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Establishing the nature of companion candidates to X-ray-emitting late B-type stars*

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ABSTRACT

The most favoured interpretation for the detection of X-ray emission from late B-type stars is that these stars have a yet undiscovered late-type companion (or an unbound nearby late-type star) that produces the X-rays. Several faint infrared objects at (sub)arcsecond separation from B-type stars have been uncovered in our earlier adaptive optics imaging observations, and some of them have been followed up with the high spatial resolution of the *Chandra* X-ray observatory, pinpointing the X-ray emitter. However, firm conclusions on their nature require a search for spectroscopic signatures of youth. Here we report on our recent ISAAC observations carried out in low-resolution spectroscopic mode. Equivalent widths have been used to obtain information on spectral types of the companions. All eight X-ray-emitting systems with late B-type primaries studied contain dwarf-like companions with spectral types later than A7. The only system in the sample where the companion turns out to be of early spectral type is not an X-ray source. These results are consistent with the assumption that the observed X-ray emission from late B-type stars is produced by an active pre-main-sequence companion star.

Key words: binaries: spectroscopic – binaries: visual – stars: pre-main-sequence – X-rays: stars.

1 INTRODUCTION

X-ray observations performed with the *Einstein Observatory* and *ROSAT* missions have revealed that X-rays are emitted by stars throughout the Hertzsprung–Russell (HR) diagram. For stars on the main sequence (MS) two mechanisms are known to be responsible for the observed emission. In O-type and early B-type stars, the X-rays are produced by instabilities arising in their strong radiatively driven stellar winds (Lucy & White 1980; Owocki & Cohen 1999), and in late-type stars a solar-like magnetic dynamo is thought to be responsible for the observed X-ray activity (Parker 1955). No X-ray emission is expected from stars whose spectral types are late B and early A. Nevertheless, X-ray detections of these stars have been reported in several works (e.g. Daniel, Linsky & Gagné 2002, and references therein).

In absence of another explanation, the X-ray emission of MS late B-type and early A-type stars is commonly attributed to unresolved late-type companions. During the last years, in order to obtain clarification of this issue, we pursued a multifold strategy: (i) an adaptive optics search for previously unresolved late-type companions to B- and A-type stars which are known to be X-ray emitters, (ii) high spatial resolution follow-up X-ray observations of those with new companions to identify the X-ray source within these systems and (iii) low-resolution spectroscopy of the X-ray-emitting objects identified with adaptive optics to establish their nature.

In 1999 we have been engaged in a multiplicity survey of *ROSAT*-selected bright late B-type dwarfs using the European Southern Observatory's Adaptive Optics Near-Infrared System (ADONIS) instrument, searching for close companions in the diffraction-limited infrared (IR) images (Hubrig et al. 2001). For the systems studied, the X-ray flux levels observed in the *ROSAT* All Sky Survey (RASS) are $\log L_{\rm X}({\rm erg\,s^{-1}}) \sim 29.5$–30.5 (Berghöfer, Schmitt & Cassinelli 1996), far too high to be explained by emission from cooler MS companion stars in the system. Nearby late-type field stars display much lower activity levels, with typically $\log L_{\rm X}({\rm erg\,s^{-1}}) \sim 26$–28 (Schmitt & Liefke 2004). The observed X-ray luminosities are similar to those of T Tauri stars, that show typically $\log L_{\rm X}({\rm erg\,s^{-1}}) \sim$ 28–31 (Preibisch et al. 2005). Therefore, a reasonable interpretation within the companion scenario is that the X-ray emission is produced by active pre-main-sequence (PMS) companion stars. Since the late B-type stars that we have studied are rather young with ages less than a few hundred million years (Hubrig et al. 2001), the detected new low-mass companion candidates are, indeed, expected to be PMS stars or very young MS stars.

In the sample of 49 late B-type stars observed with ADONIS, we found 29 faint objects near 25 stars. For 21 of these 29 IR objects our ADONIS images represent a first detection. If all these objects

