

Multiplicity of rapidly oscillating Ap stars^{★,★★}

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ABSTRACT

Context. Rapidly oscillating Ap (roAp) stars have rarely been found in binary or higher order multiple systems. This might have implications for their origin.

Aims. We intend to study the multiplicity of this type of chemically peculiar stars, looking for visual companions in the range of angular separation between 0'.05 and 8".

Methods. We carried out a survey of 28 roAp stars using diffraction-limited near-infrared imaging with NAOS-CONICA at the VLT. Additionally, we observed three non-oscillating magnetic Ap stars.

Results. We detected a total of six companion candidates with low chance projection probabilities. Four of these are new detections, the other two are confirmations. An additional 39 companion candidates are very likely chance projections. We also found one binary system among the non-oscillating magnetic Ap stars. The detected companion candidates have apparent *K* magnitudes between 6^m.8 and 19^m.5 and angular separations ranging from 0'.23 to 8'.9, corresponding to linear projected separations of 30–2400 AU.

Conclusions. While our study confirms that roAp stars are indeed not very often members of binary or multiple systems, we have found four new companion candidates that are likely physical companions. A confirmation of their status will help understanding the origin of the roAp stars.

Key words. binaries: close – stars: chemically peculiar – stars: oscillations – stars: early-type

1. Introduction

Rapidly oscillating Ap (roAp) stars are ideal targets for asteroseismology. By comparing the observed frequency spectrum with the asymptotic pulsation theory, it is possible to specify their rotation period, their temperature, luminosity, radius, mass, their atmospheric structure, their evolutionary status, and the geometry of their magnetic field. More than forty roAp stars are known at present, with effective temperatures between 6400 K and 8400 K. Kurtz et al. (2006) list 35 roAp stars; more can be found in individual papers since then. They pulsate in high-overtone, low-degree, nonradial *p*-modes, with periods in the range from 5.6 to 21 min and typical amplitudes of a few millimagnitudes (e.g. Kurtz 1982).

The roAp phenomenon is confined to a well-defined region of the Strömgren photometry parameter space (Martinez 1993). However, this region also contains other Ap stars, in which no pulsation could be detected, despite thorough searches. These apparently constant Ap stars (non-oscillating Ap stars, or noAp stars) appear remarkably similar to the roAp stars in many respects (color indices, abundances, magnetic fields).

A decade ago, after the completion of a study of the kinematic properties of rapidly oscillating Ap and noAp stars, Hubrig et al. (2000) realized that none of the roAp stars is known to be a spectroscopic binary (SB). They obtained several radial velocity

measurements for a majority of the roAp stars, but found no evidence for variations in any of these stars. The situation is quite different for other Ap stars co-existing in the same region of the H-R diagram. In contrast with roAp stars, many noAp stars for which radial velocity data exist are known as spectroscopic binaries or show radial velocity variations. The interpretation of this difference and its significance for the understanding of the origin of the pulsations in roAp stars is not clear so far. That until now no roAp star is known to be a spectroscopic binary is also in direct contrast to the situation for other types of pulsating variables (e.g., β Cep stars, δ Sct stars, or classical Cepheids), which are frequently found in SB systems.

Neither theoretically nor observationally is our present knowledge sufficient to decide confidently whether tidal interaction in binaries may reduce the amplitude of or inhibit the pulsations in cool Ap stars. To establish this, a necessary condition would be to show that essentially all noAp stars are close binaries, or, alternatively, to investigate whether all roAp stars are single stars or wide visual binaries.

Our search in the literature and catalogs for known double or multiple systems among roAp stars revealed that the three roAp stars γ Equ (HD 201601), β CrB, and α Cir, which are the brightest and best studied stars in the group of roAp stars, do have optical or physical companions. Stelzer et al. (2011) combined data from the Washington Double Star Catalog (Mason et al. 2001) and from HIPPARCOS with the measurement reported in this paper and derived a preliminary orbit for γ Equ. They estimated the mass of the companion to be $0.6 \pm 0.4 M_{\odot}$. The companion in the β CrB system at a separation of 0'.3 was frequently observed by speckle interferometry in the eighties. The companion in the

* Based on observations obtained at the European Southern Observatory, Paranal, Chile (ESO programme Nos. 079.D-0537(A) and 076.C-0170).

** Appendix A is available in electronic form at <http://www.aanda.org>

Table 1. Objects studied in the program.

| HD number | Other identifier | V | K^a | Spectral type | Parallax ^b [mas] |
|-------------------|------------------|-------|-------|---------------|-----------------------------|
| 6532 | CD-27 355 | 8.40 | 8.19 | A3 Sr Cr | 6.14 ± 1.03 |
| 9289 | BD-11 286 | 9.40 | 8.87 | A3 Sr Eu Cr | |
| 12932 | BD-19 384 | 10.36 | 9.46 | A4 Sr Eu | |
| 19918 | CD-82 53 | 9.37 | 8.78 | A5 Sr Eu Cr | 4.07 ± 0.82 |
| 24712 | HR 1217 | 5.99 | 5.26 | A9 Sr Eu Cr | 20.32 ± 0.39 |
| 42659 | BD-15 1299 | 6.77 | 6.36 | A3 Sr Cr Eu | 7.60 ± 0.51 |
| 86181 | CPD-58 1700 | 9.39 | 8.68 | F0 Sr | 3.49 ± 1.05 |
| 99563 | BD-08 3173 | 8.2 | 7.74 | F0 Sr | 3.92 ± 1.15 |
| 101065 | CD-46 7232 | 8.02 | 6.92 | F3 Ho | 8.93 ± 0.87 |
| 116114 | BD-17 3829 | 7.03 | 6.35 | F0 Sr Cr Eu | 7.71 ± 0.55 |
| 119027 | CD-28 10204 | 9.91 | 9.09 | A3 Sr Eu | |
| 122970 | BD+06 2827 | 8.30 | 7.31 | F0 Cr Eu Sr | 8.67 ± 0.70 |
| 134214 | BD-13 4081 | 7.47 | 6.67 | F2 Sr Eu Cr | 9.74 ± 0.64 |
| 137949 | BD-16 4093 | 6.68 | 6.25 | F0 Sr Eu Cr | 11.28 ± 0.67 |
| 150562 | CD-48 11127 | 9.95 | 8.88 | A5: Eu Si? | |
| 154708 | CD-57 6753 | 8.76 | 7.95 | A2 Sr Eu Cr | 6.75 ± 0.96 |
| 161459 | CD-51 11145 | 10.4 | 9.54 | A2 Eu Sr Cr | |
| 166473 | CD-37 12303 | 7.92 | 7.45 | A5 Sr Eu Cr | |
| 176232 | HR 7167 | 5.91 | 5.30 | A6 Sr | 12.76 ± 0.29 |
| 185256 | CD-30 17252 | 9.92 | 8.92 | F0 Sr Eu | |
| 190290 | CD-79 800 | 9.89 | 9.18 | A0 Eu Sr | |
| 193756 | CD-52 9483 | 9.19 | | A9 Sr Cr Eu | |
| 196470 | BD-18 5731 | 9.79 | 9.17 | A2 Sr Eu | |
| 201601 | HR 8097 | 4.71 | 4.01 | A9 Sr Eu | 27.55 ± 0.62 |
| 203932 | CD-30 18600 | 8.82 | 8.13 | A5 Sr Eu | |
| 213637 | BD-20 6447 | 9.58 | 8.54 | F1 Eu Sr | |
| 217522 | CD-45 14901 | 7.53 | 6.63 | A5 Sr Eu Cr | 11.36 ± 0.79 |
| 218495 | CD-64 1414 | 9.34 | 9.03 | A2 Eu Sr | |
| Magnetic Ap stars | | | | | |
| 40711 | BD+10 973 | 8.58 | 8.15 | A0 Sr Cr Eu | 2.66 ± 0.95 |
| 55719 | HR 2727 | 5.31 | 5.14 | A3 Sr Cr Eu | 7.93 ± 0.38 |
| 59435 | V827 Mon | 7.97 | 6.39 | A4 Sr Cr Eu | 2.70 ± 0.76 |

