (1992); (77) Herbst (1975); (78) Mel' nikov et al. (1995); (79) Walter et al. (1990); (80) Danks & Dennefeld (1994); (81) Welty & Wade (1995); (82) Levato (1975); (83) Sabbadin & Hamzaoglu (1981); (84) Wackerling (1970); (85) Oudmaijer & Drew (1997).

to the publication of the Hipparcos Catalogue (ESA 1997). In addition to measuring astrometric data, the Hipparcos mission also resulted in roughly one hundred optical broadband photometric measurements for each of these targets (van Leeuwen et al. 1997). The recent release of the final version of the Hipparcos Catalogue makes it possible to use these data to study the photometric behaviour of the HAeBe stellar group as a whole in a more systematic and unbiased way than has been done so far. In this paper we will therefore study the level of photometric variability on time scales up to a few years for all HAeBe candidates identified up to date, included in the Hipparcos Catalogue.

2. Data analysis

Our initial sample of stars to include in the present study consisted of all HAeBe candidates from the catalogue of Thé et al. (1994), measured by Hipparcos, together with all emission-line stars from the sample of HAeBe and Vega-type stars from the papers by Sylvester et al. (1996), Grady et al. (1996) and Malfait et al. (1997), as well as a few individual probable HAeBes which were overlooked in these studies. In going through the literature for all these stars, it was noted that several of the stars included in this sample are probably not young stars, although they fulfill all membership criteria of the HAeBe class: ω Ori most definitely is a classical Be star with a history of mass loss (Sonneborn et al. 1988). HD 76534 was suggested to be a classical Be star as well (Oudmaijer & Drew 1997) since it does not have the significant near-IR excess due to hot circumstellar dust found in most HAeBes. A similar conclusion was reached for BD+41°3731 by Bernacca et al. (1995). Our analysis of literature data showed that the same applies for the stars GU CMa, HD 53367 and IL Cep. HD 283817 was shown to be a post-main sequence binary system (Martín 1993), and not a pre-main sequence member of the Taurus-Auriga complex, as suggested by Walter et al. (1990). This is confirmed by the lower limit on the distance towards this star measured by Hipparcos. MWC 137 was once believed to be a Planetary Nebula (Acker et al. 1987), and its true nature is still disputed. The PMS nature of many stars showing B[e] characteristics, like HD 45677 or HD 50138, remains controversial as well. Furthermore, several stars included in the previous studies of HAeBe stars were found to have masses, obtained from their position in the HRD or from literature data, which put them in the range of T Tauris (taken as less massive than 1.5 $M_\odot$), rather than HAeBes. Although young objects as well, these low-mass stars do not belong in an analysis aimed at studying the PMS evolution of intermediate-mass stars.Hence, all these stars were not included in our analysis. An overview of our complete sample and the main results of the Hipparcos measurements are given in Table 1. In the remainder of this paper we will only indicate the probable HAeBe candidates from this Table when referring to our sample.

The first two columns in Table 1 list the number of the star in the Hipparcos Catalogue and a more common identifier. The third column lists the trigonometric parallax measured by Hipparcos and the 1σ uncertainty in this (both in milliarcseconds). The fourth column lists the percentage of measurements that had to be rejected to arrive at the solution for the parallax. In case this percentage is high, the error in the listed parallax can be much higher than that given by the formal standard deviation (Paper I). The fifth column in Table 1 gives the distance, with its 1σ uncertainty, computed from the parallax in the 17 cases in which a 3σ detection was achieved by Hipparcos. In other cases, a 3σ lower limit on the distance is indicated. A dash in this column indicates stars with $f_{\rm rej} > 3\%$, for which the astrometric data was excluded from our discussion. Note that the distances listed in column 6 are simply the inverse of the listed parallax. No correction for the Lutz-Kelker effect (Lutz & Kelker 1973) was applied because this correction will depend on the distribution of the true distances of the sample under consideration (Brown et al. 1997; Oudmaijer et al. 1997), which is essentially unknown for a sample of stars not only concentrated towards galactic star-forming regions, but also selected on historical (i.e. studied previously in literature) rather than on more rational grounds. Since we are only considering cases in which the Hipparcos mission resulted in a better than 3σ detection of the parallax, the correction for the Lutz-Kelker effect is expected to be small and will not seriously affect our results.

