Contact binaries with additional components. III.
A search using adaptive optics.

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\textbf{ABSTRACT}

We present results of the CFHT adaptive optics search for companions of a homogeneous group of contact binary stars, as a contribution to our attempts to prove a hypothesis that these binaries require a third star to become so close as observed. In addition to companions directly discovered at separations of $\geq 1''$, we introduced a new method of AO image analysis utilizing distortions of the AO diffraction ring pattern at separations of $0.07'' - 1''$. Very close companions, with separations in the latter range were discovered in systems HV Aqr, OO Aql, CK Boo, XY Leo, BE Scl, and RZ Tau. More distant companions were detected in V402 Aur, AO Cam, V2082 Cyg. Our results provide a contribution to the mounting evidence that the presence of close companions is a very common phenomenon for very close binaries with orbital periods $< 1$ day.

\textit{Subject headings:} stars: close binaries - stars: eclipsing binaries – stars: variable stars

\section{1. INTRODUCTION}

The formation of close binaries is still a puzzle: How can they be formed if the components were larger than the instantaneous orbit during the pre-main-sequence phase? One possibility is that angular momentum transfer to a third companion caused the originally wider orbit to shrink during the main-sequence (MS) phase. If this hypothesis is true, all close binaries should be accompanied by a third body (unless it was removed by an encounter, but this is unlikely by the time the stars have reached the MS). Thus, one would expect the incidence of the triples to be higher than in a sample of relatively wide ($P \gtrsim 10$ days) binaries. Tokovinin \& Smekhov (2002) and Tokovinin \textit{et al.} (2006) studied the frequency of occurrence of tertiary companions for the binary period range of 1 to 30 days and collected an impressive amount of evidence that indeed the frequency of terciaries

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increases as the binary period decreases, from a level of about 34% for orbital periods of 12 – 30 days to 50% at 9 days, and further to perhaps even 100% at 1 day.

This paper is the third in a series assessing the presence and properties of tertiary companions to very close binaries with periods shorter than 1 day. In the first paper of the series, Pribulla & Rucinski (2006, Paper I), we summarized the present state, collecting all detections of third and/or multiple components to contact binaries. This led to a heterogeneous sample, with observational biases which were difficult to quantify. Nevertheless, for our sample of contact binaries brighter than $V_{\text{max}} = 10$, it allowed us to set a firm lower limit of $59 \pm 8\%$ to the incidence of the tertiaries (for the better-observed sub-sample of the Northern hemisphere systems). The preliminary results of adaptive optics program discussed in the current paper were reported in Paper I.

In D’Angelo et al. (2006, Paper II), we presented a spectroscopic search for faint third companions. Several thousand medium-resolution spectra obtained during the David Dunlap Observatory (DDO) radial velocity program for 80 binaries were re-analyzed, and weak – but stable – spectral signatures of tertiaries were searched for in the averaged spectra. This resulted in a detection of 15 tertiaries – of which 11 were previously unknown – in a homogeneous sample of 59 contact binaries. The continuation of the radial velocity observations – 110 good accuracy orbits are now published (Pribulla et al. 2007) – will provide material for a future similar study. The spectroscopic observations permit detection of very close companions hidden in the seeing disk of the close binary (at DDO typically 1.8 – 2 arcsec) but – for faint companions – it is limited to a magnitude difference of about 5 magnitudes (e.g., in CK Boo, $L_3/(L_1 + L_2) = 0.009$, Paper II). The AO observations presented in the current paper permit detection of much fainter and redder companions, particularly in the infrared, but only at relatively large separations, and with long-period orbits, compared to those studied spectroscopically. Unlike for spectroscopic observations, where a physical bond can often be proven by similar systemic velocities or mutual revolution, visual detections for nearby ($< 300$ pc) and relatively bright ($V < 10$) binaries may suffer some contamination from projections; often, however, the density of background stars is sufficiently low that the mere presence of an object at small separation from a bright star is a strong indication of a physical bond.

The majority of the systems covered in this series of papers are genuine contact binaries. At orbital periods shorter that one day they are the most frequently detected and studied. However, our program includes also binaries with unequally deep eclipses which may be contact binaries with poor thermal contact or short-period semi-detached systems. In some cases (V1464 Aql, TT Cet), low photometric amplitudes and/or lack of spectroscopic observations preclude any meaningful classification. We note, that – evolutionary – all these types must be related to contact binaries as binaries of the least orbital angular momentum. Hence, we will interchangeably use the terms “close” and “contact” binary stars throughout this paper to mean all target binaries with periods shorter than 1 day.

This paper is structured in the following way: In Section 2, we describe our observations and
their reduction, and in Section 3 we introduce a new search technique for multiples, which uses template fitting, and present our new detections. In Section 4 we use a Monte-Carlo technique to verify our estimate of the detection limits for a given magnitude difference. In Section 5 we present tests of the physical bond between the visual companions, and in Section 7 we discuss the nature of the detected companions. Finally, in Section 8 we summarize and interpret our results.

2. OBSERVATIONS

We obtained observations aimed at the direct detection of companions of contact binary stars on the nights of 1998 January 10 and 1998 July 23, 2005 October 17 and 18, using the adaptive optics (AO) system at the Canada France Hawaii Telescope (CFHT). During the 2005 run, the specific goal was to survey the many bright contact binaries originally detected by the Hipparcos satellite and later confirmed spectroscopically during radial velocity programs (mostly at the David Dunlap Observatory; for reference, see Pribulla et al. 2006, 2007). Altogether, 80 known contact binaries stars – accessible from CFHT to an approximate limit of $V < 10.5$ – were observed with 15 objects observed on two occasions and with 2 objects observed three times. The journal of all observations can be found in Table 1 and overview of the detections is given in Table 2.

We used the PUEO AO system with the KIR camera combination (Rigaut et al. 1998), with a $1024 \times 1024$ pixel detector that covers a field of $36 \times 36$ arcsec at a scale of 0.0348 arcsec pixel$^{-1}$. In 1998, most observations were done in the infrared $K$ band or, to avoid overexposure of the contact binary, a narrow-band filter centered on the CO bands ($K_{CO}$; for details on the filters, see notes to Table 1); a few binaries were also observed in the $H$ band ($1.65 \mu m$). In 2005, we used the $H_2$ filter, which for our purposes is effectively another narrow-band $K$ filter.

In 1998, each source was observed by positioning it in each of the four quadrants of the detector, while in 2005 a fifth, central position was added. At each position, typically three to five exposures with integration times from 5 to 40 s were obtained; typically, we thus collected 12 to 25 individual images. With the image shifts and multiple exposures, we could obtain good definitions of the background and – for detected visual companions – reliable uncertainty estimates of magnitude differences ($\Delta m$), separations ($\rho$) and position angles (PA, $\theta$).

In all cases, the contact binaries themselves were sufficiently bright to be used for sensing the distortion of the wavefront and deriving the AO corrections. In the $K$ passband, the isoplanatic patch is relatively large, about $40''$, and thus encompasses the whole field of view of the KIR camera. The Strehl ratio of the AO-corrected images was found to be almost constant (around 0.30) for all images taken in natural seeing better than 0.9 arcsec. On a few occasions of a worse seeing, the Strehl ratio fell below 0.2. Although the amount of light scattered from the Airy disk into the rings increased on such occasions, the diffraction pattern was still very well defined. The measured FWHM of the AO-corrected images was 0.143 arcsec in the $K$ band, close to the expected diffraction-limited performance of a 3.6 m telescope.
The resulting point spread function (PSF) of the corrected images is a combination of a diffraction pattern defined by the aperture of the telescope with a residual Gaussian and/or Lorenzian profile of much less understood character. Its shape was found to vary depending on the declination and the hour angle of the telescope (see Section 3).

For the initial reductions, we subtracted bias and dark current from the raw images, divided by flat fields, and removed hot pixels. Next, we co-added all images for different sky displacements. For astrometry, we measured the rotation and scaling of the AO system and its detector using known wide visual pairs with very slow orbital motion. The position angles for the 1998 and 2005 observing runs had to be corrected by $-1^\circ$ and $+4^\circ$, respectively, but no corrections to the pixel scale were needed. For both 1998 runs the correction was found to be the same.

3. DETECTION OF VISUAL COMPANIONs

In order to obtain maximum sensitivity to faint, close companions, we attempted to model the observed PSF of single targets. We first used an analytical combination of the Bessell function of the first order for the diffraction-limited part and a Gaussian function for the residual uncorrected light. The resulting representations turned out to be poor due to additional asymmetries in the PSF, visible as “gaps” at various position angles in the diffraction rings. Clearly, a heuristic approach was needed which would utilize the observed PSF shape as given by this particular combination of telescope, AO system, and camera.

