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# New neighbours

## III. 21 new companions to nearby dwarfs, discovered with adaptive optics*

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**Abstract.** We present some results of a CFHT adaptive optics search for companions to nearby dwarfs. We identify 21 new components in solar neighbourhood systems, of which 13 were found while surveying a volume-limited sample of M dwarfs within 12 pc. We are obtaining complete observations for this subsample, to derive unbiased multiplicity statistics for the very-low-mass disk population. Additionally, we resolve for the first time 6 known spectroscopic or astrometric binaries, for a total of 27 newly resolved companions. A significant fraction of the new binaries has favourable parameters for accurate mass determinations.

The newly resolved companion of Gl 120.1C was thought to have a spectroscopic minimum mass in the brown-dwarf range (Duquennoy & Mayor 1991), and it contributed to the statistical evidence that a few percent of solar-type stars might have close-in brown-dwarf companions. We find that Gl 120.1C actually is an unrecognised double-lined spectroscopic pair. Its radial-velocity amplitude had therefore been strongly underestimated by Duquennoy & Mayor (1991), and it does not truly belong to their sample of single-lined systems with minimum spectroscopic mass below the substellar limit.

We also present the first direct detection of Gl 494B, an astrometric brown-dwarf candidate. Its luminosity straddles the substellar limit, and it is a brown dwarf if its age is less than ~300 Myr. A few more years of observations will ascertain its mass and status from first principles.

**Key words.** stars: binaries: general – stars: low-mass, brown dwarfs – techniques: miscellaneous

## 1. Introduction

As discussed in more detail in the first paper of this series (Delfosse et al. 1999b), stellar multiplicity is a key input for a number of important astrophysical issues. The joint distributions of system masses, mass ratios, semi-major axes and eccentricities represent powerful diagnostics of the formation and early dynamical evolution of stellar systems (e.g. Duchêne 1999; Patience et al. 1998; Bonnell et al. 1998; Kroupa 2001). For most stellar classes, unresolved companions also represent the main uncertainty when deriving the mass or luminosity function (e.g. Kroupa 2001).

The multiplicity statistics are now fairly well determined for the G and K dwarfs (Duquennoy & Mayor 1991; Halbwachs et al. 1998), but are considerably more uncertain for higher and lower-mass stars. For M dwarfs the samples are either very small (34 M dwarfs within 5.2 pc; Henry & McCarthy 1990; Leinert et al. 1997), or they have significant and uncertain completeness corrections (Reid & Gizis 1997; Fisher & Marcy 1992). The M-dwarf binary fractions derived from these data range from 26% (Leinert et al. 1997) through 35% (Reid & Gizis 1997) to 42% (Fisher & Marcy 1992). This points towards a smaller fraction of multiple stars than the 57% found amongst G dwarfs (Duquennoy & Mayor 1991), but still with relatively modest significance (~3$\sigma$ for the 5.2 pc sample). The parameter distributions, are determined only from the

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subsamples of identified binaries, and are thus even more uncertain. As just one consequence, contrasting assumptions on stellar multiplicity (Kroupa 1995; Reid & Gizis 1997) can remain compatible with the meager (and somewhat controversial) observational constraints while leading to very different luminosity functions.

To ascertain the multiplicity statistics of very low mass stars, we are surveying volume-limited samples of nearby M dwarfs for companions, combining accurate radial-velocity monitoring with adaptive optics imaging in the near-infrared. These observing techniques together ensure a good sensitivity to stars and brown dwarfs at all separations (Delfosse et al. 1999b), as well as some useful sensitivity to giant planets (Delfosse et al. 1998b). This work was initiated for a 9 pc northern sample (Delfosse et al. 1998a), using the ELODIE spectrograph at Observatoire de Haute-Provence (Baranne et al. 1996) and the PUEO adaptive optics system at CFHT (Rigaut et al. 1998). When the HIPPARCOS parallaxes became available in 1997 we altered the distance limit to 9.25 pc, to retain two stars that were already well observed at that point (GJ 2066 and Gl 424, neither of which is a binary). This also adds two other stars, LHS 2784 and the newly identified binary LHS 224. To further improve the statistics, we now monitor a larger 12 pc sample with the FEROS (Kaufer et al. 2000), ELODIE and HARPS (Mayor et al. 2003) spectrographs, and observe it with the NAOS adaptive optics system (Rousset et al. 2000) on the VLT, as well as with PUEO on CFHT.

As well as these volume-limited samples, we observe with the same instruments two smaller and more loosely defined collections of "interesting" spectroscopic or astrometric binaries, selected based on their apparent potential for accurate mass measurements, or in a few cases for having a possibly substellar companion. The first of these samples was gathered during a number of published and unpublished CORAVEL programs, while the second was culled from the literature. Neither is statistically well defined.

As a result of these programs, we recently published 16 accurate masses (Ségransan et al. 2000), and re-discussed the Mass-Luminosity relation of the M dwarfs (Delfosse et al. 2000). Here we present stellar components that were newly identified, or newly resolved, during the adaptive optics observations. Section 2 presents the observing and data-reduction techniques, while Sect. 3 discusses the properties of the individual new detections. A statistical analysis of the northern 9.25 pc sample will be published in a forthcoming paper.

