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Binaries among Herbig Ae/Be stars*

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Abstract. We have studied the circumstellar environment of 31 Herbig Ae/Be and related stars in the near infrared by means of speckle-interferometry. For the brighter objects we reach or approximate diffraction-limited resolution of $\approx 0.1''$ (typically 100 AU at the object). Of the resolved objects some show halos, some have a companion. Here we restrict ourselves to a discussion of binarity in this sample. Eleven objects have companions, five of which constitute subarcsecond binaries, mostly found by us. Although the sample is small and neither homogeneous nor complete, it indicates a similar high incidence of binaries as found in recent surveys among T Tauri stars. Where the data allow it, we discuss the nature of the companions.

Key words: stars: pre-main sequence – binaries:visual – stars: emission: Line, Be – infrared: stars – techniques: interferometric

1. Introduction

From the beginning and by their definition (as showing line emission and being associated with reflection luminosity, Herbig 1960) the Herbig Ae/Be stars were thought of as the higher mass counterparts of the T Tau stars, covering the mass range of about 2-8 $M_\odot$ just above that of the T Tau stars. High spatial resolution near infrared observations of their circumstellar environment started when the technique of speckle interferometry became available. The initial work on a few selected objects (Beckwith et al. 1984, De Warf and Dyck 1993) resulted in the detection of circumstellar matter in the form of flattened halos, with conclusions on the dynamics and characteristics of the circumstellar dust. Our near-infrared speckle observations of Herbig Ae/Be stars, started in 1985, also aimed at a study of circumstellar diffuse material. However, these data also have shown hitherto unknown close companions to these stars. We present here this aspect of the study. As in the case of the lower mass T Tau stars, the study of duplicity among Herbig Ae/Be stars is expected to give valuable information not only on the formation of binaries but also on the mechanisms of star formation for intermediate-mass stars in general. Although our sample is too incomplete and heterogeneous for a systematic study of duplicity, its results appear typical and represent a first step toward a future systematic evaluation. In addition, we discuss in Sect. 5 the individual binaries, in particular those, where measurements at several near-infrared wavelengths allow us to comment on the nature of the companions. A preliminary account of part of these data can be found in Leinert et al. (1994).

2. The sample

The sample was put together with the aim to cover those Herbig Ae/Be stars which have circumstellar material in sufficient amount and extension to allow a spatially resolved study by near-infrared speckle interferometry. Thus it was not designed to be particularly rich in binaries, and the number of companions eventually detected perhaps could be low but should not be untypically high.

The first selection criterion was to choose objects from the catalogue of Finkenzeller and Mundt (1984) which showed a large infrared excess (V–L $\geq$ 4.0). However, other selection criteria indicating youth or activity were also used, like CO outflows, optical jets, a position in the Hertzsprung-Russel diagram well above the main sequence, or strong P Cyg profiles. The source list is shown in Table 1, which in addition to the usual general information gives in column (12) the main selection criterion for each object. With the exception of G70.7+1.2, the two AFGL sources and the two IRAS sources, all objects of the source list are contained in the catalogue of Herbig Ae/Be stars by Thé et al. (1994). Although we do not consider the five extra objects as proper Herbig Ae/Be stars, we kept them in the object list, since they probably are indeed young stars, although of higher mass.

The observational coverage of the objects in the list is quite varied, ranging from a few scattered observations to extensive coverage and published results.

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* Based on observations collected at ESO, La Silla, and the german-spanish astronomical center Calar Alto

Table 1. Source list

(1) Source	(2) HBC	(3) α(1950)	(4) δ(1950)	(5) d (kpc)	(6) V	(7) J	(8) H	(9) K	(10) Sp.Type	(11) References	(12) Selection
LkHα 198	3	$00^h08^m47^s.2$	$+58^\circ32'49''$	0.6	14.3	9.87	8.72	6.38	B/Ae	22,23,35	CO outflow
V376 Cas	325	$00^h08^m47^s.9$	$+58^\circ33'22''$	0.6	15.6		8.02	6.10	B5e	6,22,35	CO outflow
BD +61°154	330	$00^h40^m21^s.9$	$+61^\circ38'15''$	0.65	10.6	8.22	6.95	5.82	B:e	1,22,36	IR excess
AFGL 4029[a]		$02^h57^m32^s.5$	$+60^\circ17'22''$	2.2			9.58	7.84	Be	30,37	jet
AFGL 490[b]		$03^h23^m38^s.8$	$+58^\circ36'39''$	0.9		10.1	7.8	5.2	B4	25,31,32,38	CO outflow
Elias 1	373	$04^h15^m34^s.6$	$+28^\circ12'01''$	0.14	15.3	8.55	6.91	5.64	A6e	19,22	IR excess
LkHα 101	40	$04^h26^m57^s.2$	$+35^\circ09'56''$	0.8	15.9			2.88	F?e	22,25,39	CO outflow
AB Aur	78	$04^h52^m34^s.2$	$+30^\circ28'22''$	0.16	7.1	6.21	5.21	4.31	B9,A0e	21,22,36	P Cyg
HK Ori	94	$05^h28^m39^s.9$	$+12^\circ06'54''$	0.46	11.6	9.5	8.02	7.36	B8/A4ep	2,22,36,37	IR excess
T Ori	154	$05^h33^m23^s.1$	$-05^\circ30'17''$	0.46	9.9	8.2	7.45	6.45	A3e	17,2,22,36	HRD
V380 Ori	164	$05^h34^m00^s.9$	$-06^\circ44'34''$	0.46	10.0	7.83	6.93	5.84	B8/A1e	3,4,22,36,37	IR excess
LkHα208	193	$06^h04^m53^s.2$	$+18^\circ39'55''$	1.0	12.7		9.85	8.88	F0eV	5,6,22,36	IR excess
R Mon	207	$06^h36^m26^s.3$	$+08^\circ46'53''$	0.8	11.3	9.06	7.15	5.26	B0e	7,8,22,36,37	IR excess
LkHα25	219	$06^h37^m59^s.5$	$+09^\circ50'53''$	0.8	12.8	11.77	10.73	9.42	B8pe	6,22,36	IR excess
Z CMa	243	$07^h01^m22^s.6$	$-11^\circ28'36''$	1.15	9.3	5.79	4.65	3.54	FUOR	20,22,37	jet
IRAS 13395-6153[c]		$13^h39^m34^s.6$	$-61^\circ53'46''$	?		13.51	9.55	6.18		34	IRAS
HR 5999	619	$16^h05^m12^s.7$	$-38^\circ58'21''$	0.15	6.8	5.91	5.18	4.33	A7e	18,22,39	HRD
V921 Sco	655	$16^h55^m33^s.8$	$-42^\circ37'37''$	0.16	11.4	7.23	5.80	4.38	Bep?	22,26,36	IR excess
KK Oph	273	$17^h07^m00^s.7$	$-27^\circ11'36''$	0.16	10.57	8.54	6.98	5.64	B,Ae	6,22,36	IR excess
IRAS 17216-3801[c]		$17^h21^m40^s.9$	$-38^\circ01'23''$	?		12.09	7.85	4.78		34	IRAS
MWC 300		18^h26^m45	$-06^\circ06'48''$	15.5	12.1		7.99	5.92	eq/BIe	6,27,40	IR excess
VV Ser	282	$18^h26^m14^s.$	$+3^\circ06'37''$	0.44	11.9	8.18	6.72	5.61	B,Ae	6,22,36	IR excess
R CrA	288	$18^h58^m31^s.1$	$-37^\circ08'24''$	0.13	10.7	7.22	5.07	3.43	A5:e	10,8,22,36	IR excess
T CrA	290	$18^h58^m36^s.3$	$-37^\circ02'09''$	0.13	13.4	10.81	9.33	8.20	F0:e	11,12,22,36	IR excess
G70.7+1.2[d]		$20^h02^m28^s.3$	$+33^\circ30'30''$	1-4.5	16.0	10.2	8.1	6.4	B:	33,41,42,43	radio cont.
BD +40°4124	689	$20^h18^m42^s.5$	$+41^\circ12'20''$	1.0	10.5	7.78	6.67	5.64	B2,3e	1,22,36	IR excess
PV Cep	696	$20^h45^m23^s.5$	$+67^\circ46'34''$	0.6	17.8	10.57	8.60	6.75	A5e	22,24,37	CO outflow
V645 Cyg		$21^h38^m10^s.6$	$+50^\circ00'43''$	3.5-5.6	14.1	9.8	7.0	4.8	O7e	27,28,37,40	CO outflow
LkHα234	309	$21^h41^m57^s.5$	$+65^\circ53'03''$	1.0	11.9	9.50	8.22	7.18	B5/7e	13,14,22,36	IR excess
LkHα233	313	$22^h32^m28^s.2$	$+40^\circ24'33''$	0.88	13.6	11.2	10.0	8.3	A7e	15,16,22,36	IR excess
MWC 1080	317	$23^h15^m14^s.9$	$+60^\circ34'19''$	1.0-2.2	11.7	7.39	5.94	4.70	B0?e	15,1,22,36,37	IR excess