Columns 6–8 in Table 1 contain names of the star forming region in which the star is located (although one has to keep in mind that this could be a projection effect). In column 6 an association with a dark cloud from the catalogue of Lynds (1962), or its extension to the southern hemisphere (Hartley et al. 1986) is given. When the name of the dark cloud is in parentheses, this indicates that the star is located near the edge, so the association of the star with the cloud might be doubtful. Note that in Table 1 some stars are associated with several dark clouds. These are local density enhancements in a larger complex, which were given separate designations in the Lynds catalogue.

The next column in Table 1 lists the reflection nebula with which the star is associated, taken from the catalogue of bright nebulae by Lynds (1965). The S-designations in this column refer to the catalogue of H II regions by Sharpless (1959), the DG designations refer to the paper by Dorschner & Gürtler (1963) and the C-designations are from the catalogue of diffuse galactic nebulae by Cederblad (1956). In a number of cases a bright nebula is clearly seen in the immediate surroundings of the star on Digital Sky Survey images of the region, but no designation for this nebula could be found. In these cases the 7th column in Table 1 lists "Anon.". The 8th column in Table 1 gives the name of a stellar aggregate with which the star is associated. A literature distance to the dark cloud, reflection nebula or stellar aggregate and a reference to the paper in which this was derived are provided in columns 9 and 10.

For all stars the Hipparcos satellite obtained broadband (3500–8500 Å) photometry at an effective wavelength of 5275 Å at some 100 distinct epochs during the 37 months (from 1989.85 to 1993.21) of its mission. These observations were made by a photon-counting image dissector tube with an instantaneous field of view of 30″ diameter. Because attenuation of the image dissector tube started at about 5″ from the center, a more realistic estimate of the spatial resolution of these observations will be 10″. For multiple systems with a separation between 10 and 30″, a correction was applied to the photometric data to subtract the light from the companion(s). For multiple systems with a smaller separation, the Hipparcos photometry refers to the total light. Typical errors in the individual measurements for this photometric system are smaller than $0\overset{\mathrm{m}}{.}011$ for stars brighter than 9th magnitude. In this paper we will only use the data in the sense of and with the accuracy of a relative photometric system, increasing the accuracy of these measurements to a few millimagnitude for such stars. A more thorough description of the Hipparcos photometric system is given in the Explanatory Supplement to the Hipparcos Catalogue. The value at measured maximum brightness of the Hipparcos magnitude, H_p, the measured range in H_p (from the 5th and 95th percentile bin of the photometry), δH_p, and the number of measurements are listed in columns 11–13 of Table 1. For normal, non-variable stars δH_p ranges from $0\overset{\mathrm{m}}{.}02$ for stars brighter than 5th magnitude to values up to $0\overset{\mathrm{m}}{.}1$ for 9th magnitude stars and increases sharply for fainter objects. Finally, column 14 gives a flag indicating probable variables: Stars which show a measured range in H_p larger than the accuracy of the measurements.

Five stars in our sample were found to be visual binaries by Hipparcos. HD 150193, now definitely a member of Sco R1, is the only newly detected one. The other binary detections are in agreement with earlier observations (Reipurth & Zinnecker 1993, Bernacca et al. 1993, Leinert et al. 1997, Pirzkal et al. 1997). Some stars which have been detected as multiple systems from ground-based speckle observations in the infrared were not detected as binaries by Hipparcos because of the large magnitude difference between primary and secondary in the optical. These are indicated by the remark IR binary in the last column of Table 1. Known spectroscopic binaries are also listed as such in the same column. Together this brings the total fraction of known binaries in our sample at 34%.