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are true physical companions, the resulting binary frequency in this spectral type domain is 51 per cent. However, our sample was biased towards low-mass companions that exhibit strong X-ray emission. For the discovered IR objects the following information has been collected in the previous studies. For 11 of the faint IR objects both J and K magnitudes were obtained with ADONIS. The near-IR photometry of these objects was compared to the evolutionary models for low-mass PMS stars calculated by Baraffe et al. (1998). For seven of them, fig. 2 of Hubrig et al. (2001) shows that their position is compatible with them being low-mass PMS stars. In the remaining four systems for which we obtained both J and K measurements with ADONIS the discovered IR objects have already evolved to the MS, and could not be fitted with PMS evolutionary tracks. For the companion candidates in the other 14 ADONIS systems to date only K-band measurements are available. Knowing the age of the late B-type primaries from their position in the HR diagram and assuming that systems are coeval, we placed the companions with known M_k values along the isochrones of the B primaries to estimate their masses, luminosities and effective temperatures (Hubrig et al. 2001). From these considerations we expect that out of these 14 systems nine contain PMS companions. Thus, our photometric study suggested that out of the observed IR objects, 16 are PMS stars. Their masses estimated from the PMS tracks range from about $1.2\,M_{\odot}$ down to $0.6\,M_{\odot}$.

In the framework of our accompanying *Chandra* programme we have obtained high spatial resolution (∼1 arcsec) X-ray observations of late B-type stars with companion candidates from near-IR photometry. Contrary to the earlier RASS data, in the *Chandra* images we were able to separate the contributions of the B-type star and the known visual companions to the X-ray emission. The *Chandra* sample was composed of 11 systems with late B-type primaries and 15 known visual companions, most of them identified in our ADONIS survey. We found X-ray emission from 12 of the new IR objects; in one case the companion is a binary that cannot be resolved with *Chandra* (Stelzer et al. 2003, 2006a). The companion candidates detected with *Chandra* show X-ray luminosities in the range $\log L_X(\mathrm{erg\,s^{-1}}) \sim 29$–30, typical for T Tauri stars (e.g. Preibisch et al. 2005). These objects can, therefore, be considered as strong candidate PMS stars.

However, companionship cannot be established based on photometry and X-ray observations alone. To confirm or reject the candidates identified as described above, we carried out a spatially resolved K-band spectroscopic study of the companions with the Infrared Spectrograph and Array Camera (ISAAC) at the Very Large Telescope (VLT). Our objective was to find out whether the detected IR- and X-ray candidate PMS companions are physically associated objects or background sources. In addition, for three studied systems we present our recent observations carried out with the Nasmyth Adaptive Optics System with Near-Infrared Imager and Spectrograph (NACO) at the VLT.

2 SAMPLE

Our sample of eight systems selected for ISAAC observations is based on the photometric survey with ADONIS and contains companions which can be easily separated with ISAAC from their parent stars during good seeing conditions and have been visible during our visitor run on 2005 May 24. Four of these systems were in the *Chandra* sample, and all their companions were detected at levels of $\log L_X(\mathrm{erg\,s^{-1}}) \sim 29$–30 (Stelzer et al. 2006a).

In addition, we observed HD 165493 and HD 104237−6. The system HD 165493 was previously studied by Lindroos (1985) in the course of his survey of visual double stars with early-type primaries. Berghöfer et al. (1996) failed to detect any X-ray emission from this system in the RASS (the companion at 4 arcsec was not resolved). However, the upper limit for the X-ray flux of $\log L_X(\mathrm{erg\,s^{-1}}) < 31.4$ is quite high and does not rule out the presence of X-ray emission at typical T Tauri star levels. The T Tauri star HD 104237−6 is a low-mass companion to the optically brightest Herbig Ae star HD 104237 at a separation of 14.88 arcsec (Grady et al. 2004). It was used in our observations as a comparison star. As was shown by Feigelson, Lawson & Garmire (2003) and Grady et al. (2004), HD 104237−6 exhibits Hα emission at a level typical of weak-line T Tauri stars. The X-ray properties of this star are also T Tauri-like, with $\log L_X(\mathrm{erg\,s^{-1}}) = 30.7$ according to Stelzer et al. (2006b).

3 OBSERVATIONS AND DATA REDUCTION

The observations were carried out using the ISAAC IR spectrograph on UT1 at the VLT in low-resolution mode ($R = 1500$) in clear weather conditions with seeing around 0.8–1.0 arcsec. The pixel size was 0.147 arcsec pixel^{-1} with a slit size of 0.3 arcsec. The exposure time for each target has been adequately chosen to reach a good S/N (> 100). The targets and telluric standards were observed with the traditional long-slit nodding pattern with a few arcsec jitter to better sample the detector. A telluric standard star was observed either just before or after the target object. The acquisition images for each target and slit position are presented in Fig. 1. A flat-field correction has been applied to all frames, using a flat-field lamp for internal calibration. The background has been removed using pairs of frames, followed by dead pixel removal. The wavelength calibration model has been obtained using xenon and argon lamp arc observations. The extracted target spectra have been corrected for the telluric features using typically two standard stars of late B and early A dwarf spectral type. We also obtained spectra of a few early G dwarfs. A set of these standard stars of solar spectral type has been used to trace possible features produced by Brγ absorptions visible in the hot standard stars and to correct for them. The final normalized spectra of the studied companions are presented in Fig. 2. We note that very faint emission features at 2.317 μm in the spectra of HD 73340 and HD 110073 are reduction artefacts left after the correction for terrestrial absorption.