Notes: [a] high mass[31], spectrum in [29] [b] high mass [31] [c] high mass YSO candidate [d] high mass YSO

References: [1] Milkey & Dyck (1973) [2] Glass & Penston (1974) [3] Nakayima et al. (1986) [4] Warner et al. (1978) [5] Herbig & Rao (1972) [6] Allen (1973) [7] Cohen & Schwartz (1983) [8] Feast & Glass (1973) [10] Wilking et al. (1986) [11] Taylor & Storey (1984) [12] Vrba et al. (1976) [13] Bechis et al. (1978) [14] Harvey et al. (1984) [15] Evans et al. (1986) [16] Lorenzetti et al. (1983) [18] Thè et al. (1981) [19] Elias (1978) [20] Herbst et al. (1982) [21] STROM et al. (1972) [22] Herbig and Bell (1988) [23] Loren (1977) [24] Lacasse (1982) [25] Grasdalen et al. (1983) [26] Glass,I.S. and Allen, D.A. (1975) [27] Thé et al. (1984) [28] Ney and Merrill (1980) [29] Ray et al. (1990) [30] Gosnell et al. (1979) [31] Henning et al. (1984) [32] Jones et al. 1990 [33] Staude, J., Neckel, Th. (1996) private communication [34] Persson and Campbell (1987) [35] Chavarria (1985) [36] Hillenbrand et al. (1992) [37] Mundt and Ray (1994) [38] Henning 1990 [39] Zinnecker and Preibisch (1994) [40] Skinner (1994) Becker and Fesen (1988) [42] Phillips et al. (1993) [43] de Muizon et al. (1988)

3. Speckle observations and data reduction

The data discussed in this paper were obtained over a period of about ten years, using different instruments at several telescopes in both hemispheres, as listed in Table 2. Here we only provide a basic description of the observing techniques and of the data reduction methods. More details can be found in previous dedicated papers (Haas 1990, Christou 1991, Haas et al. 1993).

The instruments that we used recorded either 1–D or 2–D speckle data. To the first class belongs the Calar Alto specklegraph (Leinert and Haas 1989), based on a single InSb photodiode, with a scanning slit that can be oriented at any chosen angle on the sky. The results are obviously one–dimensional, however two orientations are in general sufficient to obtain the true position angle and separation of a binary, while the interpretation can be more difficult in the case of an extended source. The field of view of the 1–D measurements is characterised by the scan length and by the height of the slit, both of which are about 10 arcsec.

To the 2–D instruments belong the Calar Alto InSb (Lenzen et al. 1990) and Nicmos (Herbst et al. 1993) cameras (the latter dubbed MAGIC), the Kitt Peak InSb camera (Beckers et al. 1988) and the ESO NTT Nicmos camera (dubbed SHARP, Hofmann et al. 1993). In this case the 2–D structure of the source is preserved, making the observations more efficient, but with the possible disadvantage that the data reduction is burdened by the need for flat–fielding and bad pixel correction and by the increased computational needs due to the two-dimensional Fourier treatment. The format of the cameras ranged from 58$\times$62 pixels for the InSb arrays to 256$\times$256 for MAGIC and SHARP, which however are limited to the 1-2.5μm range. With MAGIC and SHARP data taking was often restricted to one 128x128 pixel quadrant or to a format of 128X256 pixels, combining simultaneous object and sky measurements.

Table 2. Log of observations

Date	Objects observed*	Location	Instrument
08-14/11/85	Z CMa/BS2970 (L' 90°), R CrA/BS7234 (K 40°)	ESO 2.2m	1D
21-28/06/86	PV Cep/BS7957 (K,L' 0°,90°)	Calar Alto	1D
13-23/09/86	LkHα 198/BS21 (H,K,L' 0°,90°), V376 Cas/BS 21 (K 0°), MWC 1080/BS8881 (H,K 90°)	Calar Alto	1D
	Elias 1/BS1348 (K 90°), PV Cep/BS7957 (K, 0°), AFGL 490/BS1009 (L' 0°,90°)		
	Z CMa/BS2970 (H 90°), MWC 300/BS6940 (K 90°), MWC 300/BS6869 (L' 0°,90°)		
	V645 Cyg/BS9845 (K 135°), LkHα 233/BS 8656 (K 90°)		
	LkHα 234/BS8317 (H,K 0°)		
14-17/02/87	Z CMa/BS2970 (K,L' 90°), Z CMa/BS2508 (K 90°)	Calar Alto	1D
05-12/06/87	LkHα 198/BS21 (L' 0°), V376 Cas/BS21 (H,K,L' 0°, 90°), LkHα 234/BS8317 (H,L' 0°,90°)	Calar Alto	1D
	LkHα 234/BS8388 (K,L' 90°), MWC 300/BS6940 (H 0°)		
09-13/09/87	LkHα 198/BS21 (J,L' 90°), V376 Cas/BS 21 (H,L'K 90°), BD +61 154/BS130 ((H 0°)	Calar Alto	1D
	PV Cep/BS7957 (K 0°), LkHα 101/BS1489 (H 0°), Z CMa/BS2970 (H 0°)		
	Z CMa/BS2798 (H 0°, 22.5°), BD +40 4124/7762 (H,K 0°,90°), VV Ser/BS6935 (H 0°,90°)		
	MWC 300/BS6940 (H 0°), LkHα 233/BS 8656 (H 0°, 50°,90°,140°)		
	LkHα 234/BS8317 (K,L' 0°,90°)		
30/12/87	LkHα 198/BS21 (K 0°), V376 Cas/BS 21 (K 90°), LkHα 25/BS2555 (K 0°)	Calar Alto	1D
-07/01/88	Z CMa/BS2508 (H 0°, 22.5°), LkHα 208/BS2184 (K 0°), MWC 1080/BS8881 (H 0°)		
16-28/09/88	LkHα 198/BS21 (J,H,M 0°,45°,90°,135°), V376 Cas/BS21 (H,K,L',M 0°,30°,90°,120°),	Calar Alto	1D
	V376 Cas/BS9079 (H,K 30°,60°,120°,150°)		
	LkHα 198/BS9079 (H,L' 0°,22.5°,45°,67.5°, 90°,112.5°,135°,157.5°)		
	LkHα 101/BS1577 (H,K,L' 0°,90°), Z CMa/BS2970 (H 70°), LkHα 208/BS2184 (K 0°,90°)		
	VV Ser/BS6935 (K 90°), LkHα 233/BS 8656 (K,L' 70°, 140°), LkHα 234/BS8317 (K 0°)		
	MWC 1080/BS8679 (K 155°), Elias 1/BS1348 (K 0°)		
14-24/09/89	LkHα 198/BS9079 (H 45°,135°), V376 Cas/BS 9079 (H 30°), AFGL 4029/BS860 (H,K 0°,90°)	Calar Alto	1D
	AFGL 490/BS1071 (H,K 0°,22.5°,112.5°,135°), AFGL 490/BS915 (L' 90°)		
	Z CMa/BS2970 (K 112.5°), BD +40 4124/7800 (L' 0°,90°), VV Ser/BS6935 (J,H,K 0°,90°)		
	MWC 300/BS6940 (H,K 0°,90°), LkHα 233/BS8656 (K,H 0°,140°), LkHα 234/BS8483 (K,L' 0°)		
11-17/10/89	LkHα 198/BS21 (3.1μm 90°), V376 Cas/BS21 (3.1μm 90°), R Mon/BS2503 (K90°)	Calar Alto	1D
	Z CMa/BS2970 (J 120°), Z CMa/BS29508 (J 120°), G70.7+1.2/BS7806 (J,H,K,L',M 0°,90°)		
	V645 Cyg/BS8445 (H,K 45°,135°), LkHα 233/BS8656 (3.1μm,3.3μm 50°)		
	MWC 1080/BS8881 (J,K,L',M 0°,45°,90°), MWC 1080/BS8752 (M 90°)		
01-04/06/90	R CrA/BS 7273 (H,K 90°,135°), R CrA/BS 7259 (K 135°), T CrA (K 45°)	ESO 3.6m	1D
31/08/90	BD +61 154/BS237 (H,K 0°,90°), BD +61 154/BS60 (H,K 0°,90°), AFGL 4029/BS920 (L' 0°,90°)	Calar Alto	1D
-10/09/90	AFGL 490/BS1071 (H,K 45°,90°), AFGL 490/BS918 (K,3.1μm,3.3μm,L' 0°,90°),		
	AFGL 490/BS915 (3.1μm 90°), G70.7+1.2/BS7806 (L',M 90°), MWC 300/BS7034 (H 0°,90°)		
	LkHα 233/BS8643 (K 50°), LkHα 234/BS8483 (L' 0°,90°), MWC 780/BS8752 (M 90°)		
03/11/90	AFGL 4029/BS920 (K 0°)	Calar Alto	1D
06/12/90	LkHα 198/BS9079 (K), Z CMa/BS2970 (K)	Kitt Peak 4m	InSb camera
19-20/03/91	AB Aur/BS1529 (K 90°), MWC 300/BS7034 (H 0°)	Calar Alto	1D
19-23/09/91	BD +61 154/BS60 (K,L' 0°,90°), KK Oph/BS6354 (K 90°), KK Oph/SAO185076 (K 90°)	Calar Alto	1D
	G70.7+1.2/BS7806 (H 90°), BD +40 4124/7800 (L' 0°,90°), MWC 300/BS6940 (K 90°)		
	MWC 300/BS7034 (H 0°) V645 Cyg/BS8304 (H,K 135°), LkHα 233/BS8643 (K 90°)		
28/10/91	Elias 1/BS1287 (K), AFGL 4029/BS964 (K)	Calar Alto	InSb camera
11-14/02/92	Elias 1/BS1348 (H,K,L' 90°), AB Aur/BS1529 (K 0°), R Mon/BS2406 (H,K,L' 0°,90°)	Calar Alto	1D
	HK Ori/BS1908 (H,K 0°,45°,90°), Z CMa/BS2970 (H,K 30°,120°)		
	V380 Ori/BS1937 (H 0°,90°), LkHα 233 (K polarimetry)		
14-16/05/92	Z CMa/BS2970 (K 120°), Z CMa/BS2733 (K 120°), KK Oph/BS6459 (H,K,L 0°,90°)	ESO 3.6m	1D
	R CrA/BS7259 (H,K 0°,90°), R CrA/BS7259 (H,L 0°,90°), T CrA/BS7259 (L 0°)		
	T CrA/BS7273 (H,K 0°,90°), IRAS 13395-6153/BS5252 (K 0°)		
	IRAS 13395-6153/BS5241 (L 0°), IRAS 17216-3801 (K,L 0°)		
10/06/92	LkHα 233/BS8656 (L' polarimetry), MWC 1080/BS8894 (J 90°)	Calar Alto	1D
13-14/10/92	LkHα 198/SAO21171 (K imaging), V 376 Cas/SAO21171 K imaging), Elias 1/SAO76556 (K)	Calar Alto	InSb camera
	V380 Ori/SAO76556 (K), Z CMa/SAO76556 (K), LkHα 233/SAO52153 (K)		
10-12/11/92	Elias 1/BS1348 (J 90°), AFGL 4029/BS920 (H,K 135°), HK Ori/BS1908 (J 45°)	Calar Alto	1D
	Z CMa/BS2970 (H 120°), G70.7+1.2/BS7583 (K 90°), LkHα 208/BS2184 (K 90°)		
	LkHα 234/BS8227 (K 30°)		
04-11/01/93	Elias 1/BS1348 (J,H,K,L' 0°), R Mon/BS2406 (J 0°), AFGL 4029/BS920 (K,L' 45°),135°)	Calar Alto	1D
	V380 Ori/BS1937 (K,L' 0°), LkHα 25/BS2589 (K 90°), Z CMa/BS2508 (L',M 30°,160°)		
	Z CMa/BS2970 (H,K,L' 120°)		
30/07/93	HR 5999/BS5935 (J,H,K), KK Oph (K imaging)	ESO NTT	Nicmos camera
30/09/93	AFGL 4029/SAO12581 (K), V380 Ori/BS1937 (K), G70.7+1.2/SAO69353 (K)	Calar Alto	Nicmos camera
-07/10/93	LkHα 234/BS8227 (K), LkHα 234/SAO19534 (Kimaging)		
26-28/01/94	Elias 1/SAO76511 (J,H,K), V380 Ori/BS1918 (J), Z CMa/BS2798 (K), R Mon/SAO114234 (J)	Calar Alto	Nicmos camera
	T Ori/BS1887 (K)		
14-17/09/94	PV Cep/BS7957 (K), PV Cep/SAO19045 (H), R Mon/BS2551 (H,K)	Calar Alto	Nicmos camera
	AFGL 4029/SAO 12581 (H,K), V380 ORI/BS1918 (J), LkHα 25/SAO114220 (K)		
	G70.7+1.2/SAO69353 (K), LkHα 208/SAO95299 (K), LkHα 234/SAO19523 (H)		
13-15/12/94	V380 Ori/SAO94598 (Broadband I-K), V380 Ori/BS1918 (I)	Calar Alto	Nicmos camera
18/01/95	Z CMa/PPM217901 (1.68 μm, 2.17 μm, 2.20 μm)	ESO NTT	Nicmos camera
08-09/10/95	HK Ori/SAO94645 (I), MWC 1080/BS8797 (I,J), MWC 1080 (J,H,K imaging)	Calar Alto	Nicmos camera