3. Astrophysical parameters

To assess the stellar temperature of HAeBe stars visual spectra are essential: UV spectra often overestimate temperatures, due to the presence of heated layers in the immediate surrounding of the stars' photospheres (e.g. Blondel & Tjin A Djie 1994), and photometric methods to estimate stellar temperatures yield erroneous results when the extinction law for the circumstellar material is anomalous, as is often the case for such stars (e.g. Thé et al. 1996). Therefore a list of spectral types based on optical spectra from literature as well as on unpublished spectroscopy by the authors was assembled and is given, together with its reference, in the 15th and 16th column of Table 1. In a few cases (e.g. Z CMa) even the optical spectrum is heavily influenced by the circumstellar shell and may reflect the spectral type of this shell rather than that of the underlying stellar photosphere. Columns 17–20 give an identifier with the type of Hα emission profile, a literature estimate of $v \sin i$ and references to the papers in which this was derived. In a number of cases an e (for emission-line star) was added to the original classification when it was evident from other sources that the star is an Hα emitter.

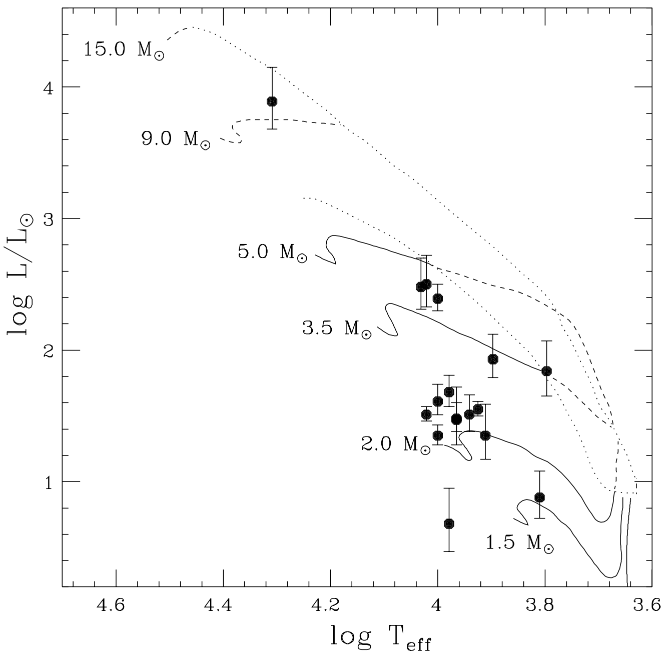

Fig. 1. Hertzsprung-Russell diagram of HAeBe stars with parallaxes measured by Hipparcos. Also shown are the theoretical PMS evolutionary tracks (solid lines and dashed lines) and the birthlines for 10^{-4} (upper dotted line) and 10^{-5} M$_\odot$ yr^{-1} (lower dotted line) by Palla & Stahler (1993).

In order to be able to compute the total luminosity of the stars in our sample, photometric data, from the ultraviolet (ANS, TD1, IUE), through the optical (Walraven $WULBV$, Johnson/Cousins $UBVRI$) to the infrared ($JHKLMNQ$, IRAS), were collected from literature. Since many of the stars in our sample show strong variations in brightness, only optical and UV data obtained near maximum brightness were used. After using the calibrations of Schmidt-Kaler (1982) to adopt an effective temperature $T_{\rm eff}$ and surface gravity $\log g$ corresponding to the star's MK spectral type, the stellar luminosity was computed following the method outlined in van den Ancker et al. (1997a). This method includes a correction for a possible anomalous extinction law towards the object. An estimate of the star's infrared excess in the L and IRAS 12 micron bands was made by computing the magnitude difference between the extinction-corrected observed magnitude and a Kurucz (1991) stellar atmosphere model fitted to the extinction-corrected optical photometry. The computed visual extinction at maximum brightness A_V, effective temperature $T_{\rm eff}$ and stellar luminosity $L_\star$ are listed in columns 21–23 of Table 1.

In Fig. 1, we plot the programme stars for which the Hipparcos mission resulted in a better than 3σ detection of the trigonometric parallax in the HRD. Typical errors in $\log T_{\rm eff}$ are about 0.05 (or one subclass in spectral type), but individual data points may have larger errors. The error in luminosity is dominated by the error in the distance and is indicated by the error bars. Also shown in Fig. 1 are the PMS evolutionary tracks and the birthline (i.e. the line where a star first becomes optically visible on its evolution to the zero-age main sequence) computed by Palla & Stahler (1993). Using these evolutionary tracks and the isochrones given by the same authors, we can make an estimate of the masses and ages of our programme stars. These are listed in columns 24 and 25 of Table 1. Note that these ages are based on the assumption that we are dealing with objects that are still contracting towards the zero-age main sequence (ZAMS). If this assumption is incorrect (e.g. HD 200775, Paper I), the listed ages will of course be erroneous as well.