Careful inspection of our images revealed that the PSF shapes were similar for most of the stars, but contained small residual deformations which depended primarily on the position of the telescope (Figures 1 and 2) and – to a lesser degree – on the instantaneous seeing and the effective Strehl ratio of the corrected image. To investigate the variation in the PSF shape, we fitted each stellar image to all images of other stars. While most systems showed just mild dependencies of the similarity in the image shape on various positional factors, some had systematically different shape. We quantified the differences by a relative (to the maximum within the image) root mean square standard deviation of all fits to a given object using other images as templates. Some of the systems showing large mismatches are well known close visual binaries where the secondary is located at very small separation (VW Cep, V2388 Oph, ER Ori, V592 Per), while some others were previously unrecognized as visual binaries (XY Leo, BE Scl). These results thus led to a cursory, but rapid identification of close pairs.

Following this preparatory stage, we analysed the images in more detail in two steps (i) we determined positions and magnitude differences of obvious and distant ($\rho > 1.0$ arcsec) companions from fluxes and centroid positions of their Airy disks (the mosaic of direct detections is presented in Fig. 3); and (ii) we performed an automated search for faint companions which were missed in visual inspections or were too close to measure their positions and brightness. For the latter search, we made direct fits to a binary model assuming that – within the isoplanatic patch – a binary can
be represented by two properly shifted and scaled images of a well-chosen template. Thus, we express the observed image intensity for a visual double, $I(x, y)$ as,

$$I(x, y) = B + A_1 \times T(x - x_1, y - y_1) + A_2 \times T(x - x_2, y - y_2),$$

where $B$ is the background level, $A_1$ and $A_2$ are the normalization factors of the two stellar images (central star and companion, if present), $T(x, y)$ is the template image, and $x_1, y_1$ and $x_2, y_2$ are the spatial shifts of the template required to match the fitted images (for non-integer pixel shifts, we use bi-linear interpolation in the template intensity). Thus, the fits involve three parameters entering linearly and four parameters entering non-linearly. The performance of our technique is illustrated in Fig. [4] for a very close companion to BE Scl$^2$.

We found that the largest difficulty in identifying faint companions which might create only slight deformations of the PSF, was to find a suitable template. To be as objective as possible, we performed an automated, brute-force search in which we fitted each object by a visual binary model which uses, in succession, all other objects observed in a given run as templates (but omitting V592 Per and other objects already recognized as close pairs). To ensure the fitting process did not converge only to local minima, and to increase chance of finding real faint/close visual companion(s), we chose 24 initial positions of potential companions: eight different position angles $\theta$, in steps of 45°, for three different initial separations $\rho$, of 0.1, 0.2, and 0.3 arcsec, (i.e., sampling the region from the core to just outside the diffraction ring). As a starting magnitude difference, we used $\Delta M = 3$ mag. For a given object and a template combination, the fit with the best statistical quality, $\chi^2$, from all possible starting sets of parameters was recorded. We rejected any fits that converged to separations closer than 0.02 arcsec.

Using as many templates as possible (e.g., 46 different stars for the 2005 observing run), we were able to assess the reliability of the detections and their significance level from the distribution of the recovered parameters. Also, with as many as 200 resulting parameter sets for a given object, we could reliably determine final (mean) values and uncertainties for the various parameters for positive detections. For the 1998 runs, we omitted a small number of $H$ and $K$ band observations and utilized only frames taken in the most frequently used filter, $K_{CO}$.

One of the main difficulties in analyses like ours is to determine the significance of detections. We assessed it using the following scheme: For each successful convergence of the secondary position to a pixel inside an area of $100 \times 100$ pixels around the primary, we added a convergence unit “count” to that pixel, and we then looked in these “convergence maps” for count clustering. In other words, we took high numbers of counts for all templates as an indication of a distortion in the image which could be due to the presence of a companion. With this method, one immediately recovers close, but obvious pairs, for which almost all object-template fits led to consistent sets of parameters.

\footnote{Similar figures for eight additional systems, OO Aql, HV Aqr, CK Boo, VW Cep, XY Leo, V2388 Oph, ER Ori, V592 Per, are available in the electronic version only, see the caption to Figure [4].}
But one can also recover less obvious cases, as is illustrated in Fig. 5 where we show convergence maps for two systems, EQ Tau and BE Scl. Here, EQ Tau is a typical case of no detection with a few spurious instances of the algorithm locking on small fluctuations within the first diffraction ring. However, for BE Scl, one sees a clear clustering of successful convergences within a small circular area indicating a genuine detection.

The approach described above has a limitation related to the increased random fluctuation noise in brighter portions of the image, particularly within the first ring, where the likelihood of the algorithm locking on random positive deviations is much larger. To assess the probability of false detections, we constructed a map similar to those we made for the individual stars, but obtained by adding the convergence maps for all stars which showed no indication of a companion (as for EQ Tau in Fig. 5). In practice, we added the low numbers of false detections in the diffraction rings for individual stars and obtained a “background map” of false detections against which our detections can be compared (Fig. 6). Note that we constructed these background images separately for 1998 and 2005 runs; encouragingly, though, the images are very similar, indicating the characteristics of the CFHT AO system did not change much between these two epochs.

With the convergence and background maps in hand, we assigned significance of the detection using two approaches, (i) by simply taking the count maximum within the map, or (ii) by integrating (summing) the counts within a small (e.g., \( r < 6 \) pixel) aperture and comparing this with the number of counts in the same region in the background map. For both approaches, the relevant quantity required normalization by the number of used object and template frames. For each object and observing run, Table 3 gives number of the object frames, \( N_f \), and the number of templates used, \( N_t \) (28 in 1998 and 46 in 2005), and the number of frames used to construct the background map, \( N_b \). For the first approach, the maximum number of counts within the count map (\( C \)) was then normalized to a typical number of object frames and templates of the 2005 run (\( N_f = 5, N_t = 46 \)) as:

\[
C_n = \frac{230}{N_f N_t}.
\]

In the second approach, the sum of counts \( S \) in a cluster within a given aperture of radius \( r \) is divided by the corresponding summed count number (within the same area) in the background image \( B \). The quality of the detection is then expressed as the normalized ratio of counts in the object and the background count maps:

\[
R_n = \frac{S}{B} \frac{N_b}{N_f}.
\]

In Table 3 we list the systems that show clustered counts within small circular apertures (with \( r < 6 \) pixels), and are thus suspected higher-order systems, while in Table 4 we give maximum normalized counts \( C_n \) for systems for which no companions are suspected. Selection of a threshold

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3The convergence count maps for all objects are available at http://www.astro.utoronto.ca/~rucinski/Triples3/
for actual detection based on the “quantities of merit”, \( C_n \) or \( R_n \), was rather difficult and somewhat
arbitrary; after some experiments, we felt a best distinction was achieved by taking as detections
those objects that had \( C_n > 20 \) or \( R_n > 50 \), as listed in the last column of Table 3. With
these thresholds, the automated search confirmed all suspected cases seen as deformation of the
diffraction structure. These thresholds lead to the confirmation of the four known tight pairs –
V592 Per, VW Cep, ER Ori (1998 run) and V2388 Oph – and four new detections – HV Aqr (this
one is also directly visible in the image), BE Scl, XY Leo and CK Boo. Among these, XY Leo is the
closest resolved system, with a separation of only 0.061 arcsec. The suspected cases – V376 And,
TZ Boo, DN Cam, YY Eri, BV Eri, V829 Her, V508 Oph, V351 Peg, and TY Pup – clearly require
new observations. The results for the automated search (presented in Tables 3 - 4) apply only for
the detection of very close companions within 0.3-0.4 arcsec. Hence, e.g., V829 Her having distant
companion clearly visible at 1.46 arcsec is given as detection “D” in Table 2 but there is only
suspicion for very close companion (Tables 3 - 4).

Measured properties for the detected companions are given in Table 5. The table gives des-
ignations of the components, the separation (\( \rho \)), the position angle (\( \theta \)) in degrees, the magnitude
differences in \( K \) and \( H \) bandpasses, the heliocentric Julian date of observation and, from the date,
the orbital phase of the binary and a correction of its brightness (see Section 5). The table lists only
systems with detected companions within 5 arcsec. Although this limit seems to be set arbitrarily,
even faint companions separated by more than 5 arcsec can be easily detected with small telescopes
without adaptive optics. A good example is GZ And, where we give only our new detection at 2.13
arcsec; the components B and C, separated by 8.6 and 13.3 arcsec, respectively, are clearly visible
even in small telescopes (Walker 1973).