*Format: Object/Reference star (wavelength range, scan direction [for 1D measurements])

The field of view for the InSb cameras usually was 4.9″x5.3″ or 9.6″x10.2″, while a quadrant size of the NICMOS cameras was 6.0″x6.0″ for SHARP and 9.3″x9.3″ for MAGIC.

The technique employed was that of speckle interferometry, by which many short exposures images (or scans in the 1–D case) are obtained. The integration time was chosen as a compromise between the coherence time of atmospheric turbulence at the given wavelength (typically 0.05s at 2μm) and the minimum time necessary to achieve a satisfactory SNR for the source on a single exposure. For the fainter sources (or in case of bad seeing) the integration time was taken a few times longer (typically 0.2–0.5s), which improved the signal but resulted in some loss in the high spatial frequency resolution. The typical observing sequence consisted of a total of $\approx 10^3$ frames for a given source, broken into blocks of $\approx 10^2$ frames each, which were interspersed with a comparable number of frames on one or more nearby reference stars, i.e. stars which are presumably point–like and which, because of their position in the neighborhood of the object, are aberrated by similar atmospheric turbulence. Sky exposures (also useful for the flat–fielding necessary for the 2–D instruments) were usually obtained next to the object and reference measurements.

The data reduction typically consisted in the reconstruction of the source visibility according to the classical power spectrum analysis (Labeyrie 1970), and additionally of the phase by means of the Knox-Thompson (1974) method or the bispectrum formalism (Lohmann et al. 1984). The number of “subplanes” used in the bispectrum reconstruction was typically several tens. From the resulting complex visibility it is possible to reconstruct a (nearly) diffraction limited image of the source, which could be analysed for objects in the circumstellar environment. However, it is more convenient to fit directly the complex visibility by the Fourier transform of model images (see for instance the example given in Fig. 4). Our fitting procedures allow to choose a number of point sources and/or sources with a gaussian profile (these latter are useful in the presence of extended emission but were not needed for the evaluation of the binaries in our sample). The parameters resulting from the fits are separation, position angle and brightness ratio of the components. For some sources we have this information at several wavelengths and thus obtain the spectral energy distributions (SEDs) for each component separately. Following usual practice we denote the component brighter at K as ’A’ and the fainter one as ’B’.

For the purposes of this study we consider two infrared sources to form a binary if their projected linear separation is less than 3600 AU. A value of 1800 AU appeared appropiate for the less massive T Tauri stars (Leinert et al. 1993) because at this separation confusion with foreground (or also background) sources started to become noticeable. The Herbig Ae/Be stars of our list are on the average four times as distant as the Taurus sources. We therefore expect roughly the same number of foreground sources if we double the allowed projected separation. This increased maximum separation is also an approximation to the effect that the more massive Herbig Ae/Be stars are gravitationally dominating a larger volume than the less massive T Tauri stars.

4. Analysis of observed spectral energy distributions

The spectral energy distributions of Herbig Ae/Be stars have been fitted with models of circumstellar dust distribution of various characteristics in order to study its spatial distribution and dynamics, notably by Hillenbrand et al. (1992, ‘.. massive circumstellar accretion disks’) and by Hartmann et al. (1993, ‘.. disks or envelopes?’). We do not try to compete with these detailed studies but occasionaly use a simple version of such models as guideline for the interpretation of our results. We do not expect that these simplified models describe the true spatial distribution of circumstellar matter but we think that they give a first approximation to the distribution of emitting dust with distance from the star.

It is mainly for the subarcsecond binaries HK Ori, V380 Ori and MWC 1080 that we obtained separate near-infrared spectral energy distributions for the components. Extrapolation of these spectral energy distributions then should allow us to associate the optical source with one of the infrared components and to estimate for both components luminosity and gross properties of circumstellar matter distribution.

We base this extrapolation on a simple model of a star surrounded by a geometrically thin disk, assuming thermal emission everywhere and calculating the optical thickness locally from the surface density of circumstellar matter. The star is characterised by $T_{\rm eff}$ and A_V, with values taken from the literature and modified only if necessary to obtain an acceptable fit. The stellar radius can be adjusted to fit the absolute level of the photometric data, a decrease of radius corresponding to additional neutral extinction. The disk is described by an inner and an outer radius, by its mass, by the disk surface temperature at 1 AU, and by power laws for surface density and temperature distribution, $\Sigma(r) \sim r^{-p}$ and $T(r) \sim r^{-q}$. Star and disk are taken to lie behind the material causing the extinction, a simplification acceptable for the above objects which appear not heavily embedded in circumstellar material. As said above, our modelling is not to imply that all or most of the circumstellar material is in the form of thin disks. And we have also to remember that the parameters of such a disk model usually are not determined uniquely from the observations (see Thamm et al. 1994). However, our modelling at least indicates the general distribution of circumstellar matter with temperature (and hence distance from the star) around the binary components and helps us to estimate luminosities in a physically acceptable way. Detailed values of the parameters are not to be taken very seriously, and we mention only those in the text which appear relevant to us or which demonstrate the character of the fits used.