## 2. Observations, data reduction and analysis

### 2.1. Instrumental setup

The observations were carried out at the 3.6-m Canada-France-Hawaii Telescope (CFHT) during many observing runs since September 1996, using the CFHT Adaptive Optics Bonnette (AOB) and two different infrared cameras. The AOB, also called PUEO after the sharp-visioned Hawaiian owl, is a general-purpose adaptive optics (AO) system based on F. Roddier's curvature concept (Roddier et al. 1991). It is mounted at the telescope F/8 Cassegrain focus, and cameras or other instruments are then attached to it (Arsenault et al. 1994; Rigaut et al. 1998). The atmospheric turbulence is analysed by a 19-element wavefront curvature sensor and the correction applied by a 19-electrode bimorph mirror. The typical control loop bandwidth is 90 Hz at 0 dB. Modal control and continuous mode gain optimization (Gendron & Léna 1994; Rigaut et al. 1994) maximize the quality of the AO correction for the current atmospheric turbulence and guide star magnitude. For our observations a dichroic mirror diverted the visible light to the wavefront sensor while a science camera recorded near-infrared light. We used either MONICA, the Université de Montréal Infrared Camera (Nadeau et al. 1994), or KIR, the CFHT infrared camera developed to take full advantage of the AO corrected images produced by PUEO (Doyon et al. 1998).

MONICA was used for the commissioning of the AOB during the first semester of 1996 and for all science runs until November 1997. It was a facility instrument based on a NICMOS-3 256 × 256 detector, and was originally designed by the Université de Montréal for the Observatoire du Mont Mégantic and CFHT F/8 Cassegrain focii. The camera was retrofitted with new optics for use at the F/20 output focus of AOB. It produced a plate scale of $0\farcs034$ per pixel, properly sampling diffraction-limited CFHT images down to the $J$ band ($1.25\,\mu$m). The resulting field size is $8.7'' \times 8.7''$.

Since December 1997, MONICA has been replaced on PUEO by KIR, an imaging camera which records a 16 times larger field on an HAWAII 1024 × 1024 HgCdTe array. KIR also has improved optical quality and detector performances, and therefore a better detectivity. The KIR plate scale is $0\farcs035$ per pixel, for a total field size of $36'' \times 36''$.

We also observed Gl 268.3 with the Keck II AO facility in February 2000. The Keck AO system uses a Shack-Hartmann wavefront sensor to measure the atmospheric distortions and a 349-actuator piezo-stack deformable mirror to correct for these distortions (Wizinowich et al. 2000a,b). The images were recorded with the KCAM infrared camera, which has a plate scale of $0\farcs0175$ per pixel and an L-shaped field-of-view of $4\farcs5$ on a long side.

### 2.2. Observations

Sources were first examined for binarity with one filter, usually $H$ ($1.65\,\mu$m). Under good to moderate seeing conditions $H$ represents the best compromise between sensitivity, corrected image quality and sky brightness. Under worse seeing conditions the $K$s filter was used instead to maintain acceptable image quality. Sources which saturate the detectors in the minimum available integration time through the $H$ ($1.65\,\mu$m) or $K$s ($2.23\,\mu$m) broad-band filter (brighter than $K = 7$ under typical conditions) were observed through corresponding narrow-band filters, usually [Fe$^+$] ($1.644\,\mu$m) and either $H_2$ ($2.122\,\mu$m) or Brackett$\gamma$ ($2.166\,\mu$m). Whenever a target appeared double or elongated, it was usually observed with additional filters to determine relative colour indices. Integration times per frame typically range between a few tenths of a second and 20 s. In order to improve the signal-to-noise ratio and to average the residual uncorrected atmospheric turbulence, series of ~4 min total integration times were accumulated in a four or five positions mosaic pattern. This observing sequence also provides for a well determined sky background and a good correction for detector cosmetic defects. Wavefront sensing was performed on the sources themselves, which are almost always bright enough ($R < 14$) to ensure diffraction-limited images in $H$ and $K$ bands under standard Mauna Kea atmospheric conditions (i.e. seeing up to 1″). The atmospheric turbulence and AO correction for a given set of observations were characterized by simultaneously recording the wavefront sensor measurements and deformable mirror commands, from which an accurate synthetic PSF was later generated (Sect. 2.3). Astrometric calibration fields, such as the central region of the Trapezium Cluster in the Orion Nebula (McCaughrean & Stauffer 1994), were observed to accurately determine the actual detector plate scale and position angle (PA) origin. Flat-field frames were obtained on the illuminated dome for each filter.

The Keck II observations of Gl 268.3 were obtained in $H$ band using a neutral density filter (ND2, attenuation of ∼100). A total of 20 individual exposures were co-added to obtain the final 40 s image. Sky subtraction was performed using images of a close-by field observed immediately after the science images. No flat-field correction was applied for these data.

### 2.3. Data reduction and analysis

For each filter, the raw images were median combined to produce sky frames, which were then subtracted from the raw data. Subsequent reduction steps included flat-fielding, flagging of the bad pixels, correction for systematic detector effects such as the suppression of the remaining 60 Hz correlated noise, and finally shift-and-add combinations of the corrected frames into one final image to increase the signal-to-noise ratio.