4. EVALUATION OF DETECTION LIMITS

The limit to which we were able to detect tertiaries for a given separation depended mainly
on (i) the magnitude difference of the components in the \( K \)-band, \( \Delta K \), and (ii) the similarity of
the PSF for the object and the template. We assessed these limits by adding artificial stars to our
real frames and applying the whole detection procedures.

We selected images of two single stars without any close (\( \rho < 10 \) arcsec) companions: AQ Psc
serving as an object and FP Eri as a template. Artificial images were produced by shifting and
co-adding the same object image for a wide range of separations (0.04 < \( \rho < 1.20 \) arcsec) and
magnitude differences (0 < \( \Delta K < 6.5 \) mag). For given \( \Delta K \), the detection limit was determined as
a minimum separation for which the algorithm would converge to the original position to within
the FWHM of the PSF (we found our result was insensitive to the exact choice of convergence
criterion). The resulting detection threshold curve, together with all actual detections, is displayed
in Fig. 7; its ruggedness reflects the complex diffraction pattern in the PSF. This curve is very
similar to curves published before for the same system (Duchêne et al. 1999, Bouvier et al. 2001).
As one can see in Fig. 7, the above criterion for the detection limit derived from artificial stars is
consistent with what we found from our automated search: all detected systems are above or at the detection limits.

5. NATURE OF THE COMPANIONS

We attempted to estimate nature of the companions – assuming they are physically bound – from the measured brightness differences and estimates of the absolute magnitude of the close binaries. The results are listed in Tables 5 and 6, with the former giving results for individual observations and the latter overall properties that we used or determined.

To obtain the best constraints on the companions, we first needed to ensure our magnitude differences were evaluated relative to the maximum brightness of the contact binary. This is important for some contact binaries showing large photometric amplitudes (e.g., GZ And, OO Aql, SW Lac, ER Ori, and U Peg with \( \Delta V > 0.70 \) mag). Thus, knowledge of the orbital phase is necessary for a proper estimate of the instantaneous brightness of the contact binary. The phases at the time of the AO observations were calculated using the Cracow on-line, up-to-date ephemeride database (Kreiner et al. 2001; Kreiner 2004). The visual magnitude of the contact binary was then estimated by using published light curves (sometimes by graphical tracing in figures) to determine the difference with the maximum brightness \( V_{\text{max}} \) (the latter usually taken from the General Catalogue of Variable stars).

To convert these \( V \) magnitude at the time of the observation to absolute magnitudes \( M_V \), we used Hipparcos parallaxes with relative precision better than 15% if available (an error of \(< 0.30 \) mag in the absolute magnitude), and the period-color-luminosity relation of Rucinski & Duerbeck (1997) (an error of \( \sim 0.30 \) mag) for systems with poorer parallaxes (GZ And, V829 Her, OO Aql, AO Cam, and ER Ori). Because all objects are nearby, we neglected interstellar absorption.

Next, to calculate expected absolute magnitudes \( M_K \) at the time of the observation, we used main-sequence colors appropriate for the spectral types of the binaries (as determined from DDO observations; see Pribulla et al. 2006, 2007 for references to previous publications). Here, we note that in comparing contact binaries with single stars, one must take into account that while they are MS objects, the energy transfer from the primary to the secondary component makes the primary component always cooler than a MS star of the same mass (Mochnacki 1981). Furthermore, because of the increased radiating area, the absolute visual magnitude \( M_V \) of a contact binary obtained directly from its trigonometric parallax and \( V_{\text{max}} \) is always brighter than the \( M_V \) corresponding to a single MS star of the same spectral type. However, for given spectral type, contact binaries appear to have the same colors (S.M.R., unpublished comparison of \( B - V \) and \( V - K \) indices), so that our simple corrections are adequate to evaluate \( M_K \).

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4http://www.as.ap.krakow.pl/ephem/

5We used the most recent electronic version (4.2), available at http://www.sai.msu.su/groups/cluster/gcvs/
Finally, with $M_K$ for the contact binary at the time of the observation, the observed magnitude difference then yields the absolute magnitude of the companion, and, with the appropriate main-sequence relations, the estimated spectral type. One sees that most of the companions appear to be late, M0–M6 dwarfs, with some, such as those of U Peg and V402 Aur, of even later spectral types.

To estimate orbital periods of wide visual orbits of triple systems, we also calculated the total masses of the contact binaries, by combining radial-velocity orbits such as those obtained at DDO (Pribulla et al. 2006, 2007), which give $(M_1 + M_2) \sin^3 i$, with photometric observations, which provide the orbital inclination $i$. In the selection of such combined solutions, we preferred the total masses determined by simultaneous light and radial-velocity curve fits (Gazeas et al. 2006). The total mass of the systems (using estimated mass of third companion) was then used to estimate an approximate orbital period of the visual pair from the angular separation and the distance.

6. THE PHYSICAL BOND

While the presence of a star close to several contact binaries is unquestionable, the physical link is often difficult to prove. There are three possible ways of assessing the physical bond:

**Observed color difference.** With observations in multiple photometric bands, one can verify that the spectral type of the companion inferred from its magnitude – assuming the same distance as the contact binary – is consistent with its colors. Unfortunately, we can do this for few systems only, since most of the data were obtained in one passband ($K$ and its narrow-band substitute). Moreover, even for systems observed in $H$ and $K$, the constraint is weak, since the $(H - K)$ color index is insensitive to the spectral type (Cox 2000): For most MS stars, it is in the range $-0.04 < H - K < 0.11$ and starts increasing to $\approx 0.33$ only at spectral types of about M5V. We find that in our current sample, the available color indices usually agree moderately well with the absolute $K$-band magnitudes of the companions (see Section 7). For future confirmations, a more suitable index would be the $(J - K)$ color index, which increases monotonously from $-0.22$ at O5 to 0.86 at M2, then becomes nearly constant in M dwarfs, again to increase strongly for L dwarfs. A disadvantage of $(J - K)$, though, is that the performance of AO systems is substantially worse in the $J$ passband.

For some binaries, we can compare the infrared magnitude differences with the visual flux ratio $L_3/(L_1 + L_2)$ obtained from the averaged spectra. This gives a much larger wavelength base, but works only in cases when the third component was located well within the spectrograph slit. For consistency, the visual flux ratio should be measured relative to maximum light of the contact binary.
Similarity of the proper motion. For systems where the contact binary has a relatively high proper motion, say $\mu = \sqrt{\mu_\alpha^2 \cos^2 \delta + \mu_\delta^2} > 50$ mas yr$^{-1}$, an optical companion would show an optical projection motion between our 1998 and 2005 observing runs, while a physically bound one would not (provided the orbital period is sufficiently long that no orbital motion is expected). To test this, we collected proper motions (Table 6) from the TICHO 2 Catalogue (Høg et al. 2000) for all systems except GZ And (which was not observed, and for which we adapted the proper motion from the UCAC2 Catalog; Zacharias et al. 2004). We found that the companions to the large proper motion contact binaries AH Aur, SW Lac, U Peg, and RZ Tau had the same relative position in both the 1998 and the 2005 runs, and therefore for all four cases we thus are virtually certain that the companions are physical ones.

Among the systems observed only on one occasion, there are a few further ones with large proper motion, for which the test should be feasible in a few years. These are HV Aqr, V508 Oph, CK Boo, and V2082 Cyg (see Table 6).

Similarity in radial velocities. Another kinematical indicator of physical association is a similarity of the center-of-mass radial velocity of the contact binary and of the radial velocity of the companion, a condition which should be valid for companions on long-period orbits. Indeed, several companions detected within the current program (GZ And, HV Aqr, CK Boo, AO Cam, and V2082 Cyg), independently found from the analysis of the averaged spectra from DDO in Paper II, show radial velocity consistent with the systemic velocity of the contact binary.

7. RESULTS FOR INDIVIDUAL SYSTEMS

We give summaries of the properties of the contact binaries with newly detected companions in Table 6. Here, we discuss some of the new detections, as well as systems with interesting non-detections. The WDS numbers below refer to entries in the Washington Double Star Catalog (Mason et al. 2001).

GZ And. A new component found in the trapezoidal multiple system GZ And (WDS J02122+4440) is very probably a physical member: the estimated $M_K$ indicates the spectral type M5V or later, and this is supported by its color $(H - K) = 0.25$, which is appropriate for a M3-4 dwarf.

HV Aqr. Indications of a faint tertiary to HV Aqr were first found in Paper II, with an estimated light contribution at 5184 Å of $L_3/(L_1 + L_2) \approx 0.022$ ($\Delta V = 4.14$ mag) and a companion temperature of $T_3 \approx 4000$ K. This is consistent with the infrared AO observations, which give $\Delta K = 2.00$ mag and from which we inferred F0 and K5 spectral types.