As can be seen from Fig. 1, one star is located slightly to the left of the ZAMS, but all other stars are located in the region between the ZAMS and the birthline, as is expected for PMS stars. The star that is located to the left of the ZAMS, HD 34282, is not very well studied. Possibly its spectral type, based on data from the Henry Draper Memorial Catalogue, is erroneous or the photometric data set used to compute the stellar luminosity was not obtained near maximum stellar brightness. The clustering of stars in the HRD near the ZAMS can be easily explained by the fact that stars evolve much slower in the part of their PMS evolutionary track near the ZAMS than in the part near the birthline. The distribution over the different masses in this diagram, with less high-mass than intermediate-mass stars, is also in accordance with the expected ratios of a standard mass distribution.

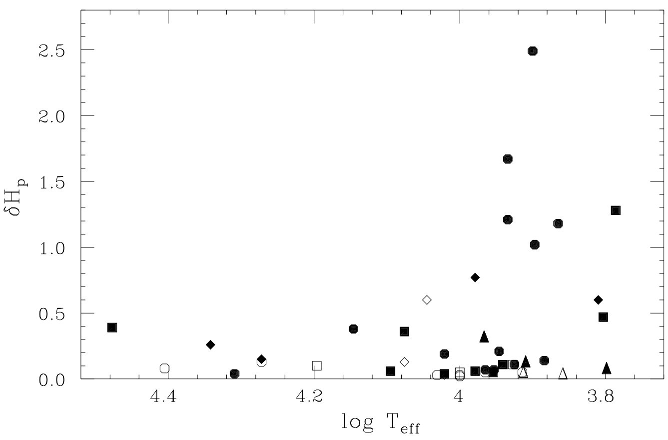

Fig. 2. Amplitude of the variations found in HAeBe stars as a function of stellar effective temperature. Circles indicate stars in which the Hα line is predominantly double-peaked, squares indicate stars in which Hα shows a P Cygni profile, triangles indicate stars with a single-peaked Hα line in emission and diamonds are used for stars in which Hα is in emission, but for which no information on its shape is available. Open plot symbols indicate stars for which the measured range in variability could be due to the uncertainty in the individual photometric measurements.

4. Photometric behaviour

Bibo & Thé (1991) analysed Strömgren photometry for 23 HAeBe candidates measured in ESO's Long Term Photometry of Variables (LTPV) programme. For the stars in common with our sample, their measured range in the Strömgren y magnitude agrees within $0\overset{\mathrm{m}}{.}1$ with our range in H_p, indicating that for these well studied cases δH_p is a good measure for the total range of variability. The number of stars in our sample is much larger than that measured by these authors (with a comparable number of measurements per star), and is much less observationally biased, which should enable us to draw statistically more significant conclusions on the level of variability of the HAeBe stellar group as a whole.

4.1. Inclination effects

A very strong correlation between the level of photometric variability of a HAeBe star and its spectral type was found by Finkenzeller & Mundt (1984): Nearly all strongly variable ($\Delta V > 0\overset{\mathrm{m}}{.}5$) stars in their sample have spectral types later than B8 and all stars with no significant variations ($\leq 0\overset{\mathrm{m}}{.}05$) are of spectral type earlier than A0. Later this result was reproduced by Bibo & Thé (1991), who suggested that this result was due to selection effects in their limited sample. Davies et al. (1990) showed several examples of *bona fide* Herbig Ae (HAe) stars which do not show the large variations predicted for such stars by Finkenzeller & Mundt (1984), suggesting that the link between photometric variability and spectral type may not be as well defined as implied by these authors.