For resolved binary systems, the separation, position angle and magnitude difference between the two stars were then determined using deconvolution within the AOPHOT software developed by Véran (1998a). For the PUEO observations the long-exposure PSF associated with each AO corrected image was reconstructed from the wavefront sensor data and deformable mirror commands recorded during each data acquisition. The available tools (Véran et al. 1997; Thomas et al. 1998) provide an accurate estimate of the AO-corrected, long-exposure PSF, when the guide source is of magnitude 13 or brighter. No wavefront sensor and deformable mirror data were available for the Keck observation, and we therefore instead had to generate a theoretical estimate of the PSF. This has no adverse consequences for that particular observation: for such a well resolved and high contrast companion the derived parameters are quite insensitive to the adequacy of the estimated PSF. In a second stage, the reconstructed or estimated PSF is used to deconvolve the AO image and obtain the pixel coordinates of the primary and secondary stars, as well as their magnitude difference. Véran et al. (1998b) provide a complete description of this method and an assessment of its accuracy.

Application of the astrometric calibrations then yields the desired parameters. Images of the newly resolved binaries are presented in Figs. 1, 2 and 3.

### 2.4. Radial velocity data

Some of the objects discussed in this paper are also spectroscopic binaries, identified during long term surveys conducted with the CORAVEL and ELODIE spectrometers. The radial velocity measurements and their reduction have been extensively described in Delfosse et al. (1999b).

## 3. New companions

In this section we discuss the properties of the new companions. Table 1 summarizes the information available on the systems, and Table 2 presents the new adaptive optics information.

### 3.1. New binaries in the volume-limited samples

#### 3.1.1. LP 467–16

Adaptive optics images in August 2000 show a 0.41″ separation pair with a $K$-band magnitude difference of 0.69 (Table 2). The spectroscopic observations also display a ∼1 km s$^{-1}$ drift of the photocentric radial velocity, as well as variations in the width of the correlation profile. From the measured $K$-band magnitude difference and the relative slopes of the $V$ and $K$ Mass-Luminosity relations, we estimate a $V$-band magnitude difference of $\Delta(V) \sim 1$. Accounting for the secondary star therefore changes the photometric parallax from 118 ± 21 mas, as listed in the CNS3 catalogue, to ∼100 mas. This pushes the system out of the 9.25 pc volume, but it probably remains within 12 pc.

#### 3.1.2. LHS 224 (G 193-27, L 1750-5)

LHS 224 is a previously rather anonymous member (only 10 references in SIMBAD) of the 9.25 pc sample, with a joint spectral type of M5V (Reid et al. 1995). We first noticed it as a double-lined spectroscopic binary, with an equivalent width ratio of 0.75 in ELODIE spectra. Shortly thereafter, an adaptive optics image resolved the system into a 0.16″ binary with $\Delta(K) = 0.14$. We have now determined a combined visual+spectroscopic orbit for this system, with a period of 3.25 years. The visual part of the orbit remains noisy because several observations were obtained under mediocre weather conditions, and for a 4-m telescope the separation of this pair often demands short-wavelength observations. With a few additional good measurements at critical phases, LHS 224 should provide two accurate masses.

#### 3.1.3. GJ 2069

Initially known as a wide (∼12″) visual binary, the GJ 2069 system was found to be quadruple by Delfosse et al. (1999b). They identified GJ 2069A as an eclipsing double-lined spectroscopic binary, GJ 2069Aab, and resolved a 0.36″ companion