AH Aur. Although the visual companion to AH Aur is relatively distant, at 3.16 arcsec, the proper motion indicates a physical association: if the visual companion was a distant background
star, the relative position of components should change by $\sim 0.15$ arcsec between the two epochs of our observations, but it has been found to be stable within 0.02 arcsec.

**CK Boo.** A late-type companion to CK Boo was first found in Paper II, with $L_3/(L_1+L_2) = 0.009$ ($\Delta V = 5.11$) and $T_3 \simeq 3900$ K. This is consistent with what is expected for the M0V dwarf inferred from our AO observations. The detection in our automated search seems to be particularly reliable because the component appears in a practically empty part of the background count map.

**VW Cep.** The companion to VW Cep (WDS J20374+7536) was discovered by Heintz (1974). The last published astrometric observation in the WDS is from 1999 with $\rho = 0.4$ arcsec and $\theta = 187^\circ$. Our position, $\rho = 0.254$ arcsec and $\theta = 167^\circ$, is closer to the periastron passage which occurred in January 1997 and is consistent with the position at $\rho = 0.249$ arcsec and $\theta = 165.2^\circ$ expected from the elements in Sixth Catalog of Orbits of Visual Binary Stars (see Hartkopf et al. (2001)). Since there appear to be no other observations close to periastron, our new position has a potential to markedly improve the companion orbit.

**CV Cyg.** From Hipparcos measurements, it was found that CV Cyg (WDS J19543+3803) consisted of two almost identical stars separated by $\rho = 0.7$ arcsec at $\theta = 140^\circ$ and $\Delta V = 0.02$. Surprisingly, though, our observations do not show any indications of a companion. Furthermore, the photometric study of Vinkó et al. (1996) found no evidence for any third light in the system, and a single spectrum of $H_\alpha$ taken by Vinkó et al. does not show any indication of triplicity. We thus suspect the Hipparcos discovery is spurious.

**V2082 Cyg.** A late-type companion to V2082 Cyg, with a light contribution of $L_3/(L_1+L_2) \approx 0.02$ and a temperature $T_3 \simeq 5100$ K, was found in Paper II. Independently, in Paper I we found an indication for a late-type tertiary from the relatively high X-ray to bolometric flux ratio, which was unexpected for the binary itself, since it has a moderately long orbital period, $P = 0.714$ days, and an early spectral type, F0 (Pych et al. 2004). At $\rho = 1.05$ arcsec, the system is very probably physically bound. The visual and infrared magnitudes are consistent with a companion of the K2/3V spectral type.

**V829 Her.** The possible multiplicity of V829 Her was indicated by a large proper-motion error and an acceptable light-time effect (LITE) solution for the contact binary (Paper I). If one uses the photometrically estimated parallax of Bilir et al. (2003), $13.53 \pm 0.54$ mas with the LITE-derived $a_{12} \sin i = 0.9 \pm 0.2$ AU, and assumes masses of components from Pribulla & Rucinski (2006), the angular separation should be about 0.08 arcsec. Thus, it is clear that the observed LITE cannot be caused the object we detected at $\rho = 1.46$ arcsec. If both the LITE and AO companions are confirmed, the system would be part of a quadruple system.

**SW Lac.** Indications for multiplicity of SW Lac were found both from spectra, which showed a late-type contribution (Hendry & Mochnacki 1998), and from complicated changes of its orbital period (Pribulla et al. 1999). Our AO observations show a relatively distant companion,
at a separation of 1.68 arcsec. Its physical bond to the contact binary is practically certain as SW Lac moved by 0.64 arcsec on the sky between 1998 and 2005 due to the fast proper motion, while the relative position of the visual components has remained stable to within 0.01 arcsec. The colors of the companion, \((H - K) = 0.11 - 0.16\), correspond to a K5 – M1V dwarf, which is consistent with the late K dwarf inferred from the K-band magnitudes. This visual companion might, despite the large separation, be responsible for the spectral signature, but cannot be responsible for the observed LITE. Thus, another companion could be hiding at still smaller separations.

**XY Leo.** The multiple nature of XY Leo was first indicated by the light-time effect, and the interpretation and expected nature of the third body was extensively discussed by Gehlich et al. (1972). Barden (1987) found spectroscopically that the companion was a BY Dra binary of a mid-M spectral type with a short orbital period of 0.805 days. Thus, the system is a quadruple consisting of two close binaries. From the mass function of the third component determined from the LITE orbit, Barden (1987) estimated that the orbital inclination of the outer orbit must be close to \(90°\). The visual pair has not yet been resolved directly. If our marginal detection (Section 3) is confirmed, then – when combined with the LITE parameters of Pribulla & Rucinski (2006) – the inclination of the outer orbit should be about 67° with the longitude of the ascending node of about 22° (or 202°). The largest separation of \(\approx 0.17\) arcsec appears to have occurred in the summer of 2003. In 2013 occurs the second maximum at a separation of 0.13 arcsec. Two or three spectroscopic runs within the orbital period of the outer binary of 20 years would be needed to lift the \(\pm 180°\) ambiguity in the orientation of the orbit (\(Ω\)) and to estimate the total mass of the whole quadruple system.

**V508 Oph.** Multiplicity of V508 Oph was first indicated by the Hipparcos astrometry, the system having an “S” flag in H61 field. The estimated color of the visual companion to V508 Oph, \((H - K) = 0.34\), indicates a M5V dwarf, consistent with the inferred absolute magnitude.

**V2388 Oph.** V2388 Oph (WDS J17543+1108) is a known close visual pair on a 8.92-year orbit with one component being the eclipsing binary. The separation of the components is only about 0.09 arcsec and the system has been a subject of many speckle interferometry observations. The visual magnitude difference of components was determined spectroscopically to be \(L_3/(L_1 + L_2) = 0.20 \pm 0.02\), corresponding to \(ΔV = 1.75 \pm 0.02\) mag (Rucinski et al. 2002). Given the F2V classification of V2388 Oph, the observed \(ΔV\) implies a G5 spectral type for the companion. Thus, one expects \(ΔK \approx 0.8\), which is consistent with what we find. Oddly, however, the position predicted by elements in Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf et al. 2001), \(ρ = 0.075\) arcsec and \(θ = 203°\), is inconsistent with our observation. Our measured \(θ = 31 \pm 13°\) suggests the components were swapped in the Sixth Catalog.

**ER Ori.** The visual companion to ER Ori (WDS J05112-0833), at \(ρ = 0.187\) arcsec, \(θ = 354.4°\) and \(ΔV = 2.0\) mag was first noticed in observations in March 1993 by Goecking et al. (1994).
In our January 1998 observations, we find the companion at practically the same position \( \rho = 0.183 \) arcsec, \( \theta = 354.4^\circ, \Delta K = 2.14 \) mag), but, curiously, in our October 2005 observations there is no trace of it. Given the excellent detection quality, the companion is almost certainly real, and almost certainly physically associated with the contact binary. We note that the proper motion of the contact binary is directed to the South, while the companion was observed to the North of the contact binary in 1993 and 1998; thus, if the stars are unrelated, the separation should have increased.

The presence of a companion to the binary is also indicated by two other effects. First, there are large acceleration terms in the Hipparcos astrometric solution, \( g_\alpha = -19.26 \pm 6.57 \) mas yr\(^{-2} \) and \( g_\delta = -17.34 \pm 4.71 \) mas yr\(^{-2} \), which suggest an orbital period of only a few years. Second, arrival times of the ER Ori eclipsing system clearly show the LITE, with an implied outer orbit with a period of about 50 years [Kim et al. 2003], a semi-major axis for the eclipsing pair of 6.7 AU, and substantial eccentricity, \( e = 0.89 \). From this orbit, periastron passage was predicted around July/August 2004, and this might explain the absence of the visual companion during CFHT 2005 observing run.

**U Peg.** Although the visual companion to U Peg is rather faint and distant, the fast proper motion of the contact binary, amounting to 0.515 arcsec between the 1998 and 2005 runs, has helped confirm the physical association: the relative position of the components remained stable within 0.03 arcsec.

**V592 Per.** This binary (WDS J04445+3953) has a known close visual companion that shows a slow orbital motion. According to the WDS, between 1977 and 2003, the PA changed from \( \theta = 190 \) to \( 209^\circ \). Our PA, \( 207 \pm 2^\circ \) is consistent with the most recent published observation in the WDS. The magnitude difference of the components as given in Mason et al. (2001) is \( \Delta V = 0.85 \). From our AO observations, we derive \( \Delta K = 0.39 \pm 0.06 \), which is fairly consistent with the estimated spectral type of the contact binary (F5-6, see Rucinski et al. (2005)) and a G0V spectral type for the visual companion. The components have very similar radial velocity (Rucinski et al. 2005).