Bibo & Thé (1991) pointed out that since these strongly variable stars spend most of their time near maximum brightness and the typical timescale of such photometric events is of the order of weeks, many accurate photometric measurements over a significantly longer period are needed to get a good unbiased measurement of the amount of photometric variability. This is a criterion which is not met in a systematic way for all data-sets present in literature. However, the Hipparcos photometry listed in Table 1 consists of roughly one hundred measurements per star, taken at essentially random time intervals with the same instrument over a 37 month period, without any bias to observe the "more interesting" cases more than others, as is often the case in ground-based work. Therefore it is much better suited to make an unbiased estimate of the level of photometric variability than the data sets used in previous studies. For this reason a new diagram of log $T_{\rm eff}$ versus δH_p was constructed, shown in Fig. 2. As can be seen from this plot, some trend between stellar temperature and level of photometric variability is clearly present: Only stars with spectral type of A0 or later can show variations with an amplitude larger than $0\overset{\mathrm{m}}{.}5$. However, moderate photometric variations, of the order of several tenths of a magnitude can be seen in all spectral types present in our sample. In fact only 15 out of 44 stars in our sample are not flagged as variable and in some cases this is clearly due to the fact that they are too faint to be measured accurately by Hipparcos. We conclude that at least 65% of all HAeBes do show photometric variability with an amplitude larger than $0\overset{\mathrm{m}}{.}05$.

In the past many authors have constructed colour-magnitude diagrams for HAeBe stars, and noted that for all stars showing large and for most stars showing intermediate brightness variations, there seems to be a good correlation between colour and

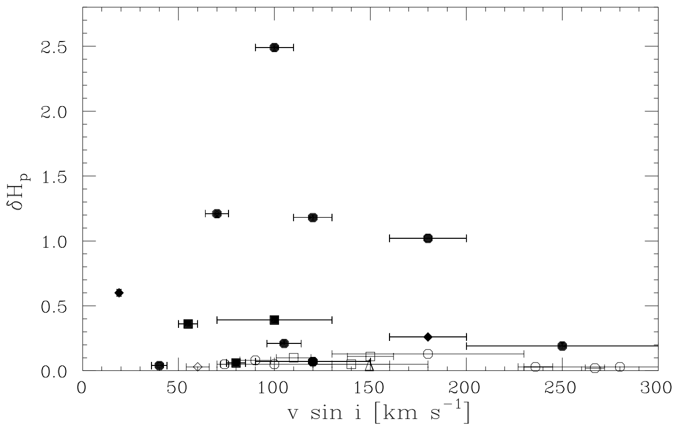

Fig. 3. Amplitude of the variations found in HAeBe stars as a function of stellar $v \sin i$. Plot symbols have the same meaning as in Fig. 2.

brightness, with a redder colour corresponding to fainter brightness. In addition to this, the linear polarization of the starlight also increases with diminishing brightness. This behaviour is characteristic of variable, presumably circumstellar, extinction of starlight by dust particles. Wenzel (1968) originally suggested that these dust particles are located in patchy dust clouds, revolving in Keplerian orbits around most HAeBes. Smaller variations superimposed on these may be explained by photospheric activity or clumpy accretion.

With this picture in mind, one possible explanation for the fact that large photometric variations only occur at spectral types later than A0 could be that since dust particles can survive closer to the star in cooler stars than in hot stars, the range of inclination angles under which we would have to observe such a system to have these dust clouds in our line of sight would be narrower for B-type stars than for A-type stars. In this picture all HAeBe stars would have these dust clouds orbiting them, but we will only see these in our line of sight and hence see large amplitude variations for systems seen more or less edge-on, recognizable by statistically larger value of $v \sin i$. If we combine the literature data given in Table 1 with the Hipparcos data to construct a diagram of $v \sin i$ versus δH_p (Fig. 3), no such correlation can be seen. One reason for this apparent lack of correlation could be that in a lot of HAeBes these $v \sin i$ determinations are difficult and sometimes even erroneous due to the lack of photospheric lines without (sometimes variable) emission components. Also, one would expect these young stars to continue to spin-up during their PMS contraction phase, so the spread in the intrinsic rotational velocity may have a stronger influence on the value of $v \sin i$ than the inclination. The fact that the range in quoted values on $v \sin i$ is quite similar to that seen in normal main-sequence stars of the same spectral type argues against the latter effect.