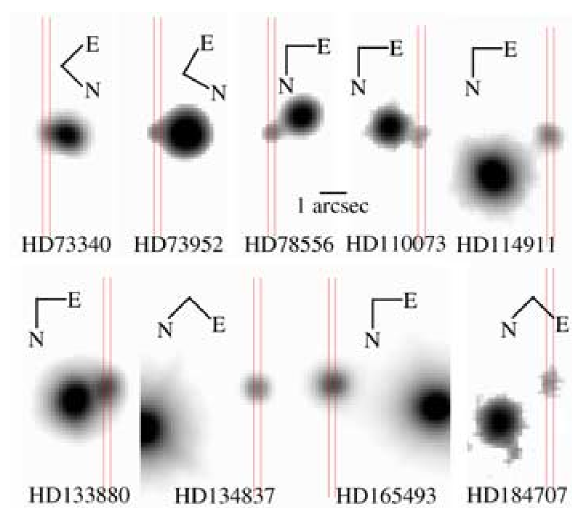

Figure 1. Acquisition images and slit positions for the observed systems with companions.

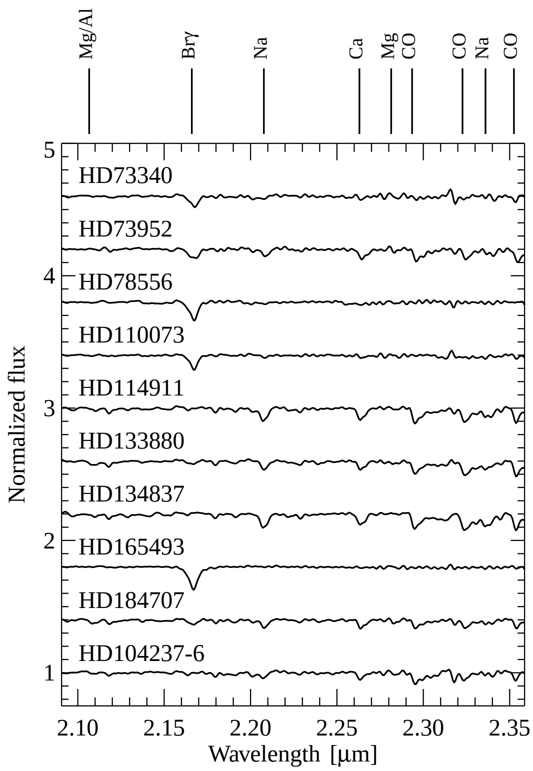

Figure 2. Normalized ISAAC spectra of the studied companions. All but the lowest are displaced upwards for display purposes.

The system HD 184707 is a possible triple system: we discover just at the detection limit a very faint additional companion on the acquisition image. It is located at 1.3 arcsec from the primary star at a position angle (PA) of 73° (see Fig. 1). However, the presence of this companion has still to be confirmed by deeper observations.

4 RESULTS

In Table 1 we present the astrometry of the X-ray-selected late B-type stars with companions. The columns from left to right-hand side give the name of the object, the separation, PA, Modified Julian Date and signal-to-noise ratio (S/N) of the final one-dimensional spectra for the new ISAAC measurements, the separation, PA and binary magnitude difference (ΔK) from our 1999 ADONIS observations (Hubrig et al. 2001), and finally the separation and PA from our recent NACO observations at the VLT obtained in 2005 February and March (Hubrig, Ageorges & Schöller 2007; Schöller et al., in preparation). The separation and PAs for ISAAC were measured on the acquisition images presented in Fig. 1. The accuracy of the projected separation measurements in ISAAC acquisition images is about ±0.07 arcsec, and the accuracy of the PA is typically about ±2°. The uncertainties of the projected separation measurements for ADONIS and NACO are about ±0.05 and ±0.02 arcsec, respectively. For the PAs, the accuracies are ±0.°2 for ADONIS and ±0.°1 for NACO. We have not attempted to make any astrometric study, since the data for the different epochs were obtained with different instruments. However, the values for separation and PAs presented in Table 1 show a good consistency of the position of the companions relative to the primary stars from 1999 (ADONIS observations) to 2005 (ISAAC and NACO observations) and did not change much within six years.