Notes. In Col. 1, we give the HD number of the objects, in Col. 2 another identifier, in Cols. 3 and 4 the magnitudes in V and K bands, in Col. 5 the spectral type, and finally in Col. 6 the parallax. Most information was collected from the SIMBAD database, except for the spectral types, which are from Renson & Manfroid (2009), and the parallaxes, obtained from van Leeuwen (2007). ^(a) For one target, SIMBAD does not list a K magnitude. ^(b) For some targets, Leeuwen (2007) does not list a parallax.

system α Cir is of spectral type K5V (Eggleton & Tokovinin 2008). All other roAp stars are considerably fainter than γ Equ, β CrB, and α Cir, and therefore have not been intensely studied with high resolution imaging instruments. Still, companions are reported for HD 99563 and HR 3831 (e.g. Dommagnet & Nys 2002).

The interpretation of a difference in duplicity between roAp and noAp stars and its meaning for the understanding of the origin of the pulsations in roAp stars is far from obvious. Even if the different internal structure of roAp stars is the reason for their pulsations, it is difficult to understand why no roAp star was found to be in a close binary.

In the following we report the results of our multiplicity study of this class of objects using NACO K -band imaging.

2. Observations and data reduction

We carried out observations of 28 roAp stars with NAOS-CONICA (NACO; Lenzen et al. 2003; Rousset et al. 2003) on the VLT in service mode between April and September 2007. Furthermore, three ordinary Ap stars were observed in

December 2005 and January 2006. We used the S13 camera of CONICA, which provides the smallest available pixel scale of 13.3 milliarcsec and a field-of-view of 13'6. All data were collected through a K_s filter in image autojitter mode, where the object is observed at typically 20 different image positions with random offsets between them. Since all our sources are bright in V , we used the visible wavefront sensor of NAOS.

The sample was picked from the list of 35 roAp stars listed in Kurtz et al. (2006) for their accessibility from the VLT during the observing period. α Cir would also have been observable, but was well studied in the past by other authors. Since the presence of companions is relatively rare among the Ap stars, we additionally chose three non-oscillating magnetic Ap stars because the presence of a companion was mentioned in the literature (Renson & Manfroid 2009, for HD 40711 and HD 59435; Pourbaix et al. 2004 and Mason et al. 2001, for HD 55719). The sample is listed in Table 1.

The data reduction was performed with the eclipse package (Devillard 1997) in the standard way. Sky background frames obtained from median averaging of the jittered frames were subtracted from the individual frames. All frames were then

Table 2. Astrometric and photometric results of the candidate binaries and multiples resolved in our study.