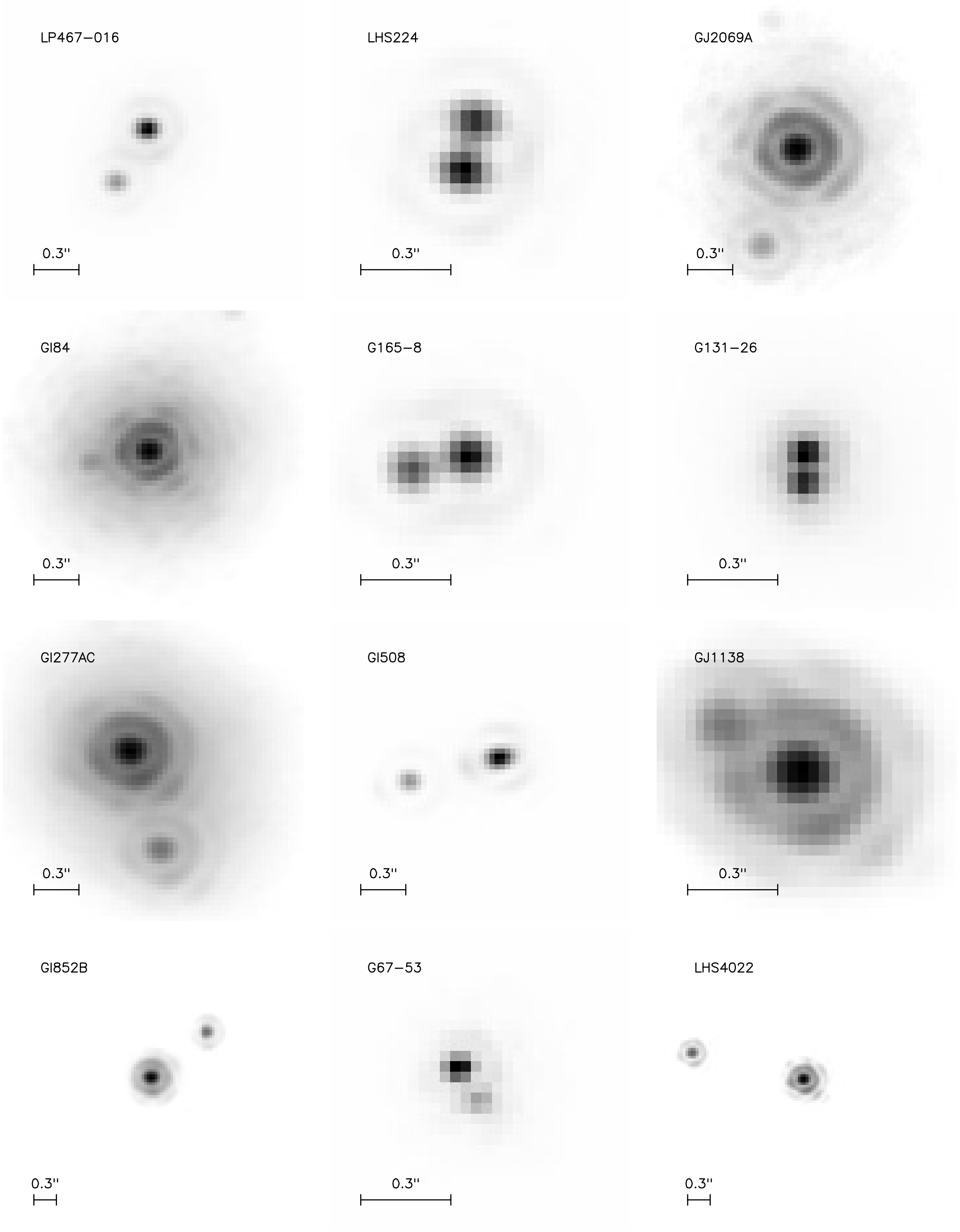

**Fig. 1.** Adaptive optics images of new binaries in the volume-limited samples. The scale of each box is indicated by a 0.3″ bar at the bottom left corner. North is up and East is left.