Table 2. The strongest features in the *K*-band spectra.

Feature	λ (μm)
Brγ	2.16
Na I	2.20, 2.21
Ca I	2.26
Mg I	2.28
CO	2.29, 2.32, 2.35

4.1 Spectral classification

The wavelengths of the strongest features in our *K*-band spectra are listed in Table 2. As was shown by Luhman & Rieke (1998), the metallic absorption features can be used in the spectral classification for spectral types later than F8. The only strong feature expected in the *K*-band spectrum of the late B-type primaries is Brγ.

The equivalent widths (EWs) of all features were measured by defining a global continuum as the best-fitting line to wavelength regions which are free of spectral lines. The absorption features presented in Table 2 are sensitive to temperature and their EWs have been used for spectral classification as suggested by Luhman & Rieke (1998).

For very close faint companions, some contamination of the spectra by the primary stars is expected, but this will not affect the

Table 1. Astrometry of late B-type stars with companions from ISAAC (columns 2–5), ADONIS (columns 6–8) and NACO (columns 9 and 10). The errors for the projected separation measurements are ±0.07 arcsec for ISAAC, ±0.05 arcsec for ADONIS, and ±0.02 arcsec for NACO. The errors for the PA are ±2° for ISAAC, ±0.°2 for ADONIS, and ±0.°1 for NACO.

Object	Separation (arcsec)	PA	Modified Julian Date	S/N	Separation (arcsec)	PA	ΔK	Separation (arcsec)	PA
	ISAAC				ADONIS			NACO	
HD 73340	0.5	214	53516.022	220	0.604	221.2	2.52	0.570	220.0
HD 73952	1.0	207	53516.040	180	1.162	205.3	4.19		
HD 78556	1.3	299	53516.060	210	1.300	298.5	3.31		
HD 110073	1.1	74	53516.101	260	1.192	75.0	3.08	1.202	73.9
HD 114911	2.6	124	53516.147	130	2.706	124.6	0.319		
HD 133880	1.2	111	53516.117	150	1.222	109.2	2.35		
HD 134837	4.7	155	53516.162	120	4.696	154.3	⩾4.66		
HD 165493	4.1	258	53516.179	360				4.043	257.3
HD 184707	2.4	175	53516.194	150	2.435	173.1	⩾2.76		
HD 104237−6			53516.134	180					

Table 3. Equivalent widths of the *K*-band absorption features.

Object	EW (Å)					Spectral type
	Brγ	Na I	Ca I	Mg I	^{12}CO(2,0)	
HD 73340	4.5 ± 0.2	1.8 ± 0.2	0.7 ± 0.1	0.8 ± 0.1	0.1 ± 0.1	F5–F7V
HD 73952	4.2 ± 0.2	3.8 ± 0.2	4.0 ± 0.1	1.3 ± 0.1	7.9 ± 0.1	K6–M0V
HD 78556	7.1 ± 0.2	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	A7–A8V
HD 110073	5.4 ± 0.2	0.6 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	F4–F5V
HD 114911	0.4 ± 0.2	4.9 ± 0.2	4.2 ± 0.1	0.9 ± 0.1	9.0 ± 0.1	K6–M0V
HD 133880	1.6 ± 0.2	2.8 ± 0.2	2.8 ± 0.1	1.2 ± 0.1	7.0 ± 0.1	K2–K3V
HD 134837	0.4 ± 0.2	5.0 ± 0.2	4.2 ± 0.1	0.5 ± 0.2	10.1 ± 0.2	K6–M0V
HD 165493	11.1 ± 0.2	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1	A3–A5V
HD 184707	1.5 ± 0.2	3.0 ± 0.2	3.1 ± 0.2	1.3 ± 0.1	4.6 ± 0.1	K2–K4V
HD 104237−6	1.0 ± 0.2	3.1 ± 0.2	2.6 ± 0.1	1.2 ± 0.1	6.8 ± 0.1	K3–K4V

Na, Ca, Mg and CO features. In hotter and more massive companion candidates with spectral types from A0 to F5 the strongest *K*-band feature is Brγ. In these cases we used the atlases by Lancon & Rocca-Volmerange (1992) and Wallace & Hinkle (1997) which present *K*-band spectra of stars of different spectral types (O to M) and luminosity types I to V. The EWs of the *K*-band absorption features in the spectra of all companions and the comparison star HD 104237−6 are presented in Table 3. The corresponding spectral types are listed in the last column.