It is a weakness of our data set that data at different wavelengths often were taken at different dates. However, as far as we can tell from repeated observations of the same object at the same wavelength, the influence of brightness variations on the shape of the SEDs is not large and does not seriously affect our conclusions.

5. Results and discussion - individual sources

In this section we discuss individually the binaries known so far in our sample, with emphasis on the nature of the companions. In addition to the known binaries, we also consider here AB Aur. This star is a good example of an unresolved object, and it serves us to demonstrate typical upper limits for the near-infrared brightness of undetected companions. Finally we examine whether we can see a trend in the character of the companions with increasing luminosity of the Herbig Ae/Be star. The results on binary separation and brightness ratio are summarised in Table 4. The binary statistics of the sample are given in Sect. 6.

5.1. LkHα 198

The Herbig Ae/Be stars LkHα 198 and V376 Cas are the dominating visible stars in a small isolated molecular cloud at a distance of 600 pc (Chavarria 1985) in Cassiopeia. Both are known for circumstellar matter extended on the scale of 1000 AU which has been studied at visible and near infrared wavelengths (Pirola et al. 1992, Leinert et al. 1991). The geometry of the close environment of LkHα 198 proved to be complicated and is not related to the conspicuous adjacent elliptical reflection nebula or to the elongated bipolar outflow (Levrault 1988) in an obvious way (Mundt and Ray 1994). In 1991 Lagage et al. (1993) discovered a deeply embedded ($A_V > 35$ mag) companion to LkHα 198, 6$''$ north of the optical source. This new source, LkHα 198 IR, is estimated to have a luminosity of $\approx$100 $L_\odot$, not much less than the total luminosity of 160 $L_\odot$ estimated for the sytem (Chavarria 1985). On this basis LkHα 198 IR appears to be the third Herbig Ae/Be star in this molecular cloud. It fits better into the outflow geometry than LkHα 198 itself and therefore has been suspected to be the actual driving source. Contrary to the similar case of LkHα 234 below, where the companion was only detected at $\lambda > 8.7$ μm, LkHα 198 IR was also seen in the near infrared from 1.2 μm to 2.2 μm (Li et al. 1994, Lenzen, private communication). The projected separation of 3300 AU is small enough for LkHα 198 to be considered a binary within the definition of this paper. Because of the small size of the molecular cloud it is probable that the two sources lie physically close together. As with other similar cases, the actual physical association cannot be demonstrated but appears plausible.

5.2. Elias 1

Elias 1 has been taken as a B9 star with extinction A_V=8.85 mag (Strom and Strom 1994) and alternatively as an A6 star with A_V=3.9 mag (Zinnecker and Preibisch 1994). Its system luminosity is $L \approx 38\ L_\odot$ (Berrilli et al. 1992). The apparently stellar companion 4$''$ in the northeast is fainter in the near-infrared by 4–5 mag, but similar in the rising near-infrared spectral distribution (SED). Only at the longest measured wavelength (3.8μm, see Table 3), its SED, although still substantially high, is decreasing again. The SED of the system Elias 1, on the other hand, is rising with wavelength throughout the infrared range.

Table 3. Photometry of Elias 1 and its companion source

Source	Date	J	H	K	L'
Elias 1	Feb.-Dec.1976[a]	8.55	6.91	5.64	4.44
	Dec.6 1977[a]	8.70	7.17	6.07	
	Dec.5 1986[b]			6.1	
	Oct.26 1991[c]			5.9	4.3
	Jan.5 1993[d]	8.60	7.19	6.25	4.67
	compiled 1995[e]	8.73	7.13	5.97	5.08
Elias 1 NE	1991[f]		11.9	10.4	9.6
	Oct.26 1991[c]			10.0	9.3
	Jan.27 1994[g]	12.8	11.0	10.3	
LkCa 5	compiled 1995[e]	10.24	9.50	9.25	9.07
+ A_V=9.5		12.74	11.16	10.26	9.47

Notes: [a] Elias 1978 [b] Tamura and Sato 1989 [c] M. Simon, private communication [d] this work [e] Kenyon and Hartmann 1995 [f] Thornley as communicated by S. Skinner [g] this work, from 1993 brightnesses and 1994 brightness differences

Therefore it is improbable that the companion provides an important contribution to the far-infrared emission of the system. Measurements at additional wavelengths would help to determine the nature of the companion, which is not a priori guaranteed to be a young star. The available measurements at least allow tentative conclusions.

The near-infrared colours of Elias 1 NE, J–H$\approx$2.0, H–K$\approx$1.0, K–L$'\approx$0.7 are too extreme for being a cool foreground dwarf. We also discard the possibility that it is a Herbig-Haro object, as was found for an infrared source 4$''$ from HV Tau (Magazzu and Martin 1994). In this case we would not expect the still comparatively strong infrared emission at 3.8 μm and the substantial radio continuum flux at cm wavelengths.

A reddened background object is also a possibility to be considered: while a B star reddened with a standard extinction law would turn out to be too faint at J by half a magnitude, a M2III giant at 500 pc behind 10 mag of visual extinction would have just the measured near-infrared colour and brightness. However, the radio continuum flux of Elias 1 NE (0.2–0.6 mJy at 6 cm, Skinner et al. 1993) tends to be higher than measured by Drake and Linsky (1986) for the M giants μ Gem and ρ Per, which are at only 50 pc and 90 pc, respectively. The spectral index of Elias 1 NE between 3.6 cm and 6 cm has been measured to $\approx$-0.75. This is also not expected for thermal emission in the wind of a red giant, and therefore we discard this possibility.

The spectral index of Elias 1 NE, however, would be typical of the radio emission of galaxies; and for a galaxy with a spectral energy distribution similar to a K giant (J–H$\approx$0.6, H–K$\approx$0.15, K–L$'\approx$0.1), the colours would turn out approximately correct for 12 mag of visual extinction. Given the adopted range of extinctions to Elias 1 of 4–9 mag, which may be lower bounds because of expected local scattering, an extinction of 12 mag could occur in this region. On the other hand, the observed variation in radio flux at 2 cm by at least a factor of 20 within 2 days is very unusual for an extragalactic source, and the dereddened K brightness of $\approx$9 mag comparatively high. Also the image of

Elias 1 NE does not look extended in our near-infrared frames. None of these arguments is fully conclusive by itself. Taken together, they lead us to come back to the interpretation of Skinner et al. (1993) that Elias 1 NE is a T Tauri star and probably a true companion.

Radio emission in T Tauri stars is not unusual. In classical T Tauri stars it is thought to arise by free-free emission in the optically thick part of a stellar wind, in weak-lined T Tauri stars it is attributed to gyrosynchrotron radiation in which coronal electrons are accelerated in strong, ordered magnetic fields (Chiang et al. 1996). Flare-like variations of radio emission on time scales of < 1 day, which can exceed the levels observed in Elias 1 NE, have been observed (Feigelson and Montmerle 1985). The spectral index for this nonthermal emission is not bound to be positive, and the near-infrared colours of a weak-lined T Tauri star with spectral type M2 reddened by 8–12 mag of visual extinction are very close to those measured for Elias 1 NE. Five examples of M2 stars picked from the first part of the Herbig-Bell catalogue (1988) all agreed reasonably well, and the best fitting one, LkCa 5, is included in Table 3 for comparison. For these reasons we adopt Elias 1 NE as T Tau companion to Elias 1 of the weak-lined type. Based on the comparison to LkCa 5 its mass and luminosity can be roughly estimated to 0.4 $M_\odot$ and 0.3 $L_\odot$. And the observed X ray luminosity of the Elias 1 system ($1.9 \pm 0.8 \times 10^{30}$ erg/s, Zinnecker and Preibisch 1994) then could be fully or in part be explained by such a configuration (Wichmann et al. 1996).

In February 1990 the VLA observations of Skinner et al. (1993) showed a second radio peak $0.7''$ north of Elias 1 NE. We see no evidence for a companion to Elias 1 NE in our near-infrared data, neither in conventional imaging, nor by standard speckle reduction, nor by speckle holography with the primary of Elias 1 as reference source. Also speckle holography with Elias 1 NE as reference source showed no signs for a close companion or of significantly extended structure close to the primary of Elias 1. In the near-infrared we basically see a wide binary system.