| HD number | MJD | Separation [$''$] | Position angle [$^{\circ}$] | K mag difference | K mag system | K mag primary | K mag secondary | Projected linear separation [AU] | Chance projection probability [%] |
|------------------------------------------------|----------|------------------------|----------------------------------|--------------------|-----------------|-----------------|-------------------|-------------------------------------|--------------------------------------|
| Binaries | | | | | | | | | |
| 9289 | 54311.35 | 0.441 ± 0.003 | 72.7 ± 0.7 | 1.70 ± 0.01 | 8.87 ± 0.02 | 9.08 ± 0.03 | 10.77 ± 0.05 | | 2.16×10^{-4} |
| 12932 | 54311.37 | 0.239 ± 0.003 | 171.4 ± 0.9 | 0.65 ± 0.01 | 9.46 ± 0.02 | 9.94 ± 0.03 | 10.59 ± 0.06 | | 4.77×10^{-5} |
| *99563 | 54210.04 | 1.784 ± 0.004 | 216.6 ± 0.5 | 0.66 ± 0.01 | 7.74 ± 0.02 | 8.21 ± 0.03 | 8.87 ± 0.05 | 455.1 ± 133.5 | 1.77×10^{-3} |
| 101065 | 54212.11 | 8.648 ± 0.005 | 140.9 ± 0.5 | 7.45 ± 0.04 | 6.92 ± 0.02 | 6.92 ± 0.02 | 14.37 ± 0.06 | 968.4 ± 94.3 | 5.47 |
| 185256 | 54233.35 | 4.965 ± 0.005 | 306.7 ± 0.5 | 8.61 ± 0.06 | 8.92 ± 0.03 | 8.92 ± 0.03 | 17.53 ± 0.08 | | 6.31 |
| 196470 | 54262.37 | 6.921 ± 0.003 | 190.9 ± 0.5 | 6.73 ± 0.02 | 9.17 ± 0.02 | 9.17 ± 0.02 | 15.90 ± 0.04 | | 6.29 |
| *201601 | 54266.25 | 0.829 ± 0.003 | 256.8 ± 0.5 | 2.71 ± 0.01 | 4.01 ± 0.26 | 4.09 ± 0.26 | 6.80 ± 0.29 | 30.1 ± 0.7 | 3.82×10^{-4} |
| 203932 | 54262.40 | 0.227 ± 0.003 | 98.2 ± 0.9 | 1.10 ± 0.01 | 8.13 ± 0.02 | 8.46 ± 0.03 | 9.57 ± 0.06 | | 7.18×10^{-5} |
| Systems with more than one companion candidate | | | | | | | | | |
| 86181AB | 54223.07 | 6.560 ± 0.004 | 116.9 ± 0.5 | 6.04 ± 0.01 | 8.68 ± 0.02 | 8.68 ± 0.02 | 14.71 ± 0.03 | 1879.7 ± 565.5 | 24.7 |
| 86181AC | | 5.549 ± 0.003 | 94.7 ± 0.5 | 6.80 ± 0.02 | | | 15.48 ± 0.04 | 1590.0 ± 478.4 | 29.5 |
| 86181AD | | 3.532 ± 0.004 | 294.3 ± 0.5 | 8.43 ± 0.04 | | | 17.11 ± 0.06 | 1012.0 ± 304.5 | 14.3 |
| 86181AE | | 7.309 ± 0.004 | 137.6 ± 0.5 | 8.97 ± 0.05 | | | 17.65 ± 0.07 | 2094.3 ± 630.1 | 48.5 |
| 86181AF | | 8.222 ± 0.005 | 44.3 ± 0.5 | 9.42 ± 0.07 | | | 18.10 ± 0.09 | 2355.9 ± 708.8 | 56.8 |
| 86181AG | | 6.848 ± 0.005 | 47.7 ± 0.5 | 9.66 ± 0.08 | | | 18.33 ± 0.09 | 1962.2 ± 590.3 | 44.1 |
| 86181AH | | 3.068 ± 0.006 | 267.5 ± 0.5 | 9.94 ± 0.09 | | | 18.61 ± 0.11 | 879.1 ± 264.5 | 11.0 |
| 86181AI | | 5.088 ± 0.005 | 268.8 ± 0.5 | 9.97 ± 0.09 | | | 18.64 ± 0.11 | 1457.9 ± 438.6 | 27.5 |
| 86181AJ | | 4.256 ± 0.009 | 342.1 ± 0.5 | 10.22 ± 0.10 | | | 18.90 ± 0.12 | 1219.5 ± 366.9 | 20.1 |
| 86181AK | | 6.497 ± 0.005 | 293.0 ± 0.5 | 10.29 ± 0.11 | | | 18.97 ± 0.12 | 1861.6 ± 560.1 | 40.8 |
| 86181AL | | 5.560 ± 0.007 | 34.0 ± 0.5 | 10.40 ± 0.11 | | | 19.08 ± 0.13 | 1593.1 ± 479.3 | 31.9 |
| 150562AB | 54222.34 | 7.872 ± 0.003 | 193.0 ± 0.5 | 4.43 ± 0.01 | 8.88 ± 0.02 | 8.88 ± 0.02 | 13.31 ± 0.03 | | 45.8 |
| 150562AC | | 2.122 ± 0.003 | 1.5 ± 0.5 | 5.58 ± 0.01 | | | 14.46 ± 0.03 | | 9.06 |
| 150562AD | | 4.459 ± 0.003 | 111.1 ± 0.5 | 6.05 ± 0.01 | | | 14.93 ± 0.03 | | 37.3 |
| 150562AE | | 3.492 ± 0.004 | 299.1 ± 0.5 | 6.28 ± 0.01 | | | 15.15 ± 0.04 | | 25.1 |
| 150562AF | | 4.725 ± 0.004 | 125.0 ± 0.5 | 6.52 ± 0.01 | | | 15.40 ± 0.04 | | 41.3 |
| 150562AG | | 5.024 ± 0.004 | 138.3 ± 0.5 | 6.91 ± 0.02 | | | 15.79 ± 0.04 | | 45.5 |
| 150562AH | | 3.224 ± 0.004 | 258.0 ± 0.5 | 8.38 ± 0.04 | | | 17.26 ± 0.06 | | 22.2 |
| 150562AI | | 2.813 ± 0.004 | 282.9 ± 0.5 | 8.43 ± 0.04 | | | 17.31 ± 0.06 | | 17.4 |
| 150562AJ | | 1.139 ± 0.005 | 101.8 ± 0.6 | 8.52 ± 0.04 | | | 17.40 ± 0.06 | | 3.08 |
| 150562AK | | 2.153 ± 0.004 | 130.9 ± 0.5 | 8.54 ± 0.04 | | | 17.41 ± 0.06 | | 10.6 |
| 150562AL | | 1.565 ± 0.005 | 99.6 ± 0.5 | 8.77 ± 0.05 | | | 17.65 ± 0.07 | | 5.74 |
| 150562AM | | 2.479 ± 0.005 | 182.2 ± 0.5 | 8.90 ± 0.05 | | | 17.78 ± 0.07 | | 13.8 |
| 150562AN | | 2.677 ± 0.008 | 128.8 ± 0.5 | 9.94 ± 0.09 | | | 18.82 ± 0.11 | | 15.9 |
| 150562AO | | 2.668 ± 0.009 | 144.8 ± 0.5 | 10.10 ± 0.09 | | | 18.98 ± 0.12 | | 15.8 |
| 150562AP | | 2.776 ± 0.007 | 32.4 ± 0.5 | 10.16 ± 0.10 | | | 19.03 ± 0.12 | | 17.0 |
| 150562AQ | | 2.055 ± 0.009 | 182.6 ± 0.5 | 10.60 ± 0.12 | | | 19.48 ± 0.15 | | 9.68 |
| 150562AR | | 2.830 ± 0.018 | 158.8 ± 0.6 | 10.61 ± 0.12 | | | 19.49 ± 0.14 | | 17.6 |
| 154708AB | 54222.31 | 8.919 ± 0.003 | 113.8 ± 0.5 | 4.65 ± 0.01 | 7.95 ± 0.03 | 7.97 ± 0.03 | 12.62 ± 0.04 | 1321.3 ± 187.9 | 3.88 |
| 154708AC | | 0.782 ± 0.004 | 53.0 ± 0.6 | 4.78 ± 0.01 | | | 12.75 ± 0.05 | 115.9 ± 16.5 | 3.43×10^{-2} |
| 154708AD | | 7.608 ± 0.003 | 89.0 ± 0.5 | 8.85 ± 0.06 | | | 16.81 ± 0.09 | 1127.1 ± 160.3 | 38.0 |
| 154708AE | | 5.185 ± 0.004 | 184.2 ± 0.5 | 9.32 ± 0.07 | | | 17.29 ± 0.10 | 768.1 ± 109.2 | 20.2 |
| 154708AF | | 9.246 ± 0.008 | 342.1 ± 0.5 | 9.59 ± 0.08 | | | 17.56 ± 0.11 | 1369.8 ± 194.8 | 51.3 |
| 161459AB | 54210.08 | 8.820 ± 0.006 | 12.6 ± 0.5 | 8.10 ± 0.05 | 9.54 ± 0.02 | 9.54 ± 0.02 | 17.64 ± 0.07 | | 50.6 |
| 161459AC | | 7.981 ± 0.011 | 231.7 ± 0.5 | 8.87 ± 0.07 | | | 18.41 ± 0.10 | | 43.9 |
| 193756AB | 54258.37 | 8.835 ± 0.005 | 144.3 ± 0.5 | 7.37 ± 0.04 | 8.65 ± 0.02 | 8.65 ± 0.02 | 16.02 ± 0.06 | | 7.73 |
| 193756AC | | 6.045 ± 0.010 | 132.9 ± 0.5 | 8.53 ± 0.07 | | | 17.17 ± 0.09 | | 3.85 |
| Magnetic Ap stars | | | | | | | | | |
| *55719 | 53729.34 | 0.714 ± 0.003 | 265.0 ± 0.6 | 2.97 ± 0.01 | 5.14 ± 0.02 | 5.21 ± 0.02 | 8.18 ± 0.04 | 90.0 ± 4.3 | 5.67×10^{-4} |