Grinin & Rostopchina (1995) argued that the same inclination effect should be visible as a correlation between the level of photometric variability and the shape of the Hα line, presumably formed in a circumstellar gaseous disk: In analogy to the situation in classical Be stars, we would expect to see a single-peaked Hα profile in stars seen pole-on, thus showing little photometric variability, and the stars with large photometric variations, seen more or less edge on, should show a double-peaked Hα profile. In this scenario, the variations seen in Hα, in which this line has one preferred shape, but in some stars is occasionally seen to switch from for example double-peaked to single-peaked could be either due to inhomogeneities in the accretion of circumstellar gas, or due to a contrast effect in which part of the circumstellar gas is obscured by inhomogeneous dust clouds (Grinin et al. 1994).

Upon closer inspection of Fig. 2, in which the different preferred types of Hα profiles from literature are indicated by different plot symbols, we note that indeed most stars showing large photometric variations show double-peaked Hα emission and all stars with single-peaked Hα profiles only show moderate photometric variations. However, not all stars with little or no photometric variability show a single-peaked emission profile. In fact many of these show a double-peaked emission line as well. Therefore we conclude that if a dependence on inclination is present in both δH_p and the shape of Hα, some other effect must be present as well to disturb the one to one correspondence.

4.2. Evolutionary hypothesis

Another possible explanation for the trend shown in Fig. 2 could be that we are seeing an evolutionary effect: According to the calculations by Palla & Stahler (1993), A-type stars are optically visible during their contraction towards the ZAMS, whereas B-type stars only become visible when they are very close to the ZAMS (c.f. the birthline in Fig. 2). In this scenario the amplitude of the variations of HAe stars would diminish with time until they would vanish after the star has finished its main sequence contraction. Support for this view comes from the observation that most stars with $\delta H_p > 0\overset{m}{.}5$ are classified spectroscopically as giants, and many of them are located right of the main-sequence in Fig. 1.

The fact that some giants do not show these strong photometric variations could be taken as evidence for the presence of an inclination effect. However, van den Ancker et al. (1996) showed that HAe stars change back and forth between a quiescent state in which they show only very moderate photometric variations and an active state in which the large amplitude variations are present many times during their evolution towards the ZAMS. The time scale over which such a star will remain in one state will be much longer than the 37 months over which our range in variability was measured. Considering the statistics in Table 1, in which there are only four *bona fide* HAe giants that do not show large photometric variations, we consider it more plausible that the photometrically inactive giants are in this quiescent state than to take this as an indication of an inclination effect. Since it is clear that other effects than inclination have a strong influence on the level of photometric variability as well, some caution must be taken in the current practice in literature of equating strongly variable HAeBe stars to Herbig stars seen edge-on.

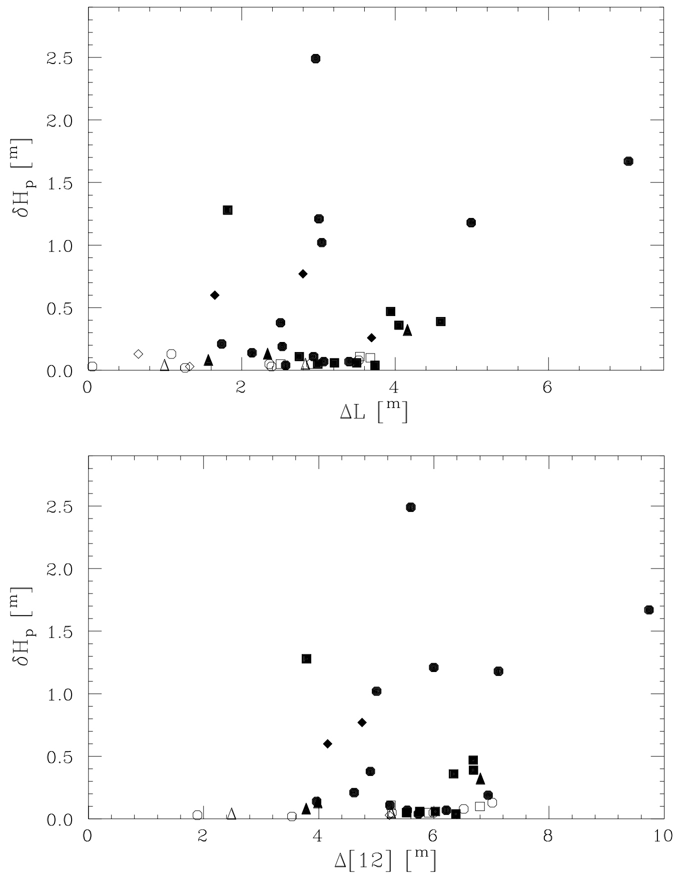

Fig. 4. Amplitude of the variations found in HAeBe stars as a function of infrared excess in the L (top) and IRAS 12 micron (bottom) bands. Plot symbols have the same meaning as in Fig. 2.