5.3. HK Ori

The results are shown in Fig. 1 and summarised in Table 4. HK Ori, with spectral type A5 and A_V = 1.2, has an observed spectral energy distribution (SED) rising from the optical region through the near-infrared to 20 μm. The strong wavelength dependence of the brightness ratio of its components in the near infrared (see Fig. 1) suggests that only one component contributes substantially to the emission longward of 5 μm. We tried to identify whether this emission is due to the main optical component or to an infrared companion. At 1.25 μm, the SEDs of components A (i.e. the brighter component at K) and B are almost crossing. The measurement at 917 nm is at the limits of the performance of our NICMOS camera for such a comparatively faint object (I=10.8). We still are able to determine the brightness ratio reasonably well to about 0.85. We also find that the northeast component is the fainter one at this wavelength, too, but this finding is less certain since the phases show distortion by noise. Therefore, in modelling the two components each by the simple star plus disk model mentioned above, we considered two extreme cases: *a)* component A is also the main optical component (as suggested by the turn down of component B between 1.25 μm and 0.9 μm in our measurements) and *b)* component A is an infrared companion and the optical radiation is dominated by component B. Both assumptions result in fits to the SEDs of similar quality longward of 1μm. Of course, shortward of 1μm a more realistic separation would also have to allow for a more even distribution of the optical radiation between the two components. But we think that such more definite modelling attempts should wait until the optical brightness ratio and the association of the main optical to one of the infrared components have been determined by optical high resolution observations.

In the more interesting case *b)*, HK Ori has an infrared companion which dominates the luminosity. In this case, both the infrared companion with an inferred luminosity of 78 $L_\odot$, and the main optial component (14$L_\odot$, T_{eff} = 8200 K) may qualify as intermediate mass stars. In case *a)*, more probable according to our measurements and shown on right side of Fig. 1, 78 $L_\odot$ are due to the dominating component, and the luminosity of component B, fitted with T_{eff} = 3800 K, would be $\approx$ 5 $L_\odot$, more typical of a T Tauri star. Optical resolution of HK Ori would allow to find a realistic description of the system between these two extreme cases.

5.4. T Ori

Shevchenko and Vitrichenko (1994) found T Ori to be an eclipsing and spectroscopic binary with a period of $14\overset{d}{.}3$. Hillenbrand (1995) finds at 2.2μm a faint companion $7.7''$ away. Because of the enhanced stellar density in the Orion area, it is not unlikely that this second companion looks close by projection only. With a system luminosity of $\approx$130 $L_\odot$, the companion, if associated to T Ori, probably would have a luminosity of less than 2 $L_\odot$, which is in the range typical of T Tauri stars.

5.5. V380 Ori

The results are shown in Figs. 2 and 3 and summarised in Table 4. V 380 Ori presents a similar case like HK Ori in the sense that the near-infrared brightness ratio of the components is also strongly wavelength dependent (see the Figures). There could be a crossover of the components' SEDs at $\approx$0.9μm. Component A (i.e. the brighter one at K) therefore again could be an infrared companion. In the case of V380 Ori we also have the same difficulty to determine which of the components is the brighter one at 917 nm. However, this uncertainty is less critical than in the case of HK Ori, because the brightness ratio at this wavelength is close to 1. Nevertheless it is not obvious how the component SEDs will continue into the optical. We again consider two extreme cases, where again each component is described by a simple star plus disk model: *a)* the optical main component is responsible for the infrared emission, too. *b)* most of the infrared emission is due to an infrared companion, while

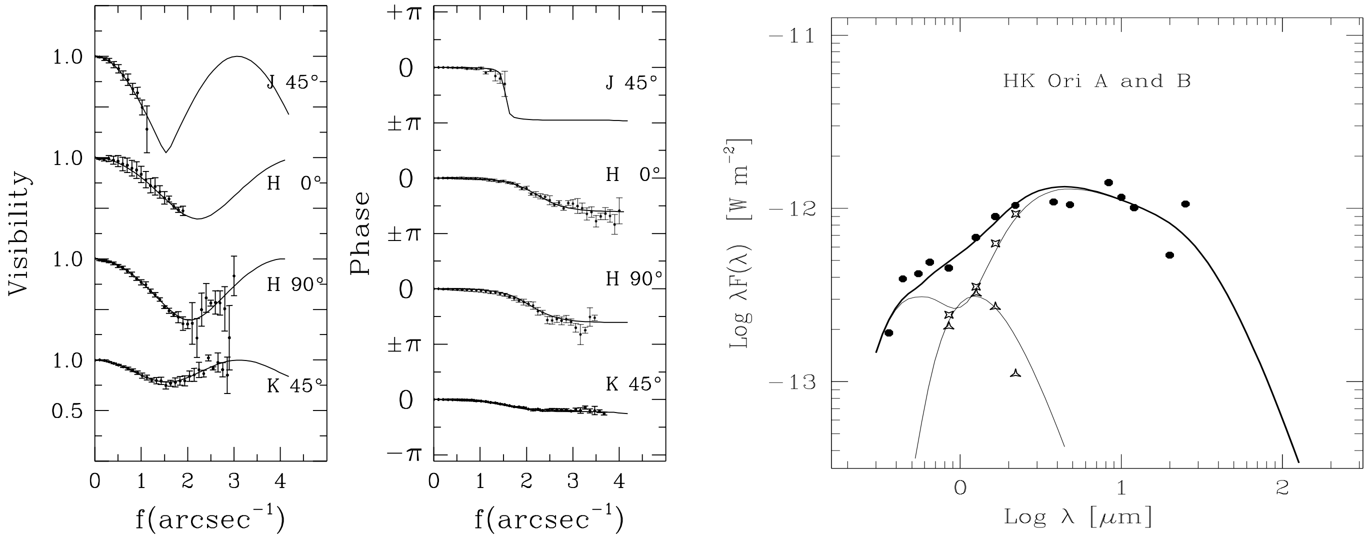

Fig. 1. *Left*: One-dimensional visibilities and phases for HK Ori. The observed values are shown with 1 σ error bars. The lines represent binary model fits. Note that at J the brightness ratio approaches 1, while at K it is about 0.1. The sign of the phase steps indicates that component B is to the northeast of component A. *Right*: Decomposition of the spectral energy distribution of HK Ori (filled circles) into spectral energy distributions for its components (A: squares, and B: triangles). The solid lines correspond to case *a)* in the text, where both the far-infrared emission and most of the optical radiation are assigned to component A.

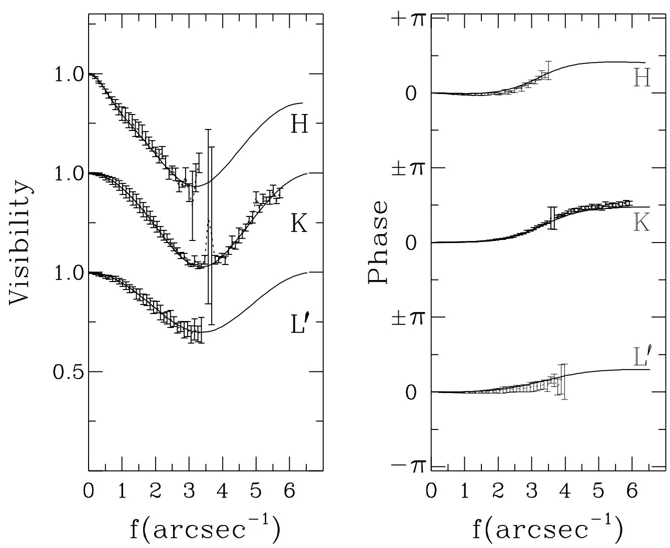

Fig. 2. One-dimensional visibilities and phases for V380 Ori measured in north-south direction. Note the wavelength dependence of the brightness ratio as evident from the varying depth of the minima in visibility and from the varying size of the steps in the phase curves.

component B is identical to the main optical component. Fig. 3 shows that in both cases satisfactory fits to the data result, such that we cannot prefer one model over the other one on the basis of our measurements. Certainly the measurements at 917 nm favour a model between the two extremes, but again we think that such more detailed modelling should be done only after the object has been optically resolved.

However, the estimates for the luminosities of the components do not dramatically depend on which association with the optical source is correct. Because of the decrease in the infrared flux of component B at 3.5 μm it is suggestive to assign the far infrared flux to component A, which then both in case *a)* and in case *b)* has a luminosity of the order of 170–180 $L_\odot$, typical of an intermediate-mass star. For component B the model fits shown result in luminosities of 30 $L_\odot$ to 70 $L_\odot$, the higher value resulting when the optical radiation is assigned to component B. Based on the luminosities, then both of the components of V380 Ori qualify as intermediate mass stars, and at least one of them shows a SED strongly dominated by thermal emission of circumstellar material.

We add a cautionary remark. In a similar case, LkHα 198, where the 100 μm emission is known to be extended by $\approx 30''$, Butner and Natta (1995) have shown, that such extended far-infrared emission is to be attributed to the optical star rather than to the deeply embedded companion. The extreme infrared companion modeled in case B in the right part of Fig. 3 therefore may not correspond to a physically acceptable solution.

5.6. LkHα 208

LkHα 208 was found to be a comparatively close binary, with a projected separation of $0.115''$ and a brightness ratio at K of 0.54 (see Fig. 4). This moderately reddened B7 star has a luminosity of $\approx$270 $L_\odot$ (Hillenbrand et al. 1992). Based on the flux partition of $\approx$ 1:2 at 2.2 μm, both primary and companion are expected to be Herbig Ae/Be stars. For further conclusions, measurements at other wavelengths are needed.