4.2 Brief notes on individual targets

In the following, we compare our findings from our previous near-IR study with the results of the *K*-band spectroscopy.

4.2.1 The comparison star HD 104237−6

This star, which is a low-mass companion to the optically brightest Herbig Ae star HD 104237 (Grady et al. 2004), has a spectral type K3 IV determined from optical spectroscopy with FEROS. We use this object as a comparison star. The EWs of the absorption features in our *K*-band spectrum indicate a spectral classification K3–K4. The strength of CO relative to Na and Ca is dwarf-like in agreement with the determination of Grady et al. (2004).

4.2.2 HD 73340

The PMS companion with a mass of 1.2 $M_\odot$ was discovered with the European Southern Observatory's ADONIS instrument in 1999 March (Hubrig et al. 2001) and later confirmed by observations with NACO at the VLT in 2005 February (Schöller et al., in preparation). The strongest spectral feature is the Brγ absorption line indicating a spectral type F5–F7 according to the near-IR stellar atlases of Lancon & Rocca-Volmerange (1992) and Wallace & Hinkle (1997). The Na, Ca, Mg and CO features are all weak, in agreement with a spectral type of a companion of a mass of 1.2 $M_\odot$.

4.2.3 HD 73952

Hubrig et al. (2001) suggested that the mass of the companion is about 0.6 $M_\odot$. Using EWs of Na, Ca, Mg and CO spectral features we conclude that the companion is a dwarf with a spectral type K6–M0. The Brγ line appears much too strong for the determined spectral type. However, because of the faintness of the companion ($\Delta K = 4.19$; cf. Table 1) and its closeness to the primary (see Fig. 1), the primary clearly contributes to the *K*-band spectrum, giving rise to the composite spectrum we observe.

4.2.4 HD 78556

This star was observed with ADONIS only in the *K* band and the determination of the mass of the companion was very uncertain. The Brγ strength and the weakness of other absorption features constrain the spectral type to about A7–A8 according to the near-IR stellar atlases. Berghöfer et al. (1996) measured an X-ray luminosity of $\log L_X(\mathrm{erg\,s^{-1}}) \sim 29.7$.

4.2.5 HD 110073

According to our previous study, the companion is a PMS star with a mass of 1.13 $M_\odot$. The *K*-band spectrum appears similar to that of the companion to HD 73340 with very faint Na, Ca, Mg and CO features and a rather strong Brγ line. Their strengths match with the spectra presented in the stellar atlases of a spectral type of F4–F5.

4.2.6 HD 114911

The mass of the PMS companion was estimated as 0.88 $M_\odot$. The Brγ absorption is very weak, and the strength of other features implies a spectral type between K6 and M0.

4.2.7 HD 133880

According to our previous study, the companion to HD 133880 is expected to be a PMS star with a mass of 1.17 $M_\odot$. The spectrum fits with a spectral type K2–K3.

4.2.8 HD 134837

Only *K*-band imaging was done for this system in our previous work. The *K*-band spectrum of the companion resembles rather well the spectrum of the companion to HD 114911. From the strength of Na, Ca, Mg and CO we derive a spectral type between K6 and M0.

4.2.9 HD 165493

Using *K*-band imaging carried out with NACO in 2005 March, we detected a companion at a separation of about 4 arcsec with a *K* magnitude about 3 mag fainter than the primary star. The spectrum exhibits only strong Brγ absorption and no other features are detected. The strength of the Brγ line implies an early spectral type between A3 and A5.

4.2.10 HD 184707

Only *K*-band imaging was done for this system in our previous work. The EWs of absorption features in our *K*-band spectrum imply a spectral classification K2–K4.

5 DISCUSSION

The detection of X-ray emission from late B-type and early A-type stars has been reported from virtually all X-ray satellites and has long remained a puzzle. MS stars of spectral type ∼B2 to A7 do not show high-speed stellar winds nor deep convection zones needed to support dynamo action; hence no X-ray emission is predicted for them. It has long been argued that late-type companion stars might be responsible for the observed X-rays but this hypothesis could not be tested observationally with previous low-spatial resolution instruments. In the past we have approached the problem with high-spatial resolution imaging in the near-IR with ADONIS and in X-rays with *Chandra*. The results from these studies suggest that many late B-type stars drawn from the RASS have faint IR objects nearby and these companion candidates are responsible for at least a fraction of the X-ray emission.