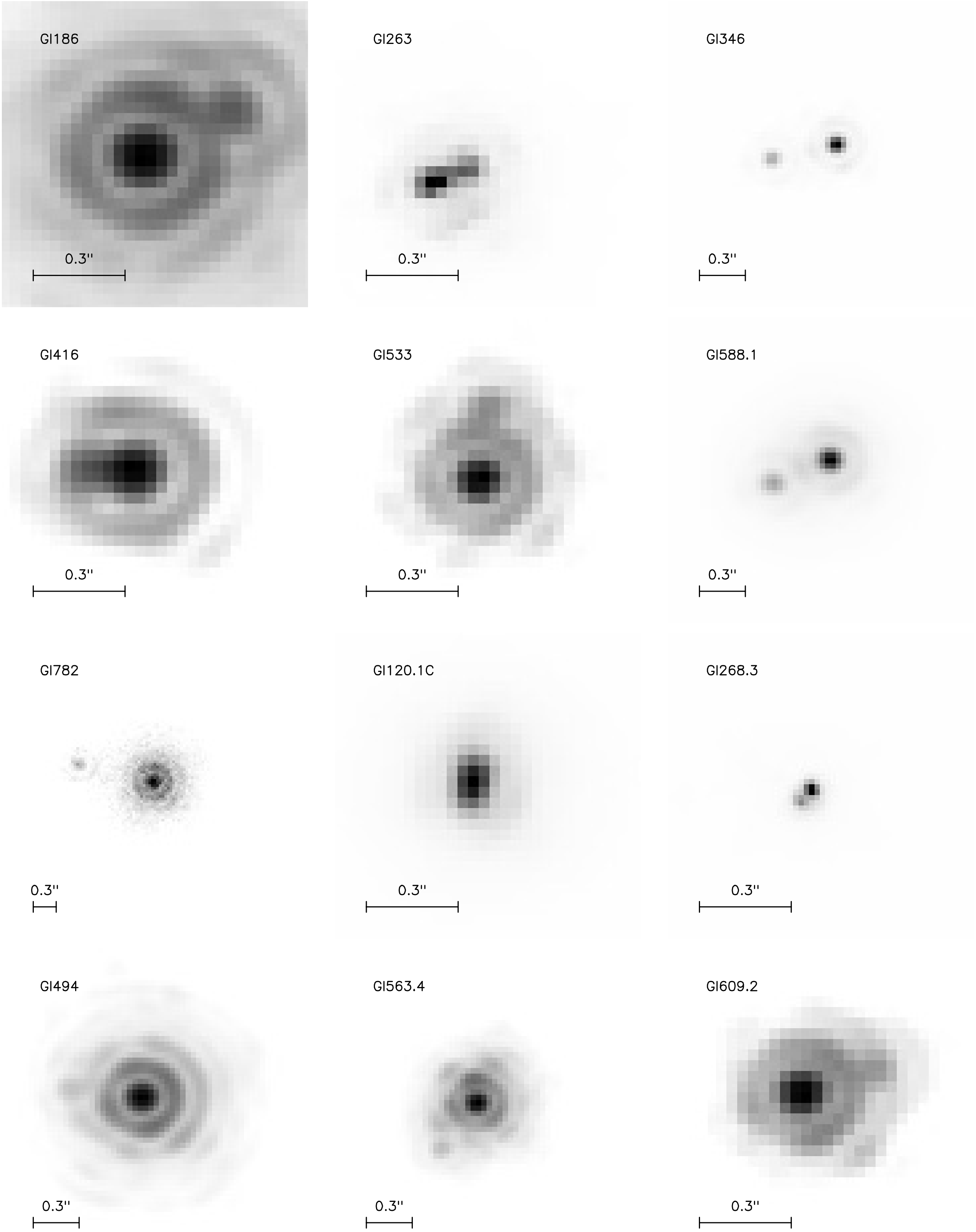

**Fig. 2.** Adaptive optics images of additional newly resolved binaries. Scale and orientation are as in Fig. 1.

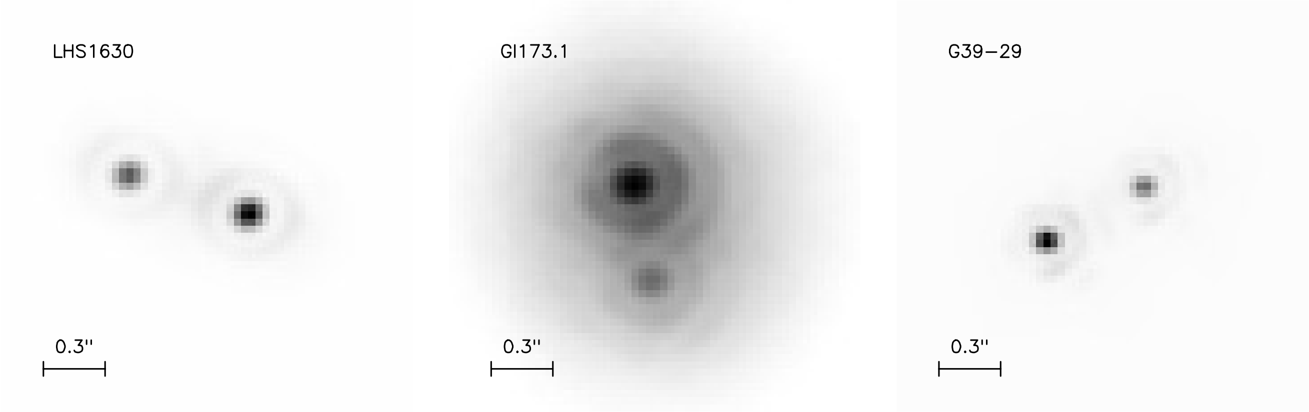

**Fig. 3.** Continuation of Fig. 2.

to GJ 2069B, GJ 2069C, with a *K*-band magnitude difference of 0.45 (Table 2 contains a better measurement on an additional date). Delfosse et al. (1999a) and Ségransan et al. (2000) determined masses with 0.2% precision for the two spectroscopic components of GJ 2069A, and suggest that the system is metal-rich by ~0.5 dex. We now find that adaptive optics images of the GJ 2069A spectroscopic pair additionally resolve a fainter companion, GJ 2069D, with $\Delta(K) = 3.2$ and $\rho = 0.68''$ in early 2000. The system is thus actually quintuple.

The extrapolated A–D luminosity contrast in the *V* band is $\Delta(V) = 4{-}5$, and detecting D in integrated visible spectra would therefore require a much better *S/N* ratio than what we have secured up to now. Eventually the gravitational pull of GJ 2069D will also cause a measurable drift in the systemic velocity of GJ 2069Aab. We have attempted to fit the velocities of Aa and Ab for this drift, in addition to the elements of the Aab orbit, but find that this does not significantly decrease the $\chi^2$ of the adjusted model. The indeterminacy of this drift indicates that the period of the Aab–D system is much longer than the present ~6-year span of our radial-velocity data, consistently with the period estimated from the separation. In the long run masses can be determined for all 5 components of the GJ 2069 system, and the radii for the two components of the eclipsing pair have been measured (Ribas 2003). The system will eventually provide an extremely tight test of low-mass theoretical isochrones.

### 3.1.4. G 165-8 (FIRST J133146.7+291637, LP 323-158, 1RXS J133146.9+291631)

With $v \sin i = 50$ km s$^{-1}$, G 165-8 is one of only three known M dwarf ultra-fast rotators ($v \sin i > 30$ km s$^{-1}$) within 10 pc (Delfosse et al. 1998a). As a consequence of this fast rotation it is magnetically very active, as illustrated by its figuring in the catalogues of both the FIRST radio and the ROSAT X-ray surveys. An adaptive optics image shows that it is a binary with $\Delta(K) = 0.16$ and a separation of $0.17''$ in early 2000. From this we infer a *V* band magnitude difference of $\Delta(V) = 0.25$, and correct the photometric parallax from the CNS3 value of $126 \pm 22$ mas to $95 \pm 20$ mas. G 165-8 therefore most likely does not truly belong to the 9.25 pc volume, but probably remains within 12 pc.