**CW Sge.** The binary was suspected to be a member of a short-period visual pair because it is flagged by “X” (stochastic astrometric solution) in the H59 Hipparcos catalog field (Paper I). This resulted in a Hipparcos parallax with a large error, \( \pi = 2.57 \pm 4.14 \) mas. The Hipparcos so-called “cosmic error”, \( \epsilon = 7.64 \pm 1.32 \) mas, suggests a rather small size of the astrometric orbit. The companion detected by our AO observations at a separation of 1.84 arcsec cannot be identified with the one causing the rapid astrometric motion. Therefore CW Sge may be a member of a system with higher multiplicity.

**BE Scl.** Multiplicity of BE Scl was indicated by the large “cosmic error”, \( \epsilon = 13.36 \pm 1.35 \) mas, in its Hipparcos astrometric solution. Our analysis shows a close companion at \( \rho = 0.1 \) arcsec with \( \Delta K = 1.1 \ldots 1.4 \). This companion is likely responsible for the observed astrometric motion. With the large photometric amplitude of about 0.45 mag, the eclipsing pair is an
easy object for timing of the eclipses and is expected to show variations on time scales shorter than 1 year.

**RZ Tau** The possible multiplicity of RZ Tau was first indicated by the Hipparcos astrometry, RZ Tau having an “S” flag in the H61 field. The physical association of the visual pair is supported by a stable relative position of its component between the 1998 and 2005 observations, despite the fact that proper motion of the contact binary caused it to move 0.21 arcsec on the sky.

8. SUMMARY

We present the results of an AO search for companions of contact binary stars conducted on four nights in 1998 and 2005, in an attempt to confirm their high apparent incidence indicated by various approaches in Paper I. The preliminary results of the 1998 observations were included in Papers I and II; the new observations, taken in 2005, have contributed additional six companions to the magnitude-limited sample ($V_{\text{max}} = 10$). The 2005 observations covered the Fall part of the CFHT sky and were much more consistent in terms of the object selection than the 1998 observations. Fig. 8 gives the updated distribution of projected separations for all objects of our program. Our new discoveries fall into the range of relatively small separations within $0.5 < \log a (\text{AU}) < 2.0$.

For separations larger than one arcsec, the companions were easily visible in the images, but for sub-arcsec detections we relied on an automated search technique which was able to find companions hiding within the AO diffraction rings. This new technique permitted us to approach the effective resolution limit of the CFHT AO system of about 0.07 – 0.08 arcsec in the $K$-band. The main results are shown in Fig. 7 and are listed in Table 5. Thanks to this new technique we were able to detect very close companions to XY Leo, V2388 Oph and BE Scl, while for additional nine systems very close companions are suspected and these systems require further observations. Especially encouraging are the AO detections of companions previously indicated by other techniques in Papers I and II (e.g., OO Aql, V2082 Cyg, V829 Her, CW Sge, BE Scl). We note that contact binaries with third components with $\rho < 1''$ are perfect objects for tests of ground-based interferometric system imaging because a companion can provide an ideal phase reference source.

From our detection limits shown in Fig. 7 we can evaluate our selection biases, and estimate how many systems might have been missed by our AO observations at large magnitude differences $\Delta K$ and small separations $\rho$. From this figure, one sees that the distribution of companions as a function of magnitude difference is rather flat at large separations, $\rho > 1$ arcsec. Similarly, for relatively bright companions, one sees that the distribution in $\log \rho$ is relatively flat. If the two distributions are independent, then this suggests that in addition to the eleven systems at sub-arcsecond separations that we detected, another eleven or so may have fallen below our separation detection limit (to $\Delta K \simeq 6$). If we corrected our results for those presumably missed companions,
the implied incidence would increase from \((31 \pm 6)\%\) (25 detections in a sample of 80 contact binaries) to \((45 \pm 8)\%\).

By combining the current results for the actual detections for binaries with \(V_{\text{max}} < 10\) with our earlier AO detections reported in Paper I, we obtain the total fractional incidence of triple systems of \((61 \pm 8)\%\) for Northern objects and \((19 \pm 5)\%\) for Southern objects, strengthening the hypothesis that all close binaries are members of multiple systems. Finally, we note that from the 151 known contact binaries brighter than \(V_{\text{max}} = 10\) mag, so far only 51 have been observed with an AO system. Extrapolating the detection rate from the present sample, one would expect some 30 new AO detections or confirmations (of the cases listed in Paper I) for the one hundred binaries which remain to be observed with the AO technique. For the reason that still about 2/3 of all systems remain to be observed, we defer a detailed comparison of the current results with the statistics of the solar-type field stars of Duquennoy & Mayor (1991) until such a full sample becomes available.

The research made use of the SIMBAD database, operated at the CDS, Strasbourg, France and accessible through the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada. This research made also use of the Washington Double Star (WDS) Catalog maintained at the U.S. Naval Observatory. Support from the Natural Sciences and Engineering Council of Canada (NSERC) to SMR and MHvK is acknowledged with gratitude; visits of TP to the University of Toronto were supported by the NSERC grant of SMR.

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Fig. 1.— Similarity of the point-spread functions as a function of the angular distance on the sky. The relative standard deviation of mutual fits for all possible pairs of stellar images. The images were matched within each night separately, as marked by different symbols. The system V592 Per stands out, as expected given that it has a very close, relatively bright companion.
Fig. 2.— Similarity of the point-spread functions as a function of elevation. The relative standard deviation is computed for all templates used to fit PSF of a given object. Objects showing large mismatches are suspected to have companions.
Fig. 3.— A mosaic showing systems for which the presence of a companion was obvious. The width of each panel corresponds to 7 arcsec.
Fig. 4.— The process of fitting a model binary using a template to the very close visual binary BE Scl. The four panels show, from the top left, clockwise: (1) the object image, (2) the template, (3) the secondary component after subtraction of the primary (its location marked by a white cross) and (4) the residuals from the best fit. We used the five individual images (obtained by stacking several exposures at a given quadrant displacement) and fitted them by the best single exposures from 46 templates. Of the resulting 230 fits, 211 succeeded, while 19 did not; the figure shows one of the successful ones. Similar figures for the eight remaining very close systems are available in the electronic version of the paper only. In this and the following figures, the images are oriented with North up and East left.
Fig. 5.— Convergence count maps from the automatic search routine (as described in the text) for BE Scl and EQ Tau, the cases where images did not show any obvious evidence of a companion, but the automatic search showed a clear detection for BE Scl, and no companion for EQ Tau. The total number per pixel is indicated by color. The circle for BE Scl encompasses a tight cluster of counts, in which 179 out of 211 of the fits indicated a companion could be present, indicating a real detection. No similar clustering is seen for EQ Tau. The maximum number of counts per pixel anywhere in the image is 4 for EQ Tau, but 52 for BE Scl. Similar figures for all systems analyzed with the automatic search routines are available in the electronic version of the paper.
Fig. 6.— The background of false detections for all stars which do not show any visual companions (as observed in 2005; the 1998 images are very similar). The first diffraction ring and traces of the second ring are clearly visible.
Fig. 7.— Detections of companions in our program as a function of the angular separation from the central star and the $K$ magnitude difference. The detection limit evaluated by Monte Carlo experiments is shown by the continuous curve. Detections resulting from our automated search and modeling are shown by full circles while wider pairs for which the measurement of the components was done separately are shown by open circles. Of the three sources near the detection limit, the detection of the faint companion to OO Aql is unambiguous, but the cases of CK Boo and XY Leo require confirmation (see Section 7 for details).
Fig. 8.— Distributions of projected separations (in AU) for resolved systems brighter than $V_{\text{max}} = 10$. This figure is an update to Fig. 9 in Paper I (Pribulla & Rucinski 2006). The distributions are shown separately for both hemispheres (relative to the equator), since the Northern hemisphere has been better studied. The six new systems – OO Aql, HV Aqr, V402 Aur, AO Cam, V2082 Cyg, and XY Leo – are all located in bins between $0.5 < \log a(\text{AU}) < 2.0$. 
Table 1. Journal of the AO observations during the three observing runs of January 10, 1998, July 23, 1998 and October 17–18, 2005. The full table is available only in electronic form.

| Frame No. | Object   | HJD−2,400,000 | Filter |
|-----------|----------|---------------|--------|
| 419979    | AQ Psc   | 50824.7062    | K_{CO} |
| 419980    | AQ Psc   | 50824.7081    | K_{CO} |
| 419981    | AQ Psc   | 50824.7100    | K_{CO} |
| 419982    | AQ Psc   | 50824.7122    | K_{CO} |
| 419983    | AQ Psc   | 50824.7144    | K_{CO} |
| 419984    | AQ Psc   | 50824.7165    | K_{CO} |
| 419985    | AQ Psc   | 50824.7184    | K_{CO} |
| 419986    | AQ Psc   | 50824.7203    | K_{CO} |
| 419987    | TT Cet   | 50824.7291    | K      |
| 419988    | TT Cet   | 50824.7316    | K      |

Note. — The first 10 rows of the table are shown. The central wavelength and bandwidth of filters used are as follows:

- $K_{CO}: \lambda_{cen} = 2.298 \mu m, \text{FWHM} = 0.027 \mu m$;
- $K: \lambda_{cen} = 2.22 \mu m, \text{FWHM} = 0.4 \mu m$;
- $H: \lambda_{cen} = 1.65 \mu m, \text{FWHM} = 0.29 \mu m$;
- $H2: \lambda_{cen} = 2.122 \mu m, \text{FWHM} = 0.02 \mu m$.