5.7. Z CMa

Z CMa with a system luminosity of $\approx$3000 $L_\odot$ (Hartmann et al. 1989) is a FU Orionis star and one of the best observed

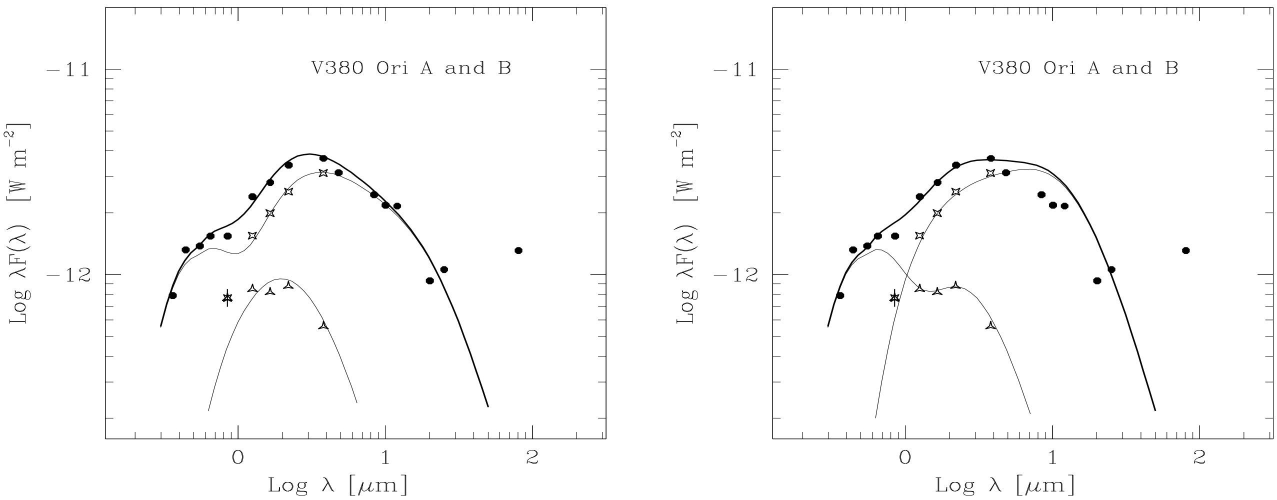

Fig. 3. Two alternative model fits to the spectral energy distribution of V380 Ori (filled circles) and its components (A: squares, and B: triangles). For 917 nm, components A and B have the same brightness. This is the value with the highest uncertainty, and the 1 σ error bar is shown. *Left*: case *a)*, with the primary dominating the companion at all wavelengths. *Right*: case *b)* with an optically dominating star and an infrared companion.

Table 4. Parameters of companions with projected separations $\rho < 3600$ AU

				Brightness Ratio (mag)					
Source	PA°	$\rho('')$	ρ(AU)	I'	J	H	K	L'	M
LkHα 198[a]	3 ± 1	5.5 ± 0.2	3300		4.0±0.2	3.5±0.1	3.8±0.1		
Elias 1[b]	23.4 ± 0.5	4.10 ± 0.04	570		4.18±0.03	3.78±0.02	4.01±0.02		
HK Ori	41.7 ± 0.5	0.34 ± 0.02	156	±0.15±0.15	0.10±0.10	0.92±0.05	2.30±0.10		
T Ori[c]	72.6 ± 0.5	7.7 ± 0.2	3500				> 4.5		
V380 Ori	204.2 ± 0.9	0.154 ± 0.002	71	0.0±0.15	0.65±0.08	0.97±0.08	1.14±0.09	1.86±0.11	
LkHα 208	113.5 ± 0.3	0.115 ± 0.002	115				0.67±0.04		
Z CMa[d]	122.5 ± 00.2	0.100±0.007	115	2.14±0.07^h	1.7±0.4	1.1±0.3	-0.86±0.14	-1.9±0.8	-2.1±0.6
HR 5999	114.6 ± 0.5	1.43 ± 0.01	214		3.25±0.07	3.44±0.05	3.58±0.04		
[e]	111.0 ± 0.4	1.45 ± 0.01			2.99±0.03	3.09±0.03	3.60±0.03		
KK Oph	247.2 ± 0.5	1.61 ± 0.02	258			1.99±0.19	1.96±0.17	2.13±0.21	
LkHα 234[f]	315 ± 25	2.7 ± 0.8	2700				>5.2		
MWC 1080[g]	267 ± 1	0.76 ± 0.02	1220	2.95±0.25	2.9±0.1	3.3±0.1	3.25±0.08	2.8±0.1	2.45±0.15

Notes: [a] detected by Lagage et al. 1993, values from Li et al. 1994 (K) and from observations on December 30, 1993 by R. Lenzen (J, H, ΔK = 4.1±0.1, private communication); emission at J is diffuse, upper limit for point source is $\Delta J > 4.8$. [b] detected by Skinner et al. 1993, our photometry [c] see Hillenbrand 1995, Table B.1. Shevchenko and Vitrichenko 1994 found T Ori also to be an eclipsing binary with a period of 14.26 days. [d] Koresko et al. 1991, p.a. from Haas et al. 1993 [e] observations by Stecklum et al. 1995 [f] embedded source detected by Cabrit et al. 1994, Weintraub et al. 1994 [g] Shevchenko et al. 1994 found MWC 1080 also to be an eclipsing binary with a period of 2.88 days. ^{h}) given value is at 660 nm, measured by Barth et al. 1994

young star binary systems. Leinert and Haas (1987) could only partially resolve this system with projected separation of 0.115″ and preferred a halo as explanation for the structure of this system. Koresko et al. (1991) achieved better spatial resolution and showed that Z CMa had an infrared companion. Haas et al. (1993) noted the substantial variability of both components. Whitney et al. (1993) proposed a model in which the infrared companion actually is the primary of the system, heavily obscured and seen in scattered light only, at least at the shorter wavelengths. The finding that the infrared companion is relatively bright at optical wavelengths (Barth et al. 1994) agrees with this model. Spatially resolved polarisation observations would make the case still stronger. The X-ray emission of $1.4\pm0.7\times10^{31}$ erg/s is attributed by Zinnecker and Preibisch (1994) to the optical component. Based on their luminosities, both components could be intermediate mass stars. – The claim of having seen a circumbinary disk at 3–5 μm (Malbet et al. 1993) has been questioned (Tessier et al. 1994).

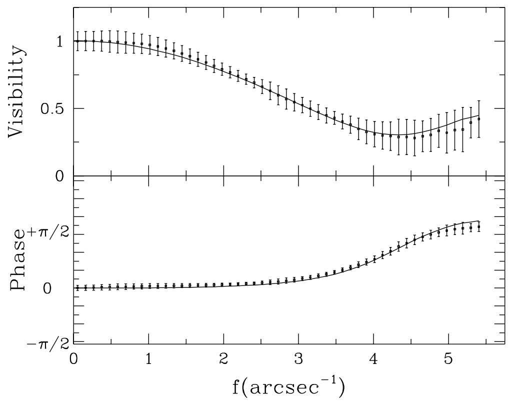

Fig. 4. Visibility and phase for LkHα 208. The figure shows the projection of the two-dimensional data onto the radius at PA 114°. The fit curves similarly represent the projection of a fit to the two dimensional visibility and phases.

5.8. HR 5999

This A7III-IV star with a luminosity of ≈130 $L_\odot$ has long been known to have a nearby companion, Rossiter 3930, fainter by about 4.5 mag in V (Jeffers et al. 1963). The system has been studied recently by Stecklum et al. (1995). The relative near-infrared brightnesses of HR 5999 and Rossiter 3930 appear to have changed by 0.1–0.2 mag between our 1993 measurements and their measurements one year later. Both sources could be variable on this scale. Stecklum et al. argue that Rossiter 3930 probably is a T Tauri star companion to HR 5999 and might be responsible for a considerable fraction of the X ray flux of $3.1\pm0.7\times10^{30}$ erg/s found by Zinnecker and Preibisch (1994) for this system.

5.9. KK Oph

This A6 star with a luminosity of ≈35 $L_\odot$ (Hillenbrand et al. 1992) has a spectral energy distribution typical of Hillenbrand's group I: with the photospheric decrease out to 1 μm, followed by a rising spectral energy distribution through the near-infrared wavelength range. There is a possible association with a 3.6 cm radio source nominally 1.5 ″ to the NE. The companion appears to have a similar spectral energy distribution as the main component: in the visible it was estimated to be fainter than the primary by about 1 mag (Herbig and Bell 1988), while we found it in the near infrared fainter by about a factor of 6. Since the apparent luminosity of KK Oph is dominated by emission from 2 μm to 10 μm, the luminosity of the companion may be in the range of 5–10 $L_\odot$. As far as luminosity and spectral energy distribution are known at present, they would qualify the companion as a classical T Tauri star.