Notes. In Col. 1, we list the HD number for each system as well as the pair designation for the systems with more than one companion candidate, and Col. 2 gives the modified Julian date for the observations. In Cols. 3–5, we show the separation, position angle (from North to East), and magnitude difference in the K band between the components, as retrieved by aperture photometry from our images. In Col. 6, we give the K band magnitude for the whole system, as derived from the 2MASS or DENIS catalogs, and in Cols. 7 and 8 we give K band magnitudes for the primary and secondary component, as determined from Cols. 5 and 6. Whenever we have a parallax available, we give the projected linear separation in Col. 9. Column 10 finally lists the chance projection probability of the secondary component, as described in Sect. 3.2. An asterisk preceding the HD number in Col. 1 indicates systems where the companion was known before our study.

flat-fielded and corrected for bad pixels using calibration files provided by ESO.

After identifying all companion candidates in the resulting images visually, we obtained astrometry and relative photometry of the multiple systems using the IRAF package DAOPHOT. Since for some sources the errors determined by DAOPHOT were small, we adopted as a floor for systematics 1/10th of a pixel for the position of the individual objects and 1% for the flux ratio. The final errors in the relative positions are estimated by combining quadratically the rms variations in our

astrometric analysis with the uncertainty in the plate scale (13.26 ± 0.03 mas) and detector orientation ($\pm 0.5^{\circ}$), both provided by Masciadri et al. (2003).

3. Results

We were able to detect companion candidates around 13 roAp stars and one magnetic Ap star. The astrometric and photometric results are presented in Table 2 for all multiple systems of our sample.