The $K_{CO}$ filter is entered as “CO” in the ASCII online version of the table.
Table 2. Overview of observed systems and detections of visual companions

| Object     | Detection | Object    | Detection | Object    | Detection |
|------------|-----------|-----------|-----------|-----------|-----------|
| AB And     | NN        | RW Com    | N--       | V753 Mon  | N--       |
| GZ And     | DD        | RZ Com    | N--       | V502 Oph  | N--       |
| V376 And   | N--       | SX Crv    | N--       | V508 Oph  | N--       |
| EL Aqr     | N--       | CV Cyg    | N--       | V566 Oph  | NN        |
| HV Aqr     | D         | DK Cyg    | NN        | V839 Oph  | N--       |
| OO Aql     | D         | V401 Cyg  | NN        | V2388 Oph | C         |
| V417 Aql   | N--       | V1073 Cyg | NN        | ER Ori    | N--       |
| V1464 Aql  | N         | V2082 Cyg | D         | V1363 Ori | N--       |
| AH Aur     | D-D       | LS Del    | N         | U Peg     | DD        |
| V402 Aur   | D         | SV Equ    | N--       | BB Peg    | NN        |
| V410 Aur   | D         | UX Eri    | N--       | V335 Peg  | N--       |
| V449 Aur   | N--       | YY Eri    | N-N       | V351 Peg  | N--       |
| TZ Boo     | N--       | BV Eri    | NN        | V357 Peg  | N--       |
| VW Boo     | N--       | FP Eri    | N         | KN Per    | N--       |
| XY Boo     | N--       | AK Her    | N-D       | V592 Per  | N-D       |
| AC Boo     | N--       | V829 Her  | D         | VZ Psc    | N--       |
| CK Boo     | C         | V972 Her  | N         | AQ Psc    | NN        |
| AO Cam     | D         | FG Hya    | N--       | TY Pup    | N--       |
| DN Cam     | N         | SW Lac    | D-D       | CW Sge    | D         |
| BH CMi     | N         | V407 Lac  | N--       | BE Scl    | C         |
| V523 Cas   | N         | UZ Leo    | N         | RZ Tau    | D-D       |
| VW Cep     | D         | XY Leo    | C         | EQ Tau    | N--       |
| TT Cet     | NN        | XZ Leo    | N         | V781 Tau  | N-N       |
| CL Cet     | N         | AP Leo    | N         | AG Vir    | N--       |
| CT Cet     | D         | VZ Lib    | N--       | AH Vir    | D--       |
| DY Cet     | N         | UV Lyn    | N         | GR Vir    | N--       |
| RS Col     | N         | V752 Mon  | D         |           |           |

Note. — Results of the three observing runs of January 10, 1998, July 23, 1998 and October 17–18, 2005 are in coded in three columns as follows: ◦ = not observed in a given run, N = no detection, D = detection at a separation of < 5 arcsec, C = a very close pair; possible detection through a deformation of the diffraction pattern.
Table 3. Results of an automated search for close companions to observed contact binaries: New detections and suspect cases.

| Name       | Year | $N_f$ | $N_t$ | $N_b$ | $C$   | $C_n$ | $r$ | $S$   | $B$   | $R_n$ | Flag |
|------------|------|-------|-------|-------|-------|-------|-----|-------|-------|-------|------|
| V376 And   | 2005 | 10    | 46    | 268   | 11    | 5.5   | 4   | 46    | 84    | 14.7  | S    |
| HV Aqr     | 2005 | 5     | 46    | 268   | 51    | 51.0  | 4   | 141   | 4     | 1839.4| D    |
| TZ Boo     | 1998 | 4     | 28    | 176   | 8     | 16.4  | 3   | 25    | 54    | 20.8  | S    |
| CK Boo     | 1998 | 8     | 28    | 176   | 13    | 13.3  | 5   | 103   | 15    | 155.7 | D    |
| DN Cam     | 2005 | 5     | 46    | 268   | 20    | 20.0  | 4   | 154   | 350   | 23.6  | S    |
| VW Cep     | 1998 | 4     | 28    | 176   | 63    | 129.4 | 3   | 107   | 4     | 1209.4| D    |
| YY Eri     | 2005 | 5     | 46    | 268   | 9     | 9.0   | 4   | 80    | 830   | 5.2   | S    |
| BV Eri     | 2005 | 5     | 46    | 268   | 12    | 12.0  | 5   | 89    | 820   | 5.8   | S    |
| V829 Her   | 2005 | 5     | 46    | 268   | 11    | 11.0  | 6   | 144   | 597   | 12.9  | S    |
| XY Leo     | 1998 | 8     | 28    | 176   | 23    | 23.6  | 4   | 98    | 104   | 20.9  | D    |
| V508 Oph   | 1998 | 4     | 28    | 176   | 7     | 14.4  | 5   | 58    | 336   | 7.6   | S    |
| V2388 Oph  | 2005 | 5     | 46    | 268   | 21    | 21.0  | 4   | 144   | 109   | 70.8  | D    |
| ER Ori     | 1998 | 8     | 28    | 176   | 41    | 42.1  | 4   | 188   | 44    | 93.6  | D    |
| V351 Peg   | 2005 | 10    | 46    | 268   | 13    | 6.5   | 4   | 38    | 54    | 18.8  | S    |
| V592 Per   | 2005 | 5     | 46    | 268   | 134   | 134.0 | 4   | 221   | 62    | 192.2 | D    |
| TY Pup     | 1998 | 8     | 28    | 176   | 8     | 8.2   | 6   | 121   | 358   | 7.4   | S    |
| BE Scl     | 2005 | 10    | 46    | 268   | 93    | 46.5  | 4   | 372   | 127   | 78.4  | D    |

Note. — Explanation of columns: Name – Variable star name in the General Catalog of Variable Stars; Year – year of the observing run; $N_f$ – number of object frames used for the count map; $N_t$ – number of templates used; $N_b$ – number of frames coming into the background map; $C$ – maximum count for the object; $C_n$ – normalized maximum count (see text for the definition); $r$ – radius of the aperture for the determination of the integrated counts in the object count map; $S$ – sum of counts within the selected aperture in the object map; $B$ – corresponding sum of counts in the background map; $R_n$ – normalized ratio of the summed counts in the object and the background map (see the text for the definition); Flag – flag indicating status of the detection: “D” – detection, “S” – suspected case. The detection level is set at $C_n > 20$ or $R_n > 50$. Only detections with automated search are taken into account; binaries with directly visible components are listed in Table 2 (see also Fig. 3).
Table 4. Results of an automatic search for close companions: Contact binary systems not detected to have visual companions