5.10. LkHα 234

LkHα 234, one of the brightest objects in the star forming region NGC 7129, is a B3 or B5e-B7e star with a luminosity of ≈2300 $L_\odot$ at ≈1000 pc (Hillenbrand et al. 1992). It is associated with a CO outflow (Edwards and Snell 1983) and an optical jet (Ray et al. 1990). Within 12″ of LkHα 234 there are several faint infrared sources, many of which appear to be field stars (Li et al. 1994, Weintraub et al. 1994). The latter group of authors conclude from their 2 μm polarisation map that besides LkHα 234 itself there must be a deeply embedded companion at the center of the observed elliptical polarisation pattern, approximately 3″ NW of LkHα 234. They also proposed that this companion actually be the source driving the CO outflow around LkHα 234. It coincides with the infrared companion IRS 1 found 2.5″ NW of LkHα 234 by Cabrit et al. (1994b) at 10 μm, and which has a steeply rising spectrum in this wavelength range. The detection of radio continuum only at the position of LkHα 234 IRS 1 (Skinner et al. 1993) is also an indicator that this source is related to wind and outflow. With a projected separation of 2500–3000 AU between LkHα 234 and the companion source IRS 1, they can be considered as a binary system within the definition of this paper. The luminosity is difficult to estimate from the presently available data. Cabrit et al. (1994b) mention that it has about 1/4 of the flux of the infrared companion to LkHα 198 at $\lambda\approx10\mu$m. Both infrared companions are considered to be sources driving outflows or jets. Since the polarization pattern around LkHα 234 at 2μm is oriented towards the embedded source IRS 1, the intrinsic K band luminosity also should not be very low. Based on this scattered information we assume that LkHα IRS 1 is similar to the infrared companion of LkHα 198 also in luminosity, and probably an intermediate mass star.

5.11. MWC 1080

This high luminosity object (spectral type B0, L ≈6500 $L_\odot$) has a strong, fast wind with velocities of up to 1100 km/s. It was found to be an eclipsing binary with a period of 2.89 days (Shevchenko et al. 1994). Zinnecker and Preibisch (1994) consider this close system as an example where the observed X ray luminosities of $9.4\pm4.9\times10^{31}$ erg/s could be due to colliding winds from the components.

Our 1D speckle observations showed an additional companion 0.76″ west (see Fig. 5). Based on the observed brightness ratios and published magnitudes, its broad band spectrum is increasing from 0.9 μm to 5 μm. This means that most of the observed luminosity of the companion is due to emission by circumstellar dust, as is the case for the main component. To obtain approximate information on the distribution of circumstellar dust around the components, we fitted the spectral energy distribution by the models of stars surrounded by geometrically thin disks mentioned above. We stress again that, since the actual spatial distribution of dust is not known, such a fit only provides a qualitative description of the the general distribution of the material with temperature (rather flat for these spectra, q ≈ 0.4–0.5). For the primary, Fig. 5 shows that our simple two-component model is not completely adequate, but certainly a large extent and large mass of the circumstellar material are needed to account for the long-wavelength measurements at 100μm to 1.3 mm (see also Hillenbrand et al. 1992). For the

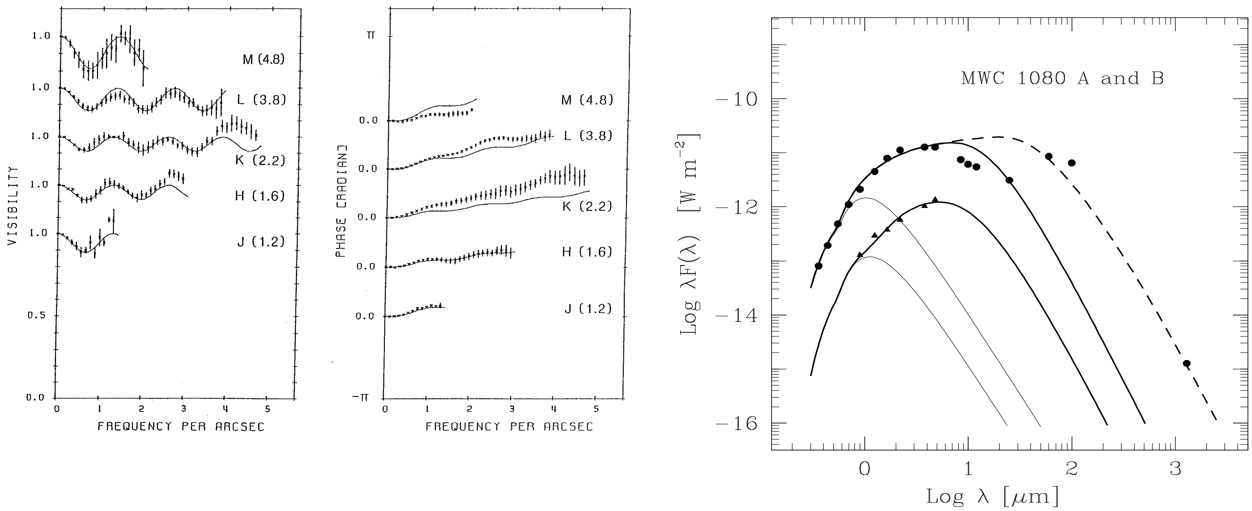

Fig. 5. *Left*: One-dimensional visibilities and phases for MWC 1080. *Right*: Observed spectral energy distribution for the primary of MWC 1080 (dots) and its visual companion (triangles) compared to models comprising reddened stars and thermal radiation from thin disks with a power-law temperature profile. In each case, the thin lines show the direct stellar contribution (with A_V = 5 mag and T_{eff} = 27000 K and 12000 K, respectively). The bold lines give the system flux predicted by the models. For the primary component, two models are shown, one emphasising the mid-infrared measurements (solid line) with disk mass, outer radius of the disk and system luminosity of $\geq$ 0.001 $M_\odot$, 50 AU and , and 3500 $L_\odot$, and one emphasising the far-infrared and millimeter fluxes (broken line, 1.5 $M_\odot$, 330 AU and 6200 $L_\odot$). The corresponding parameters for the companion are $\geq$ 0.00001 $M_\odot$, 20 AU and 240 $L_\odot$.

companion, we found the assumption most convincing that it is fainter than the primary at all wavelengths. The adopted fit predicts a luminosity for he companion of ≈250 L⊙, which would classify it as a Herbig Ae/Be star, too.

5.12. AB Aurigae

The spectroscopically very well studied B9/A0 star AB Aur has a both a fast wind, as seen from its P Cyg profiles (see, e.g. Finkenzeller and Mundt 1984), a strong near-infrared excess similar to a classical T Tauri star and cool dust as detected in the IRAS bands and in the continuum at 1.3 mm (see Hillenbrand et al. 1992). The object is unresolved in our one-dimensional speckle observations at K (Leinert et al. 1994). The data lead to the following limits on the extent of the source or the presence of a companion: an upper limit for the FWHM of 0.030″, or alternatively an upper limit of 0.1″ for the FWHM of a compact halo contributing 10% to the object brightness. The brightness contribution of a possible halo larger than 50 AU (0.″3) is limited to a fraction of at most 8% of the system brightness, which corresponds to an upper limit on the mass of about $10^{-5} M_\odot$ under standard assumptions on dust scattering properties; but this estimated mass increases with the square of the halo radius (see Leinert et al. 1991). We do not expect to resolve the source of the near-infrared excess radiation which, be it hot dust (the colour temperature of the near-infrared excess is ≈1800 K) or free-free emission in the stellar wind, in any case is expected to be within 1 AU from the star.

AB Aur also was found to be an X-ray source with an X ray luminosity (0.1–2.4 keV) of $3.3 \pm 0.9 \times 10^{29}$ erg/s (Zinnecker and Preibisch 1994). A possible explanation of the X ray emission would be an unresolved T Tauri star companion. In this case our observations give an upper limit for the brightness contribution at 2.2 μm due to such a companion of 0.04 at separations $\geq$ 0.1″, rising for smaller separations to 0.2 at 0.03″ (4 AU). The luminosity for AB Aur has been given as $\approx 80 L_\odot$ (Hillenbrand et al. 1992). Our upper limits therefore do not exclude the existence of a moderately faint or moderately close T Tauri star companion but show that, if it exists, it would be difficult to detect.