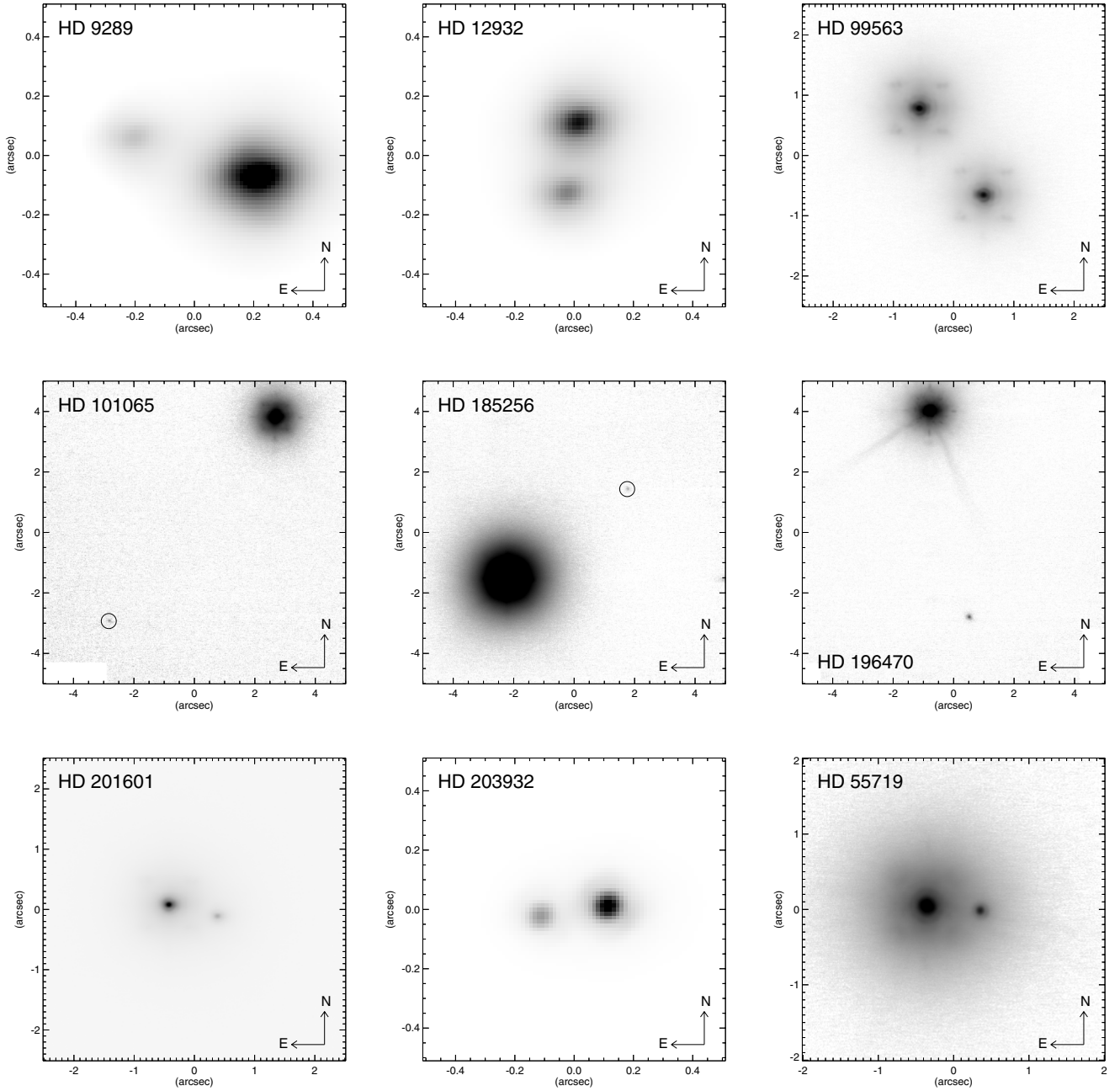


Fig. 1. Images of the potential binary systems detected in our VLT/NACO survey.

The images of the resolved potential binary systems are shown in Fig. 1, while the systems with more than one companion candidate can be found in Fig. 2. All images are displayed using a logarithmic scale. In the images with the closest companion candidates, showing just the inner 1'', this logarithmic scale had to be adapted to enhance the image details. While we have tried to show all companion candidates in these images, please note that this was not possible for HD 86181 and HD 150562. The only companion candidate that is likely physical in the systems with more than one companion candidate can be seen on the lower right of Fig. 2.

3.1. Limits for undetected companions and completeness

The detection limits were computed using the method described in Correia et al. (2006). At each radial distance and position

angle from the star, the standard deviation in the flux was calculated over a circular region of radius 70 mas, i.e., equivalent to the mean size of the point spread function (PSF) core. The detection limit as a function of separation from the star is the average of the 5σ flux over all position angles except those lying in the direction of the companion candidate.

For any given component of the potential binary systems as well as for the unresolved sources, we thus have the limiting flux ratio for undetected companion candidates as a function of separation. We can therefore produce a completeness map for each of these sources, i.e. a map giving the probability of detecting a companion candidate as a function of separation and magnitude difference. The total completeness map of all sources is simply the average of all individual completeness maps.

Figure 3 shows the total completeness map. The lines represent the completeness of our observations at levels 99%, 90%,

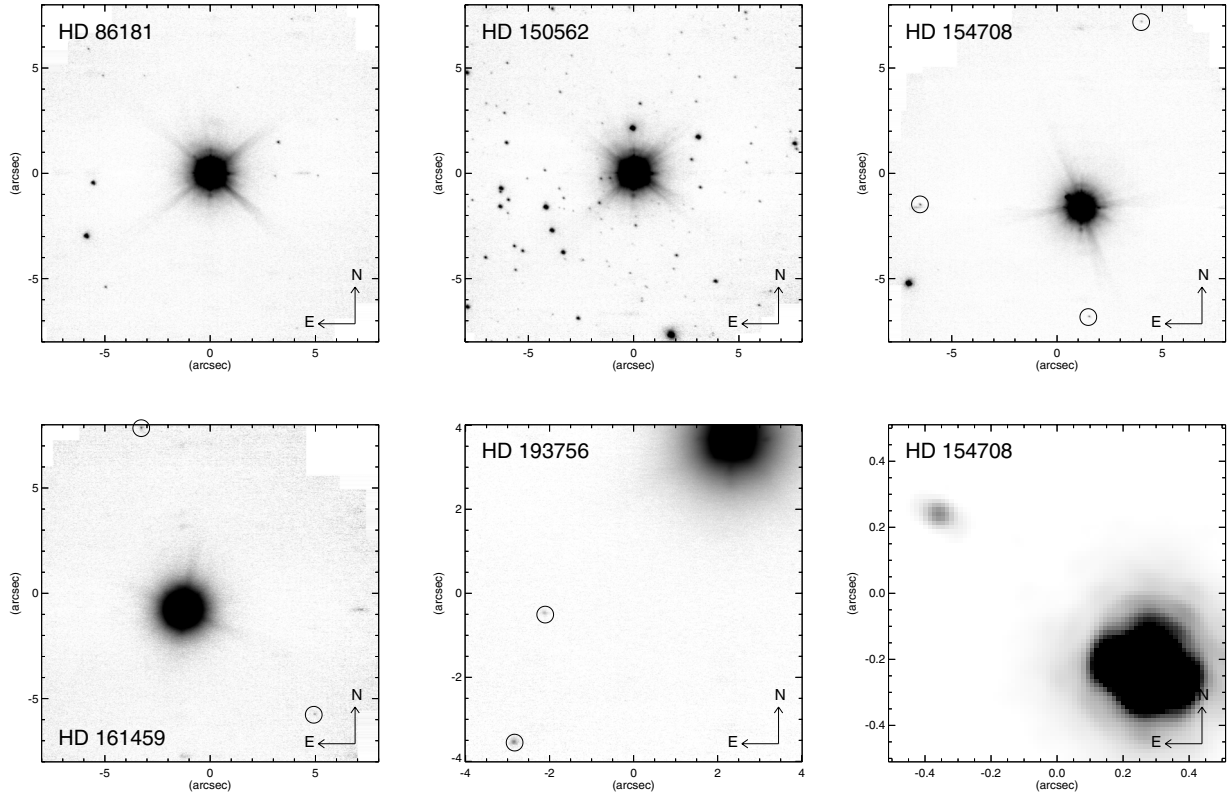


Fig. 2. Images of the systems with more than one companion candidate detected in our VLT/NACO survey.