| Name       | Year | $C_n$ | Name       | Year | $C_n$ | Name       | Year | $C_n$ |
|------------|------|-------|------------|------|-------|------------|------|-------|
| AB And     | 1998 | 6.2   | DK Cyg     | 2005 | 2.0   | V566 Oph   | 2005 | 7.0   |
| AB And     | 2005 | 2.5   | V401 Cyg   | 1998 | 8.2   | V839 Oph   | 1998 | 14.4  |
| GZ And     | 1998 | 2.1   | V401 Cyg   | 2005 | 7.0   | ER Ori     | 2005 | 4.5   |
| GZ And     | 2005 | 9.0   | V1073 Cyg  | 1998 | 12.3  | V1363 Ori  | 2005 | 3.0   |
| EL Aqr     | 1998 | 8.2   | V1073 Cyg  | 2005 | 7.0   | U Peg      | 1998 | 4.1   |
| AH Aur     | 2005 | 4.0   | V2082 Cyg  | 2005 | 3.0   | U Peg      | 2005 | 2.0   |
| V449 Aur   | 2005 | 10.0  | LS Del     | 2005 | 4.0   | BB Peg     | 2005 | 6.0   |
| OO Aql     | 2005 | 4.0   | SV Equ     | 1998 | 16.4  | V335 Peg   | 2005 | 4.5   |
| V417 Aql   | 1998 | 8.2   | YY Eri     | 1998 | 6.2   | V357 Peg   | 2005 | 4.0   |
| V1464 Aql  | 2005 | 6.0   | BV Eri     | 1998 | 2.1   | KN Per     | 2005 | 6.0   |
| V402 Aur   | 2005 | 1.5   | FP Eri     | 2005 | 2.5   | VZ Psc     | 1998 | 10.3  |
| V410 Aur   | 2005 | 3.0   | AK Her     | 1998 | 4.1   | AQ Psc     | 1998 | 3.1   |
| VW Boo     | 1998 | 2.1   | V972 Her   | 2005 | 10.0  | AQ Psc     | 1998 | 2.1   |
| AC Boo     | 1998 | 4.1   | SW Lac     | 1998 | 10.3  | AQ Psc     | 2005 | 5.0   |
| AO Cam     | 2005 | 7.0   | SW Lac     | 2005 | 7.0   | CW Sge     | 2005 | 4.0   |
| BH CMi     | 2005 | 6.0   | V407 Lac   | 2005 | 9.0   | EQ Tau     | 2005 | 2.0   |
| V523 Cas   | 2005 | 2.0   | XZ Leo     | 1998 | 4.1   | RZ Tau     | 1998 | 2.1   |
| CL Cet     | 2005 | 4.5   | AP Leo     | 1998 | 2.1   | RZ Tau     | 2005 | 3.0   |
| CT Cet     | 2005 | 9.0   | VZ Lib     | 1998 | 4.1   | V781 Tau   | 1998 | 3.1   |
| DY Cet     | 2005 | 4.5   | UV Lyn     | 1998 | 6.2   | V781 Tau   | 2005 | 3.0   |
| RS Col     | 2005 | 11.0  | V752 Mon   | 2005 | 5.0   | AG Vir     | 1998 | 2.1   |
| RZ Com     | 1998 | 3.1   | V753 Mon   | 2005 | 5.0   | AH Vir     | 1998 | 6.2   |
| SX Crv     | 1998 | 4.1   | V502 Oph   | 1998 | 6.2   | GR Vir     | 1998 | 3.1   |
| CV Cyg     | 2005 | 2.0   | V566 Oph   | 1998 | 10.3  |           |      |       |

Note. — Explanation of columns: Name – Variable star name in the General Catalog of Variable Stars; Year – year of the observing run; $C_n$ – normalized maximum count (see text for the definition).

Note: AQ Psc was observed both in January and July 1998.
Table 5. Companions of contact binaries detected or confirmed during this program

| Name   | HJD       | Phase | ∆$V_0$ | $\mu \Delta t$ | $\rho$ | $\theta$ | $\Delta K$ | $\Delta H$ | $K$ | $M$ | Sp. |
|--------|-----------|-------|--------|-----------------|-------|---------|-------------|------------|-----|-----|-----|
|        | 2 400 000+|       |        |                 |       |         |             |            |     |     |     |

**New detections**

GZ And 51019.1015 0.484 0.66 0.0 2.130(6) 33.55(7) 2.45(5) 5.99 M3V
GZ And 51019.1102 0.513 0.67 0.0 2.131(11) 33.51(10) 2.625(9) 6.24 M3-4
GZ And 53660.9608 0.815 0.16 0.0 0.510(16) 290(2) 5.1(3) 7.2 >M5V
HV Aqr 53660.7804 0.315 0.04 0.0 116.5 2.163(7) 29.25(13) 3.069(11) 5.99 M3V
OO Aql 53660.7339 0.835 0.16 0.0 3.189(4) 62.91(13) 4.31(4) 6.30 M5V
AH Aur 50824.9048 0.072 0.29 0.0 3.188(6) 62.98(18) 4.31(4) 6.26 M3-4V
AH Aur 50824.9169 0.097 0.21 0.0 3.188(6) 62.98(18) 4.31(4) 6.26 M3-4V
AH Aur 53662.1136 0.170 0.06 154.0 3.159(4) 57.3(6) 4.74(5) 6.49 M5V
V402 Aur 53661.0890 0.990 0.13 0.0 0.12(4) 198(5) 2.554(9) 5.03 M1 V
AO Cam 53662.0455 0.057 0.43 0.0 1.309(5) 87.87(15) 4.65(7) 7.68 >M5V
V2082 Cyg 53660.7223 0.927 0.06 154.0 3.159(4) 57.3(6) 4.74(5) 6.49 M5V
V829 Her 53661.7171 0.190 0.03 0.0 1.463(9) 344.69(22) 1.72(6) 4.07 K1V
SW Lac 51019.0182 0.825 0.10 0.0 1.680(1) 85.33(9) 2.554(9) 5.03 K9V
SW Lac 51019.0251 0.847 0.12 0.0 1.680(1) 85.33(9) 2.554(9) 5.03 K9V
XY Leo 50825.0225 0.915 0.20 0.0 0.12(4) 198(5) 2.554(9) 5.03 K9V
V508 Oph 51018.9071 0.229 0.00 0.0 2.395(3) 18.89(9) 4.275(11) 6.84 >M5V
U Peg 51019.0677 0.149 0.10 0.0 4.052(5) 275.38(9) 5.232(21) 7.78 >M5V
U Peg 53660.8900 0.206 0.02 515.0 4.076(5) 271.21(11) 5.60(5) 8.07 >M5V
U Peg 53661.8843 0.861 0.12 0.0 0.102(19) 72(4) 1.4(7) 3.8 G5V
CW Sge 53660.7637 0.097 0.19 0.0 0.163(3) 60.68(17) 2.17(3) 3.51 G5V
BE Scl 53660.9444 0.059 0.33 0.0 1.686(11) 74(4) 1.1(7) 3.4 G5V
RE Scl 53661.9577 0.55 0.35 0.0 0.794(6) 43.7(4) 3.61(4) 6.23 M5V
RZ Tau 50824.8140 0.206 0.00 0.0 0.12(4) 198(5) 2.554(9) 5.03 K9V
RZ Tau 50824.8249 0.059 0.45 0.0 0.106(23) 74(4) 1.1(7) 3.4 G5V
RZ Tau 53661.8890 0.206 0.02 515.0 4.076(5) 271.21(11) 5.60(5) 8.07 >M5V
RZ Tau 53661.9577 0.55 0.35 0.0 0.794(6) 43.7(4) 3.61(4) 6.23 M5V
RZ Tau 53662.0090 0.503 0.58 210.5 0.801(4) 38.93(11) 4.29(5) 6.89 >M5V

**Confirmed detections**

V410 Aur 53661.0756 0.244 0.03 0.0 1.716(6) 224.59(10) 1.091(15) 3.52 K2V
VW Cep 51019.9257 0.326 0.06 0.0 0.254(8) 166.8(20) 1.42(2) 4.13 K2V
CT Cet 53661.9190 0.795 0.05 0.0 3.492(8) 206.73(8) 0.09(4) G3V
AK Her 51018.8769 0.615 0.14 0.0 4.495(9) 324.37(9) 2.019(9) 4.13 K2V
V752 Mon 53661.1142 0.862 0.01 0.0 1.686(4) 23.89(15) -0.50(2) F0V
V2388 Oph 53661.7303 0.531 0.22 0.0 0.099(18) 31(13) 1.0(5) 3.52 K2V
Table 5—Continued

| Name     | HJD 2400000+ | Phase | $\Delta V_\phi$ | $\mu \Delta t$ | $\rho$ | $\theta$ | $\Delta K$ | $\Delta H$ | $M_K$ | $M_H$ | Sp. |
|----------|--------------|-------|----------------|----------------|-------|---------|-----------|-----------|-------|-------|-----|
| ER Ori 4 | 50824.8540   | 0.197 | 0.03           | 0.0            | 0.178(14) | 356(5)  | 2.0(4)    | K2V       |
| ER Ori 2 | 53661.1312   | 0.981 | 0.63           | 207.3          | K2V     |
| V592 Per | 53661.0618   | 0.675 | 0.0            | 0.183(3)       | 207.9(14) | 0.39(12) | G0:       |
| AH Vir 1 | 50825.1084   | 0.380 | 0.15           | 0.0            | 1.707(2)  | 16.50(7) | 1.551(21) | 3.98      | K1V   |

Note. — Explanation of columns: Name = Variable star name in the General Catalog of Variable Stars; HJD = Heliocentric Julian date of the particular AO observation; Phase = Orbital phase of the binary calculated from the ephemeris given below; $\Delta V_\phi = V_{\text{obs}} - V_{\text{max}}$: Correction required to bring the magnitude to the maximum visual brightness of the eclipsing pair for the instant of observation (see text); $\mu \Delta t$: Cumulative proper motion of the binary counted from the first observation (always zero for stars observed during a single night); $\rho$: Angular separation of the components; $\theta$: Position angle of the secondary (fainter) component; $\Delta K$ and $\Delta H$: Measured magnitude differences between the visual companion and the binary (without correction for the phase of the eclipsing pair); $M_K$ and $M_H$: Absolute magnitude of the companion determined from the estimated absolute $K$ and $H$ magnitude of the contact binary (Table 4), $\Delta K$ and $\Delta H$ and $\Delta V_\phi$ (see text); Sp.: estimated spectral type of the visual companion.