Of the two other ultra-fast rotators, Gl 791.2 also is a binary (Hershey 1978; Benedict et al. 2000) with a similar separation. The third ultra-fast rotator, G 188-38, has to date no detected companion. Its fast rotation would prevent the radial-velocity detection of any close companion, so that a link between fast rotation and the presence of a companion remains a possibility. The apparent correlation, however, could well represent no more than a fluke of small number statistics.

### 3.1.5. G 131–26 (LP 131–26, LTT 10045)

G 131-26, an M 4.5 flare star with X-ray and extreme-UV detections, was observed in August 2001 and found to have a close companion. We have no radial velocity information yet, but judging from the magnetic activity of the system the two stars are likely to be fast rotators. This would make them less than ideal for radial velocity follow-up, and an accurate mass determination would then require obtaining an astrometric orbit.

### 3.1.6. Gl 84 (LHS 149, HIP 9724)

Gl 84, an M 2.5 dwarf at ~10 pc, was identified as a ~15 year low amplitude single-lined spectroscopic binary by Nidever et al. (2002), who derived preliminary orbital elements. Our adaptive optics observations resolve the secondary at a ~4 AU projected separation, and the large contrast from the primary suggests that it is a late-M dwarf. An unreduced observation confirms the relatively rapid movement and the reasonable prospects for mass measurements.

### 3.1.7. LHS 1630 (LP 833-42)

This M 3.5 dwarfs nominally belongs to the 12 pc sample, but our detection of a fairly bright secondary pushes its photometric parallax somewhat beyond the distance limit.

**Table 1.** Systems with new low-mass companions in the solar neighbourhood. Spectral types are from Reid et al. (1995), except for Gl 173.1, Gl 416, Gl 120.1C, Gl 563.4, and Gl 609.2 which were taken from SIMBAD. They always refer to the combined light of the system. Parallaxes (in milliarcseconds) are taken from (*h*) the HIPPARCOS catalogue (ESA 1997), (*y*) the Yale parallax catalogue (van Altena et al. 1995), (*s*) Söderhjelm 1999, or are photometric parallaxes from (*g*) the CNS3 (Gliese & Jahreiss 1991) or (*r*) spectrophotometric parallaxes from Reid et al. (1995) that we approximately correct for the previously unrecognized multiplicity. Program codes are S9 and S12 for the 9.25 and 12 pc volume-limited surveys, C for the unpublished CORAVEL spectroscopic binaries, and L for the spectroscopic and astrometric binaries from the literature. A number of objects belong to multiple samples, and some targets from the nominally volume-limited samples have now been found to lie at larger distances.

| Name | Parallax (mas) | Spectral type | $m_V$ | Prog. |
|---|---|---|---|---|
| G 131–26 | 79 ± 14$^{(r)}$ | M 4.5 | 13.54 | S12 |
| LP 467–16 | 100 ± 20$^{(r)}$ | M 5 | 11.47 | S9 |
| Gl 84 | 105.94 ± 2.04$^{h}$ | M 2.5 | 10.19 | LS12 |
| Gl 120.1 | 38.87 ± 1.50$^{(h)}$ | K2 | 7.84 | L |
| LHS 1630 | 75 ± 25$^{r}$ | M 3.5 | 12.4 | S12 |
| Gl 173.1 | 35.21 ± 1.81$^{(h)}$ | K3 | 9.20 | C |
| G 39–29 | 84 ± 20$^{r}$ | M 4 | 12.53 | S12 |
| Gl 186 | 37.93 ± 5.00$^{h}$ | K5 | 8.28 | C |
| LHS 224 | 108.5 ± 2.1$^{(y)}$ | M 5 | 13.30 | S9 |
| Gl 263 | 64.96 ± 2.74$^{(h)}$ | M 3.5 | 10.95 | C |
| Gl 268.3 | 81.05 ± 2.42$^{(h)}$ | M 2.5 | 10.85 | L |
| Gl 277 | 87.15 ± 4.85$^{(h)}$ | M 2.5 | 10.52 | S12C |
| GJ 2069 | 78.05 ± 5.69$^{(h)}$ | M 3.5 | 11.89 | S9 |
| Gl 346 | 33 ± 10.0$^{(p)}$ | K7 | 9.70 | C |
| GJ 1138 | 102.9 ± 3.2$^{(y)}$ | M 4.5 | 13.02 | S12 |
| Gl 416 | 44.00 ± 1.93$^{(h)}$ | K4 | 9.05 | C |
| Gl 494 | 87.50 ± 1.51$^{(h)}$ | M 0.5 | 9.75 | LS12 |
| Gl 508 | 95.4 ± 1.6$^{(s)}$ | M 0.5 | 8.54 | S12C |
| G165–8 | 95 ± 20$^{(p)}$ | M 4 | 11.95 | S9 |
| Gl 533 | 47.95 ± 1.77$^{(h)}$ | K7 | 9.80 | C |
| Gl 563.4 | 42.26 ± 1.04$^{(h)}$ | F5 | 5.15 | L |
| Gl 588.1 | 34.28 ± 1.81$^{(h)}$ | K7 | 11.28 | C |
| Gl 609.2 | 45.56 ± 0.89$^{(h)}$ | G8 | 7.10 | L |
| Gl 782 | 63.82 ± 1.49$^{(h)}$ | K4 | 8.92 | C |
| Gl 852 | 99.6 ± 3.3$^{(y)}$ | M 5 | 14.4 | S12 |
| G 67–53 | 79 ± 25$^{(r)}$ | M 3.5 | 12.10 | S12 |
| LHS 4022 | 91 ± 27$^{(r)}$ | M 4 | 11.50 | S12 |