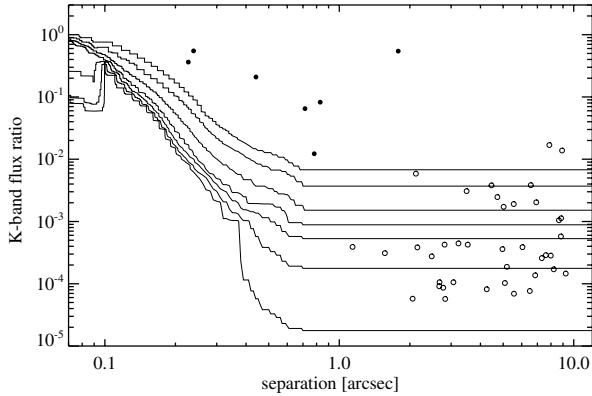


Fig. 3. Completeness map for our survey. The lines represent the completeness of our observations as derived from the sensitivity limit for undetected companion candidates (see Sect. 3.1). The lines are, from top to bottom, 99%, 90%, 70%, 50%, 30%, 10%, and 1% completeness. The full circles represent the companion candidates found in our study that we consider to be physical, while the open circles represent the companion candidates we consider to be chance projections.

70%, 50%, 30%, 10%, and 1% completeness, from top to bottom. The full circles represent the companion candidates found in our study that we consider to be physical, i.e. with low chance projection probabilities (see Sect. 3.2), while the open circles represent the companion candidates that we consider to be chance projections. All companion candidates that we consider physical fall above the 99% completeness level, while all but two companion candidates that we consider as chance projections fall below the 99% completeness level, and those two are at the edge of the field. Please note that our method is not very accurate inside

of the first Airy ring. Overall, we are confident in the completeness levels. Assuming that both the distribution of separation and the distribution of flux ratio of companion candidates are flat (which is obviously a very rough assumption), we estimate that the completeness is above 90% for separations of a) between $0''.25$ and $0''.4$ and above a flux ratio of 10^{-1} , b) between $0''.4$ and $1''$ and above a flux ratio of 10^{-2} , and c) between $1''$ and $8''$ and above a flux ratio of 5×10^{-3} . It should be noted that the S13 camera of NACO is incomplete in the detection of companion candidates at large separations ($> \sim 7-8''$).

3.2. Chance projections

To identify the systems whose components are gravitationally bound and those that are only the result of a chance projection, we used a statistical approach (see e.g. Correia et al. 2006). In a first step, we determined the local surface density of background/foreground sources in each field. For this purpose, we compiled the number of 2MASS objects brighter than the companion candidates in the K -band in a $30' \times 30'$ field surrounding each primary. This leads to the average surface density of objects brighter than the limiting magnitude $\Sigma(K < K_{\text{comp}})$. Assuming a random uniform distribution of unrelated objects across the field, the resulting probability $P(\Sigma, \Theta)$ of at least one unrelated source being located within a certain angular distance Θ from a particular target is given by

$$P(\Sigma, \Theta) = 1 - e^{-\pi\Sigma\Theta^2}.$$

The last column of Table 2 gives the resulting probability for a companion candidate to be unrelated to the primary of the system. Since the 2MASS Point Source Catalog is incomplete for stars fainter than $K = 14.3$, the calculated chance projection

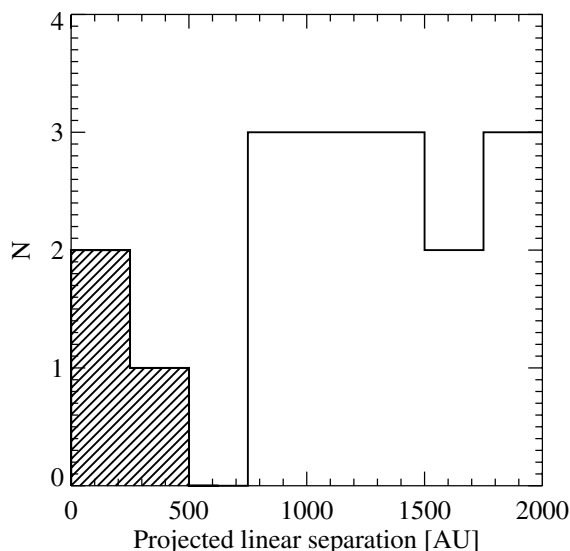


Fig. 4. Distribution of the projected separations of the studied systems with roAp primaries. For this figure, we have used all companion candidates where a parallax was available for the roAp star. The shaded region shows the three objects where the chance projection probability is smaller than 1%.

probabilities are only lower limits for sources fainter than $K = 14.3$. This is the case for all sources with high chance projection probability except for HD 154708AB, which is $K = 12.62$ and has a chance projection probability of 3.88%, while all companion candidates with a low chance projection probability are brighter than $K = 13$. Out of the eight companion candidates detected in our survey in potential binary systems, five have probabilities to be projected unrelated stars well below the percent level. This means that they are very likely bound to their primaries, although considering probabilities of individual sources is known to be prone to error (see e.g. Brandner et al. 2000, for a discussion). The three other companion candidates have chance projection probabilities on the order of 6%. In the systems with more than one companion candidate, all except one companion candidate (HD 154708AC) are very likely chance projections, with chance projection probabilities between 3% and 57%. On the other hand, while the vast majority of the objects with high chance projection probabilities should be background stars, some of them could have been captured (see e.g. Kouwenhoven et al. 2010; Moeckel & Clarke 2011).

4. Discussion

Here, we announce the detection of 45 companion candidates in 13 of the observed 28 roAp stars, with 39 of these very likely being chance projections. They have K magnitudes between $6^m.8$ and $19^m.5$ and angular separations ranging from $0'.23$ to $8'.9$, corresponding to linear projected separations of 30–2400 AU. For the eight companion candidates in potential binary systems, three have a high probability to be chance projections. In the systems with more than one companion candidate, all companion candidates but HD 154708AC are very likely chance projections. All companion candidates, except for the companion candidates of HD 99563 and HD 201601, were detected by us for the first time. The companion candidate for the noAp star HD 55719 was also known before. In Fig. 4 we show the distribution of the projected linear separations for the studied multiple systems with roAp primaries. The distribution is missing the 26 companion

candidates where no parallax information is available for the roAp star. For only three companion candidates with low probability to be a chance projection exist parallax data. These are the three objects with a projected linear separation below 500 AU.