Ephemerides ($HJD_{\text{min}} - 2,400,000 + \text{period in days}$) used for the computation of phases:
- GZ And: 52500.1198 + 0.3050177; HV Aqr: 52500.2163 + 0.3744582;
- OO Aql: 52500.261 + 0.5067932; AH Aur: 52500.3848 + 0.4941067;
- V402 Aqr: 52500.567 + 0.60349867; V410 Aur: 52500.0033 + 0.3663562;
- CK Boo: 52500.026 + 0.3551538; AO Cam: 52500.1061 + 0.3299036;
- VW Cep: 52500.0321 + 0.2783108; CT Cet: 48500.1847 + 0.2564863;
- V2082 Cyg: 52466.1122 + 0.714084; AK Her: 52500.2709 + 0.421523;
- V829 Her: 52500.159 + 0.358153; SW Lac: 52500.1431 + 0.3207165;
- XY Leo: 52500.0872 + 0.2840978; V752 Mon: 48500.2837 + 0.462902;
- V508 Oph: 52500.0545 + 0.3447901; V2388 Oph: 52500.379 + 0.8022979;
- ER Ori: 52500.1715 + 0.4234018; U Peg: 52500.1288 + 0.3747766;
- V592 Per: 53399.3400 + 0.715722; CW Sge: 52500.567 + 0.6603631;
- BE Scl: 52500.0549 + 0.42290144; RZ Tau: 52500.3968 + 0.4156776;
- AH Vir: 52500.3174 + 0.407532;
Table 6. Properties of contact binaries with newly detected companions

| Name       | $V_{\text{max}}$ | $\Delta V$ | $\pi$  | $\sigma_\pi$ | $\mu$  | Sp. type | $(B - V)_0$ | $M_V$ (calc) | $M_V$ (spec) | $M_H$ (spec) | $M_K$ (spec) | $M_K$ (corr) | $M_{12}$ | Sp. type comp. | $M_3$ | $a$  | $P_{\text{vis}}$ |
|------------|------------------|------------|--------|--------------|--------|----------|-------------|--------------|--------------|--------------|--------------|-------------|----------|----------------|------|------|----------------|
| GZ And     | 10.83            | 0.78       | 5.33   |              | 16.1   | G5V      | 0.68        | 4.46         | 5.10         | 3.52         | 3.58         | 2.94        | 2.88     | 1.708          | M3-4V | 0.3  | 400            |
| HV Aqr     | 9.71             | 0.40       | 5.33   |              | 112.0  | F5V      | 0.44        | 3.34         | 3.50         | 2.40         | 2.44         | 2.28        | 2.24     | 1.569          | K2-3V | 0.7  | 74             |
| OO Aql     | 9.20             | 0.80       | 7.19   |              | 66.2   | G5V      | 0.68        | 3.48         | 5.10         | 3.52         | 3.58         | 1.96        | 1.90     | 1.954          | >M5V  | <0.2 | 71             |
| AH Aur     | 10.20            | 0.37       | 6.18   | 2.05         | 19.8   | F7V      | 0.49        | 2.96         | 3.83         | 2.57         | 2.61         | 1.74        | 1.70     | 1.967          | M5V   | 0.2  | 510            |
| V402 Aur   | 8.84             | 0.14       | 7.01   | 1.31         | 11.3   | F2V      | 0.35        | 2.15         | 3.60         | 2.78         | 2.82         | 1.37        | 1.33     | 1.965          | >M5V  | <0.2 | 156            |
| CK Boo     | 8.99             | 0.27       | 6.38   | 1.34         | 111.9  | F7.5V    | 0.51        | 3.66         | 3.92         | 2.61         | 2.64         | 2.37        | 2.35     | 1.569          | M1V   | 0.45 | 19             |
| AO Cam     | 9.50             | 0.50       | 7.98   |              | 0.0    | G0V      | 0.58        | 4.01         | 4.40         | 2.99         | 3.04         | 2.65        | 2.60     | 1.605          | >M5V  | <0.2 | 164            |
| V2082 Cyg  | 6.63             | 0.05       | 11.04  | 0.56         | 97.0   | F0V      | 0.30        | 1.84         | 2.70         | 2.00         | 2.03         | 1.17        | 1.14     | K2V            | 0.75  | 95             |
| V829 Her   | 10.10            | 0.29       | 4.97   |              | 19.6   | F7V      | 0.49        | 3.58         | 3.83         | 2.57         | 2.61         | 2.36        | 2.32     | 1.806          | K1V   | 0.77 | 295            |
| SW Lac     | 8.51             | 0.88       | 12.30  | 1.26         | 88.8   | G5V      | 0.68        | 3.96         | 5.10         | 3.52         | 3.58         | 2.44        | 2.38     | 2.204          | K9V   | 0.54 | 136            |
| XY Leo     | 9.45             | 0.48       | 15.86  | 1.80         | 81.3   | K0V      | 0.81        | 5.45         | 5.90         | 3.94         | 4.02         | 3.57        | 3.49     | 1.188          | K6V   | 0.64 | 3.8            |
| V508 Oph   | 10.06            | 0.63       | 7.68   | 2.14         | 47.4   | G0V      | 0.58        | 3.92         | 4.40         | 2.99         | 3.04         | 2.56        | 2.51     | 1.520          | >M5V  | <0.2 | 310            |
| U Peg      | 9.23             | 0.84       | 7.18   | 1.43         | 71.2   | G2V      | 0.63        | 3.92         | 4.70         | 3.24         | 3.29         | 2.51        | 2.46     | 1.554          | >M5V  | <0.2 | 560            |
| CW Sge     | 11.13            | 0.88       | 2.57   | 4.14         | 2.1    | F5V      | 0.44        | 2.25         | 3.50         | 2.40         | 2.44         | 1.19        | 1.15     | G5V            | 0.92  | 715           |
| BE Scl     | 10.24            | 0.43       | 9.76   | 5.11         | 19.5   | F8V      | 0.52        | 3.35         | 4.00         | 2.65         | 2.70         | 2.05        | 2.00     | G5-8V          | 0.8-0.9| 10            |
| RZ Tau     | 10.08            | 0.63       | 5.74   | 1.85         | 27.1   | F0V      | 0.30        | 2.72         | 2.70         | 2.00         | 2.03         | 2.05        | 2.02     | >M5V           | <0.2  | 139           |

Note. — Explanation of columns: Name = Variable star name General Catalog of Variable Stars; $V_{\text{max}}$: Johnson or transformed Hipparcos $H_p$ maximum light magnitude; $\Delta V$: Amplitude of the light variations; $\pi$ and $\sigma_\pi$: Trigonometric parallax and its error (if given without error, photometrically determined parallax; see text); $\mu$ = $\sqrt{(\mu_\alpha \cos \delta)^2 + (\mu_\delta)^2}$: Proper motion; Sp. type (12): Spectral type of the binary; $(B - V)_0$: the de-reddened color index; $M_V$ (calc): Absolute visual magnitude calculated from $V_{\text{max}}$ and Hipparcos parallax (for V2082 Cyg, SW Lac, and XY Leo) or from the Rucinski & Duerbeck (1997) calibration; $M_{V,H,K}$ (spec): Absolute $V, H, K$ magnitudes corresponding to a main sequence star of the same spectral type as the contact binary; $M_H,K$ (corr): Corrected absolute magnitudes of the contact pair (see text); $M_{12}$: Total (not projected, $\sin i$ accounted for) mass of the contact binary; Sp. type comp.: estimated spectral type of the visual companion; $M_3$: estimated mass of the visual companion (according to tabulation in Cox (2000)); $a$: Projected separation in astronomical units determined from angular separation and distance; $P_{\text{vis}}$: Estimated period of the visual orbit.