4.3. Correlations with infrared excess

If the interpretation of the large photometric variations as being due to variable extinction by circumstellar dust is correct, one could expect some form of correlation between the infrared excess and level of photometric variability in HAeBe stars. From the typical time scales of days to weeks associated with these variations, it was shown that the dust clouds responsible for this must be at roughly one AU from the central star (Thé & Molster 1994). At these distances the dust clouds should be heated up sufficiently by the central star to radiate efficiently at infrared wavelengths. Therefore one would expect that stars with smaller infrared excesses do not show photometric variations, whereas the ones with larger infrared excesses can show both large and smaller photometric variations, depending on the inclination angle under which they are seen.

To check for the presence of such a correlation we plot our δH_p against the excess at 3.6 and 12 microns (Fig. 4). Indeed, none of the Herbig stars with small excesses at these wavelengths shows strong photometric variability, whereas the ones with larger excesses show a large spread in δH_p. It is interesting to extrapolate this result to young stellar objects with less circumstellar material than the stars we have included in our sample. Probably these will be recognizable as β Pic-like systems (Paper I), with usually smaller infrared excesses and with less circumstellar gas than the HAeBes. Therefore we compiled a list of 52 B-, A- and F-type candidates for stars with circumstellar dust and Hipparcos data. None of these stars shows a range in H_p larger than $0^{\mathrm{m}}.1$. In fact, the Hipparcos photometry of β Pic itself is constant at the millimagnitude level. This shows that the trend seen in our sample of HAeBes can be smoothly extrapolated to the Vega-type stars and that there may indeed be an evolutionary link between the two.

5. Conclusions

In this paper we have studied the photometric behaviour of a sample of 44 candidate HAeBe stars using a uniform data-set, provided by the Hipparcos astrometric satellite, which is superior to those used in previous studies. We have shown that most ($> 65\%$), and possibly all, HAeBes show photometric variations at the level of at least a few hundredths of a magnitude.

As was already suggested by previous authors, Herbig stars with a spectral type earlier than A0 only show moderate (amplitude $< 0^{\mathrm{m}}.5$) photometric variability, whereas the ones of later spectral type in our sample can show variations larger than $2^{\mathrm{m}}.5$. These HAe stars showing strong photometric variability are relatively uncommon: More HAe stars show moderate than large variations. Previous studies have shown that these large photometric variations are due to variable extinction by circumstellar patchy dust clouds, whereas a variety of mechanisms could be responsible for the moderate to small ones. We suggest that these patchy dust clouds are only present during the PMS evolution of a star, and either vanish or become more homogeneous when a star has reached the ZAMS. Probably this evolutionary effect, as well as the spin-up of a star as it evolves towards the ZAMS, explains the poor correlation between $v \sin i$ or the Hα profile and the level of photometric variability.

It was found that the Herbig stars with the smallest infrared excesses in our sample do not show large photometric variations, whereas the ones with larger infrared excesses can (but not necessarily have to) show variation up to $2^{\mathrm{m}}.5$. This can be understood by identifying the stars with lower infrared excesses with the more evolved objects in our sample. Since Vega-type stars do not show these variations due to variable circumstellar extinction and also display smaller infrared excesses, this is compatible with a scenario in which these Herbig stars will in time evolve into more massive equivalents of β Pic.

Acknowledgements. The authors would like to thank Rens Waters and Mario Pérez for careful reading of the manuscript prior to publication. We would also like to thank the referees, Floor van Leeuwen and George Herbig, for many useful suggestions and comments. MvdA received financial support through an NWO *Pionier* grant to L.B.F.M. Waters. DDW is supported in part by Spanish grant DGICYT PB94-0165. This research has made use of the Simbad data base, operated at CDS, Strasbourg, France.

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