In our survey, we found in six of the 28 studied systems with an roAp primary one visual companion candidate that has a high probability to be a physical companion, resulting in a multiplicity fraction of $21 \pm 9\%$. This is low compared with similar surveys of A type stars. On the other hand, should all of the objects we believe to be chance projections turn out to be physical companions, the multiplicity fraction may be as high as $46 \pm 13\%$. We introduced a bias in the sample by removing the well studied α Cir, which has a companion. Inserting α Cir in the sample, we get a multiplicity fraction of $24 \pm 9\%$.

Kouwenhoven et al. (2005) studied the binarity of A and B stars in the OB association Sco OB2 with adaptive optics using a K_s filter and a similar field-of-view. 65 of the 199 stars in their sample have at least one companion candidate, leading to a binary fraction of $33 \pm 4\%$. If one restricts the survey to the 113 A type stars, there are 40 stars showing multiplicity, giving a multiplicity fraction of $35 \pm 6\%$. We should note however that the distance to the stars in our sample is on average higher compared with the 130 pc to Sco OB2, with nearly half of the stars in our sample having no parallax determined. Ehrenreich et al. (2010) find in their volume limited sample of 38 late B to F-type stars, observed with NACO and PUEO, companion candidates to 17 objects. If one restricts their sample to the 19 A-type stars, this leaves companion candidates to seven objects, or a binary fraction of $37 \pm 14\%$. While Ehrenreich et al. employ on some of their observations a larger field-of-view, they consider all companion candidates to A-type stars with separations larger than $7''$ as background stars. The distances to these A stars are lower than 67 pc, and only two of our own sources would fall into this distance range. Schröder & Schmitt (2007) looked at the A-type stars listed in the Bright Star Catalog (Hoffleit & Jaschek 1991) and found for the 1966 objects listed therein a binary frequency of $16 \pm 1\%$. Looking at a volume limited complete sample of all A stars up to a distance of 50 pc, they find 82 binaries among 220 stars, a binary frequency of $37 \pm 4\%$. They identified companion candidates from catalogs, variations in radial velocity or proper motions, variations in ROSAT X-ray light curves at different time scales, and rotational velocity. Since Schröder & Schmitt did not make use of high spatial resolution observations, they could have missed a number of companion candidates, leading to an underestimation of the true object multiplicity. Assuming that the three different surveys listed above can be summed up, this would lead to 129 binaries for 352 systems, or a binary frequency of $37 \pm 3\%$.

Even taking into account the different observing strategies and object distances used in the studies discussed above, we believe that the 1σ difference hints that our sample shows in comparison a somewhat lower number of stars harboring a companion, assuming that all objects found to have high chance projection probabilities are indeed no physical companions.

Since our sample is quite heterogeneous with respect to distance, we could suffer from a bias that allows us to detect companion candidates only around the nearby roAp stars. We believe that this is not the case. If we separate the sample into three groups with different parallaxes, then we find one companion candidate with low chance projection probability among the five objects with parallaxes above 10 mas, two among the ten objects with parallaxes below 10 mas, and three among the 13 objects with no parallax measurement, not favoring nearby systems.

Table 3. Overview of the known multiplicity of the objects studied in this article.

| HD | SB1 | Astrometric or visual | Comment |
|-------------------|-----|--------------------------|----------|
| 6532 | | | |
| 9289 | | 1 | ND |
| 12932 | | 1 | ND |
| 19918 | | | |
| 24712 | | | |
| 42659 | | | |
| 86181 | | | |
| 99563 | | 1 | CD |
| 101065 | | | |
| 116114 | X? | 1 | NR |
| 119027 | | | |
| 122970 | | | |
| 134214 | | | |
| 137949 | | | |
| 150562 | | | |
| 154708 | | 1 | ND |
| 161459 | | | |
| 166473 | | | |
| 176232 | | | |
| 185256 | | | |
| 190290 | | | |
| 193756 | | | |
| 196470 | | | |
| 201601 | | 3 | CD+NR+NR |
| 203932 | | 1 | ND |
| 213637 | | | |
| 217522 | | | |
| 218495 | | | |
| Magnetic Ap stars | | | |
| 40711 | X? | | |
| 55719 | X | 1 | CD |
| 59435 | X? | | |

Notes. An X in the second column denotes an SB1 system; the ? indicates objects where there are only hints for an SB1 system. In the last column we point out the new detections (ND), the confirmed detections (CD), and the not reachable companions (NR). The not reachable companions are either potentially very narrow (HD 116114) or outside of our field-of-view (HD 201601).

In Table 3, we present the list of the observed roAp stars with notes about their multiplicity. For each object, we indicate whether it is known to be an SB1 and how many astrometric or visual high probability companion candidates are known. Note that there are no known SB2 in our sample. Since the roAp stars have been observed quite extensively for radial velocity variations, the probability that spectroscopic binaries have been missed is quite low. On the other hand, it is not impossible that long term radial velocity variations have been overlooked for individual sources. Of the 28 roAp stars studied, only HD 116114 is a potential SB1 system. It is also an astrometric binary. Six objects have visual high probability companion candidates. Another seven stars have visual companion candidates that are very likely chance projections. 15 roAp stars do not show any hint at being part of a binary. We also looked into why the found companion candidates were not detected in radial velocity surveys. For the companion of HD 201601, which

is the closest we found in our sample with a projected linear separation of 30.1 AU, we used the orbital parameters published by Stelzer et al. (2011) and computed a radial velocity amplitude of 1.7 km s^{-1} for the primary. Kochukhov & Ryabchikova (2001) found the largest pulsation amplitudes of 0.8 km s^{-1} for spectral lines of rare-earth elements. We believe that the accuracy and time span of radial velocity measurements obtained so far is not sufficient to detect radial velocity changes induced by the companion for HD 201601. The other likely companions have projected linear separations of 455.1 AU (HD 99563), 968.4 AU (HD 101065), and 115.9 AU (HD 154708AC), which lead to even lower radial velocity amplitudes.

Our recent study (Schöller et al. 2010) of another group of chemically peculiar stars with Hg and Mn overabundances using diffraction-limited near-infrared imaging with NACO led to the detection of 34 near IR companion candidates for the 57 stars studied, confirming that this type of chemically peculiar stars is frequently formed in multiple systems. The interpretation of the difference in duplicity between roAp and HgMn stars and its meaning for the understanding of the origin of the chemical anomalies and pulsations in roAp stars is not straightforward. We assume that most late B-type stars formed in binary systems with certain orbital parameters become HgMn stars (e.g., Hubrig & Mathys 1995; Hubrig et al. 2007; González et al. 2010; Hubrig et al. 2006). Our results hint at the possibility that magnetic Ap stars become roAp stars if they are not born in a close binary system.