To examine the nature of these objects we performed follow-up spectroscopy. In the sample of nine-candidate multiple systems presented here we confirm the PMS nature of the companion candidate. In five systems (HD 73953, HD 114911, HD 133880, HD 134837 and HD 184707) the studied companions exhibit dwarf-like *K*-band spectra consistent with spectral types between K and M. The spectra of these low-mass companions resemble well the spectrum of the T Tauri star HD 104237−6 of spectral type K3 IV. All of them lack emission features at the positions of the Brγ line and of the CO band heads, indicating that these companions could be classified as weak-line T Tauri stars. The companions of three systems (HD 73340, HD 78556 and HD 110073) are more massive and their *K*-band spectra are consistent with spectral types late A to mid F. Considering that the spectra of all the studied companions suggest spectral types later than A7 and all of them show dwarf-like values for the luminosity indicator, it is very unlikely that they are background sources.

In the case of HD 165493, the companion in the system is relatively hot with a spectral type between A3 and A5. A detection of X-ray emission is not expected for stars of this spectral type because there is no known X-ray production mechanism. In fact, Berghöfer et al. (1996) were not able to detect X-ray emission from this system. However, their upper limit for the X-ray flux of $\log L_{\rm X}({\rm erg\,s^{-1}}) < 31.4$ is not conclusive, and a deeper X-ray image with *Chandra* resolving the binary would be useful.

We note in this context, that two more systems with suspected PMS companions discovered previously with ADONIS, HD 75333 and HD 145483, have been subsequently observed in 2001 with the NIRSPEC instrument at medium resolution $R = 3500$ on the Keck II telescope together with the adaptive optics system (Hubrig et al. 2005). Similar to the results presented in this study, these observations have confirmed the late-type spectral classification with spectral types between K5 and M0.

Based on the results presented in this study we conclude that it is reasonable to attribute the observed X-ray emission from late B-type stars to active late-type PMS stars. The physical association of the studied companions with the B-type star is also anticipated from the consistency of our photometric observations with ADONIS with the predictions obtained from evolutionary models (Hubrig et al. 2001) as well as spatially resolved X-ray images of a small sample carried out with *Chandra* (Stelzer et al. 2003, 2006a).

Binary star formation mechanisms represent an important, but still not completely understood part of star formation. Considerable data have been accumulated for both MS and evolved late-type stars (Duquennoy & Mayor 1991), for PMS stars and for stars of intermediate mass and age in open clusters (Duchêne 1999; Duchêne et al. 2004; Haisch et al. 2004). Generally, these surveys come to the conclusion that for the examined range of separations at young ages there are twice as many binaries as in the field. In contrast, the multiplicity properties of higher-mass stars remain poorly known and previous studies have provided inconclusive results. The percentage of close (both visual and spectroscopic) binaries among B-type stars was found to be higher than among solar type stars, and earlier spectral types seem to have a higher companion star fraction than later spectral types (e.g. review by Zinnecker & Bate 2002). On the other hand, an adaptive optics survey in the ScoOB2 association led to the discovery of several new binaries of late B and A spectral type, suggesting that the apparent decrease of the binary fraction towards later spectral types may be the result of observational biases (Kouwenhoven et al. 2005). Searches for binaries among Herbig Ae/Be stars have been carried out by means of IR imaging (Bouvier & Corporon 2001), optical spectroscopy (Corporon & Lagrange 1999) and spectroastrometry (Baines et al. 2006). All these studies suggested a high binary frequency (the largest value, 68 ± 11 per cent, being achieved by the spectroastrometric study), but were restricted to a limited sample.

Our previous ADONIS observations yielded an observed binary frequency of 51 per cent for the RASS selected sample. In this paper we have shown that, when followed-up spectroscopically, most of the photometric companion candidates are confirmed as late-type stars. The high binary frequency in our sample is certainly due to the fact that the stellar sample contained only X-ray-selected stars and, in addition, was biased towards low-mass companions which exhibit strong X-ray emission. One of the future important tasks would be to study a sample of late B-type stars not detected in the RASS. Recently, Ivanov et al. (2006) started a search of companions to intermediate-mass stars in the field. The main goal of their study was to derive the binary frequency of a volume-limited sample of BA stars in the solar neighbourhood with distances smaller than 300 pc. Such observations are necessary to get further insight in the formation mechanisms of intermediate-mass binaries.

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