5.13. Classification of the companions

In Table 5 we summarise the binaries in our sample by luminosity and try to assign a stellar type to the companions on the basis of the inferred luminosity: we assume that the companion should be a T Tauri star for luminosities less than 10 $L_\odot$ and a Herbig Ae/Be star for luminosities $L > 40 L_\odot$. There are no companions in Table 5 with estimated luminosities in the intermediate range.Admittedly, this assignment is a coarse approximation which also neglects the difference between stellar luminosity and accretion luminosity, which may be an important effect. All of the classifications given below therefore are somewhat uncertain, and those qualified by a question mark are uncertain indeed. On the other hand, if we take the six most luminous T Tauri stars in Taurus from the extensive list of Kenyon and Hartmann (1995), we have the triple star RW Aur (> 54 $L_\odot$), the class I sources L1551 IRS5 (22 $L_\odot$) and Haro 6-10 (7 $L_\odot$) and the prominent class II sources T Tau N (16 $L_\odot$), RY Tau (17 $L_\odot$) and HL Tau (7 $L_\odot$), where the classes are assigned according to Lada (1987). Our tentative classification given in

Table 5. Proposed stellar type of the companions

Source	Luminosity of system	Luminosity of companion	References	Type
LkHα 198	160 $L_\odot$	100 $L_\odot$	1,2	Ae/Be
Elias 1	38 $L_\odot$	$\approx$0.3 $L_\odot$	3,4	WTTS[a]
HK Ori	41 $L_\odot$	$\approx$5 $L_\odot$	5,4	T Tau
T Ori	130 $L_\odot$	$<$2$L_\odot$?	5,6	T Tau ?
V380 Ori	180 $L_\odot$	$\approx$50$L_\odot$	5,4	Ae/Be ?
LkHα 208	270 $L_\odot$	$\approx$100$L_\odot$?	5,4	Ae/Be ?
Z CMa	$\approx$3000 $L_\odot$	2100 $L_\odot$	7,8	Ae/Be ?
HR 5999	135 $L_\odot$	3.9 $L_\odot$	5,9	T Tau
KK Oph	35 $L_\odot$	5–10 $L_\odot$	5,4	T Tau ?
LkHα 234	2300 $L_\odot$	?	5,10	Ae/Be ?
MWC 1080	6500 $L_\odot$	$\approx$250 $L_\odot$	4	Ae/Be

Notes: [a] weak-lined T Tauri star
References: (1) Chavarria 1985 (2) Lagage et al. 1993 (3) Berilli et al. 1992 (4) this paper (5) Hillenbrand et al. 1992 (6) Hillenbrand 1995 (7) Hartmann et al. 1989 (8) Koresko et al. 1991 (9) Stecklum et al. 1995 (10) Cabrit et al. 1994b

Table 5 therefore appears acceptable, and it is a convenient and informative way to summarise the individual data on binarity.

It appears from Table 5 that the higher luminosity sources also have higher luminosity companions, and that this correlation looks more pronounced than expected e.g. for random pairing of the components from an initial stellar mass function. Part of this relation must be a selection effect, since it is difficult to detect faint companions close to bright sources. Insofar we are back to the point that we may have underestimated the multiplicity in our sample. On the other hand, this effect could also be a natural outcome of intermediate mass star formation. This question should be followed up in future observations of Herbig Ae/Be stars.

6. Multiplicity

After the discussion of the individual systems we now give a statistical overview of the data. Among the 26 Herbig Ae/Be stars in our sample, 8 have a companion with a projected separation between 50 AU and 1300 AU. In addition there are three cases where the projected separation of the companion falls between 2000 AU and 3600 AU. These latter are not free of the suspicion to be chance projections, given the fact that many Herbig Ae/Be stars are situated in small clusters of stars. We measure the binarity by the degree of multiplicity (also called "fractional multiplicity"), which we define as *(number of binary or multiple systems)/(total number of systems in sample)*, as we did in our previous similar study on the low-mass young stars in Taurus (Leinert et al. 1993). The resulting degree of multiplicity for our sample then is 31$\pm$10% (42$\pm$13%), where the number in parentheses includes the more doubtful companions with separations $>$ 2000 AU.

Recent studies of the multiplicity of T Tauri stars (Ghez et al. 1993, Leinert et al. 1993) have shown a distinct overabundance of young binaries with respect to their main–sequence counterparts. We want to see whether this effect can also be found in our sample. Therefore we compare to what appears the best data set on the duplicity on the main sequence (Duquennoy and Mayor 1991). Since these authors give their results in logarithmic bins of orbital period, we convert our measured projected separations to periods by the following assumptions: a system mass of 4$M_\odot$, a uniform distribution of orbital planes and longitudes of perihelia, a "relaxed" excentricity distribution of $n(e) = 2e$. Then on the average, the semimajor axis is a=1.02$\cdot d$, where d is the projected separation (see Leinert et al. 1993). The statistically predicted orbital periods in our sample then range from 320 to 20000 years ($\approx 10^5$ years for the three wide systems), which we take to correspond to the logarithmic intervals of period P = 10^5 - 10^7 days (10^5 - $10^{7.5}$ days). In these period ranges, Duquennoy and Mayor (1991) found a duplicity of 15$\pm$3% (18$\pm$3%). We should not overemphasize a statistical result for such a small and somewhat heterogeneous sample, but it appears that there is an excess of duplicity in Herbig Ae/Be stars by about a factor of two (1σ–2σ) with respect to G type main sequence stars.

We briefly consider the importance of two systematic effects. First, our results could be incomplete. We may have missed a few close, faint companions. Indeed we know that we could not have seen close ($<0.1''$) companions, which are fainter by more than a factor of twenty than the primary. As possible indication that this effect actually may occur in our sample, we note that only one of the five subarcsecond binaries has a brightness difference of $\Delta K \geq 1$ mag, while the five widest binaries all have $\Delta K > 3$ mag. Second, among the wider binaries we may have included one or two spurious companions due to chance projections. These two systematic effects counteract each other and, depending on the actual statistics of companion brightness and separation, may even cancel. We therefore take our results as an acceptable estimate of the duplicity in our sample. Our results could also represent a lower limit on duplicity only. This would be the case if the wide binaries in our sample represent true physical associations and at the same time there are some undetected faint close companions.

The above comparison to main sequence G stars is informative, but it would be more meaningful to compare our results to the duplicity for intermediate mass main–sequence stars of spectral types A and B. We are not aware of a recent survey of duplicity for a A and B stars of similar quality and completeness like the survey of G stars by Duquennoy and Mayor. But Abt (1983) concludes that binary frequency, period distribution and secondary mass distribution do not vary drastically along the main sequence from B to G stars. Indeed, the degree of multiplicity of 51% given by him for the B stars compares well with the values found for G dwarfs of 48% (Duquennoy and Mayor 1991) or 55% (Abt 1983). The same is true for the number of companions per primary star, given as 0.69 for the B stars (as observed, upper limit) and as 0.60 (Duquennoy and Mayor 1991) or 0.54 (Abt and Willmarth 1992) for G dwarfs. We conclude that in terms of duplicity the study of Duquennoy and Mayor is also representative for intermediate mass A and B stars and that our sample of Herbig Ae/Be stars therefore shows an excess in duplicity by a factor of about two (1σ–2σ) also with respect to their counterparts of spectral type A and B on the main sequence.

The distribution of brightness ratio of the binary components in our sample is sharply increasing towards small companion brightnesses. Nine out of 11 of the binaries in Table 4 have near-infrared brightness ratios at K of > 2 mag, and if a couple of them had to be rejected as chance projections, the fraction would still be 6 out of 9. We will see that this distribution in brightness ratio is more steeply rising towards faint companion brightnesses than found for T Tauri stars.

Most of the binary Herbig Ae/Be stars in Table 5 have strong infrared excess or even SED's rising with wavelength through the near- to mid-infrared, i.e. they belong mostly to class II, partly to class I in the classification scheme of Lada (1987). There is the possibility that companions to these infrared emitters will look systematically too faint relative to their primaries compared to the ratio of the 'stellar' brightnesses. To largely avoid this bias, we compare only to those T Tauri stars in the list of Leinert et al. (1993) which also belong to class I and class II according to Kenyon and Hartmann (1995). Out of these 32 pairs, only 8 companions have a brightness ratio > 2 mag at 2.2 μm. Although the involved number of Herbig Ae/Be binaries is small, and although the conversion from K brightness to mass may be different for the typical companions to T Tau or Herbig Ae/Be stars, we see in these data an indication that the mass ratio distribution for Herbig Ae/Be binaries is also more peaked towards small masses than for T Tauri stars. Such a steep distribution has been found for main sequence B star binaries by Abt and Willmarth (1992).

We note that qualitatively such relations would be expected if the mass distribution in binaries were the result of random association from a Miller-Scalo (1979) initial mass function. Then for a 3 $M_\odot$ Ae/Be star 75% of the companions would have a mass less than 1/6 of the primary, while for a T Tauri star of 1.2 $M_\odot$ this percentage would be only 45%. Given the the statistical uncertainties due to the small number of binaries in our sample all we can conclude is that the present results do not obviously contradict the concept of random association from an initial mass function as a summary description of binary mass ratios. In detail, as discussed in Sect. 5.13, luminosity (and perhaps also mass) of the primaries and companions may be correlated.

7. Summary and conclusion

We have studied 26 of the more active Herbig Ae/Be stars for duplicity by means of high angular resolution imaging. Combining our results with those available in the literature, we find the following:

– There are 11 binaries in the sample, five of which have subarcsecond separations, and nine of which have projected separations ≤ 1000 AU. This degree of duplicity appears to be in excess by roughly a factor of two over the duplicity observed for main sequence A and B stars.

– In the near-infrared, most of the companions are fainter by 2 mag or more than the brighter components. In total, this is similar to what would be expected if the binaries were formed by random association from a Miller-Scalo initial mass function. But in detail there is a trend that in the more luminous systems the companions are also more luminous.

– In most cases the optically dominating star is also brighter in the near-infrared and probably carries most of the far-infrared flux. In the cases of V380 Ori, HK Ori and LkHα 208 this has still to be decided; in the first two of these cases optical, high spatial resolution measurements are needed for this purpose.

In broad outline then the duplicity of Herbig Ae/Be stars in our sample is similar to that of the better studied sample of T Tauri stars.

However, to put such conclusions on a firm basis, the multiplicity of both young and main-sequence Ae/Be stars still needs better definition.

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