Tidal forces might conceivably also play a non-negligible role in systems with a larger separation, provided that their eccentricity is large enough. Interaction would then occur mostly on the part of the orbit when the components are closest, since tidal forces are strongly dependent on the distance between the components. At present, though, almost nothing is known about the orbital eccentricities of the noAp binaries. For the roAp star HD 201601, Stelzer et al. (2011) give an eccentricity of 0.56 ± 0.05 .

On general grounds, the issue of whether duplicity affects pulsation through tidal interaction is unsettled. From the theoretical point of view, while some authors (e.g., Cowling 1941; Zahn 1977) have conjectured that tides in close binary systems may act as an external perturbing force driving oscillations, the question whether tidal interaction may also be efficient in damping already existing pulsations does not seem to have ever been addressed. Recently, significant advances have been made in tidally-driven pulsations in eccentric binaries with Kepler data. There are 18 heartbeat stars in Thompson et al. (2012), one of which is KOI-54 (Welsh et al. 2011; Burkart et al. 2012; Fuller & Lai 2012). The theory of Kumar et al. (1995) fits these heartbeat stars beautifully. Observationally, in the same region of the parameter space in which pulsations were detected, there is only one binary system with a noAp primary presently known, in which the two components are close enough so that significant tidal interaction occurs between them (Giuricin et al. 1984), the SB1 HD 200405 with $P = 1.63 \text{ d}$ (North 1998).

The results of our study support our suspicion that roAp stars are rarely found in binary and multiple systems. However, companionship can not be established based on K photometry alone, and confirming the nature with a near-infrared spectrograph is essential for establishing their true companionship. Future spectroscopic observations in the near-infrared should be used to determine the mass of the companions much more accurately, and explore the physics in their atmospheres by comparison of observed and synthetic spectra.

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Appendix A: Notes on individual systems

A.1. Systems unresolved in our study

HD 116114: This star was marked by Renson & Manfroid (2009) as a potential binary with a period of 4000 d. Dommanget & Nys (2002) mark this star in the CCDM catalog as an astrometric binary from HIPPARCOS.

HD 40711: This star was marked by Renson & Manfroid (2009) as a potential binary with a period of 1245 d.

HD 59435: This star was marked by Renson & Manfroid (2009) as a potential binary with a period of 1386 d.

HD 6532, *HD 19918*, *HD 24712*, *HD 42659*, *HD 119027*, *HD 122970*, *HD 134214*, *HD 137949*, *HD 166473*, *HD 176232*, *HD 190290*, *HD 213637*, *HD 217522*, and *HD 218495*: There are no references in the literature that indicate multiplicity for these objects.

A.2. Systems resolved in our study, but very likely chance projections

HD 86181: There are no references in the literature that indicate multiplicity for this object. We find a total of eleven objects between *K* magnitudes 15 and 19, with separations of 3'' to 8'' around this star. All of them have chance projection probabilities above 10%.

HD 101065: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 8''.648 and a position angle of 140.9°. A chance projection probability above 5% suggests that this companion candidate might not be a physical companion.

HD 150562: There are no references in the literature that indicate multiplicity for this object. We find a total of 17 objects between *K* magnitudes 14.5 and 19.5, with separations of 1''.1 to 8'' around this star. All of them have chance projection probabilities above 3%.

HD 161459: There are no references in the literature that indicate multiplicity for this object. We find two objects with *K* magnitudes around 18, with separations of 8'' and 9'' around this star. Both have chance projection probabilities above 40%.

HD 185256: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 4''.965 and a position angle of 306.7°. A chance projection probability above 6% suggests that this companion candidate might not be a physical companion.

HD 193756: There are no references in the literature that indicate multiplicity for this object. We find two objects with *K* magnitudes around 16 and 17, with separations of 9'' and 6'' around this star. They have chance projection probabilities of 8% and 3%.

HD 196470: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 6''.921 and a position angle of 190.9°. A chance projection probability above 6% suggests that this companion candidate might not be a physical companion.

A.3. Systems resolved in our study

HD 9289: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 0''.441 and a position angle of 72.7°.

HD 12932: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 0''.239 and a position angle of 171.4°.

HD 99563: The Washington Double Star Catalog (Mason et al. 2001) lists a companion at a separation of 1''.8 and a position angle of 218°. Dommanget & Nys (2002) list this component in the CCDM catalog at a separation of 1''.7 and a position angle of 213°. We find this companion at a separation of 1''.784 and a position angle of 216.6°.

HD 201601: The Washington Double Star Catalog (Mason et al. 2001) lists one companion at a distance between 1''.5 and 2''.1 and position angles between 264° and 277°, a second companion at a distance between 25''.0 and 57''.3, and a third companion at a distance of about 6''. We find the close companion at a distance of 0''.829 and a position angle of 256.8°. Stelzer et al. (2011) used this new measurement and combined it with the data from the Washington Double Star Catalog and from HIPPARCOS to derive a preliminary orbit for γ Equ with a period of 274.5 yr. They estimated the mass of the companion to be $0.6 \pm 0.4 M_{\odot}$.

HD 203932: There are no references in the literature that indicate multiplicity for this object. We detect a new companion candidate to this star at a separation of 0''.227 and a position angle of 98.2°.

HD 154708: There are no references in the literature that indicate multiplicity for this object. We find five objects around this star. Only the component AC, with a separation of 0''.782 at position angle 53.0° and a *K* magnitude of 12.75 has a chance projection probability below 10^{-3} . The other four objects between *K* magnitudes 12.5 and 17.5, with separations of 5'' to 9'' have chance projection probabilities above 3%.

HD 55719: This system is an SB1 with a period of 46.3140 d, according to the 9th Catalog of Spectroscopic Binary Orbits (Pourbaix et al. 2004). The Washington Double Star Catalog (Mason et al. 2001) lists a companion at a distance of 0''.8 and a position angle of 258°. We find the companion at a separation of 0''.714 and a position angle of 265.0°.