### 3.1.8. G 39–29 (LTT 11472)

The detection of a fairly bright secondary around this magnetically active M 4 dwarfs moves its photometric parallax to the 12 pc distance limit of our extended volume-limited sample.

### 3.1.9. Gl 277 (BD+36 1638, LDS 6206)

Gl 277A is an M 2.5 dwarf at a distance of 11.5 pc and forms a 40″ proper-motion pair with the fainter Gl 277B. It is listed in the CNS3 as a spectroscopic binary, presumably based on the 45 km s$^{-1}$ spread in eight M$^{t}$ Wilson radial velocities from the mid-40s (Abt 1970). 11 CORAVEL measurements evenly spread over 6000 days however do show long-term radial-velocity variations, but with an amplitude of only 4 km s$^{-1}$. With hindsight, the earlier report probably reflects underestimated measurement errors for this faint star, even though Gl 277A truly is a low-amplitude single-lined spectroscopic binary. Adaptive optics images in April 2000 resolve it into a 0.68″ pair with a $K$ band contrast of 2 mag. The likely orbital period is consistent with the spectroscopic lower bound.

### 3.1.10. Gl 508 (ADS 8862, Hu 644)

The Gl 508 AB pair is a well known long-period orbital binary ($P$ = 49 yr, $a$ = 1.5″), with an observational history that goes back to the beginning of the 20th century. Individual masses for the two visual components were first determined by Heintz (1969), and the system actually contributed two data points to the classic Henry & Mc Carthy (1993) Mass-Luminosity paper. The CNS3 catalogue however notes the primary as a possible spectroscopic binary, the Fourth Catalogue of Interferometric Measurements of Binary Stars (Hartkopf et al., on-line version[1]) similarly mentions tentative evidence for an additional faint component, and Söderhjelm (1999) remarks that the primary is overmassive. Gl 508 is indeed seen as a triple-lined spectroscopic system in many CORAVEL scans, and a preliminary orbit for the inner pair has $P$ = 450 days. Gl 508A is also obviously elongated in adaptive optics images obtained in April 2000, with an estimated contrast of $\Delta(K) \sim 0.4$ and a separation of approximately 0.1″. It is now clear that Gl 508 must be analysed as a triple system. Given the wealth of existing visual data for the long-period orbit, the system offers excellent prospects of shortly determining all three masses.

### 3.1.11. GJ 1138 (LHS 293, G119-36)

GJ 1138 is a previously rather anonymous M4.5V member of the close solar neighbourhood, at a distance of ~10 pc. April 2000 adaptive optics images turn out to resolve it into a 0.30″ pair with a $K$ band contrast of 2 mag. An unreduced measurement in 2001 demonstrates a rapid movement, and confirms the excellent prospects for shortly obtaining two accurate masses.

### 3.1.12. Gl 852 (LDS 782, LHS 3787/3788, Wolf 1561)

The Gl 852 system, up to now known as a 7″ M 4 + M 5 pair, actually turns out to be at least triple. Adaptive optics observations resolve the B component into a 1″ pair. With a near-IR contrast of only 1 mag, the new component can most likely be detected in uncorrected CCD images under good seeing. Like many of the systems where we detect new components, the system is magnetically very active. This probably indicates a relatively young age, since all identified orbital periods are much too long for tidal synchronisation.

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[1] `http://www.chara.gsu.edu/CHARA/DoubleStars/Speckle/intro.html`

**Table 2.** Adaptive optics measurement of the new low-mass companions. Gl 268.3 was observed with the Keck adaptive optics system. All other observations were obtained at CFHT with the PUEO adaptive optics system. Periods listed within parentheses are estimated from the observed separation, the distance to the system and its approximate mass. They are uncertain by a factor of approximately 3. 0.5 dex.

| Name | $\rho$<br>″ | $\theta$<br>deg | $\Delta m$ | Date | Filt. | Period<br>(yr) | Accurate mass<br>prospects |
|---|---|---|---|---|---|---|---|
| G 131–26AB | 0.111 | 169.9 | 0.46 | 07 Aug. 2001 | *H* | (4) | Excellent |
| LP 467–16AB | 0.409 | 147.2 | 0.69 | 16 Aug. 2000 | *K* | (20) | Fair |
| Gl 84 | 0.39 | 101 | 3.59 | 23 Jul. 2002 | *H* | (15) | Fair |
| Gl 120.1CD | 0.083 | 170.1 | 0.02 | 15 Aug. 2000 | *H* | 1.54 | Mediocre |
| LHS 1630 | 0.61 | 72 | 0.34 | 18 Sep. 2002 | *K* | (50) | Poor |
| Gl 173.1AabC | 0.474 | 188.0 | 1.91 | 05 Mar. 1999 | *K* | (80) | Poor |
| G 39–29 | 0.54 | 299 | 0.42 | 13 Sep. 2002 | *K* | (35) | Mediocre |
| Gl 186 | 0.31 | 298 | 2.00 | 19-Sep. 2002 | *K* | (40) | Mediocre |
| LHS 224AB | 0.163 | 344.7 | 0.14 | 18 Apr. 2000 | *K* | 3.19 | Good |
| Gl 263AB | 0.110 | 287.4 | 0.46 | 26 Feb. 1999 | *H* | 3.62 | Excellent |
| Gl 268.3AB | 0.054 | 153.6 | 0.57 | 25 Feb. 2000 | *H* | 0.834 | Excellent |
| Gl 277AC | 0.684 | 195.0 | 2.02 | 20 Apr. 2000 | *K* | (35) | Mediocre |
| GJ 2069AD | 0.682 | 158.0 | 3.20 | 18 Feb. 2000 | *K* | (40) | Fair |
| GJ 2069BC | 0.549 | 219.1 | 0.52 | 18 Feb. 2000 | *K* | (30) | Fair |
| Gl 346AB | 0.431 | 101.0 | 0.80 | 04 Apr. 1999 | *H* | (60) | Poor |
| GJ 1138AB | 0.303 | 56.1 | 1.89 | 20 Apr. 2000 | *K* | (10) | Good |
| Gl 416AB | 0.138 | 85.0 | 1.05 | 19 Feb. 2000 | *K* | 7.33 | Good |
| Gl 494AB | 0.475 | 81.5 | 4.41 | 19 Feb. 2000 | *K* | 14.5 | Good |
| Gl 508AC | 0.092 | 281.7 | 0.43 | 20 Apr. 2000 | *K* | 1.22 | Good |
| Gl 508AB | 0.579 | 102.0 | 0.29 | 20 Apr. 2000 | *K* | 49 | Fair |
| G165–8AB | 0.174 | 253.3 | 0.16 | 19 Feb. 2000 | *K* | (7) | Good |
| Gl 533AB | 0.230 | 352.8 | 2.02 | 04 Apr. 1999 | *H* | 7.36 | Fair |
| Gl 563.4AB | 0.383 | 139.0 | 3.40 | 26 Feb. 1999 | *H* | 16.07 | Fair |
| Gl 588.1AB | 0.408 | 109.6 | 0.97 | 04 Apr. 1999 | *K* | (60) | Poor |
| Gl 609.2AB | 0.220 | 287.0 | 2.04 | 04 Apr. 1999 | *H* | 12.15 | Good |
| Gl 782AB | 0.991 | 74.5 | 3.26 | 03 Jul. 2001 | *K* | (100) | Poor |
| Gl 852BC | 0.978 | 305.8 | 1.18 | 07 Aug. 2001 | *K* | (70) | Poor |
| G 67–53AB | 0.142 | 209.0 | 1.17 | 05 Aug. 2001 | *J* | (5) | Excellent |
| LHS 4022AB | 1.527 | 74.3 | 1.43 | 05 Aug. 2001 | *H* | (150) | Poor |

#### 3.1.13. G 67–53 (G 68–5, LTT 16843)

G 67–53, an M 3.5 UV Cet variable and a flare star, is also magnetically active. It is resolved into a close pair, with one of the shortest estimated periods amongst the new detections. Its magnetic activity will most likely hinder precise radial velocity measurements, but astrometric observations will be able to produce very precise masses.

#### 3.1.14. LHS 4022 (G 30–23, LTT 17025)

At a separation of over 1.5″, LHS 4022 is the widest of the new detections, and within easy reach of visual and CCD observers. We have not yet established the common proper motion of the two stars, but the absence of any other object in the 36″ field of view makes their physical association very likely.

### *3.2. New binaries from CORAVEL samples*

#### 3.2.1. Gl 173.1 (HD 286955, HIP 21710)

The K3-dwarf Gl 173.1A forms a 34″ common proper motion pair with the M3-dwarf Gl 173.1B. CORAVEL observations show that A is a single-lined spectroscopic binary with a 610-day period. A March 1999 adaptive optics image also resolves it into a 0.47″ pair with $\Delta(K) = 1.9$. At the 28 pc distance of the system, the semi-major axis of a one solar mass system with the 610 days spectroscopic period is 0.05″, well below the observed separation. The spectroscopic (Gl 173.1Ab) and adaptive optics Gl 173.1C) companions of Gl 173.1Aa are therefore different objects, and the Gl 173.1 system is at least quadruple. The expected period of the AC pair is of the order of a century, making it of limited interest for mass determinations. The spectroscopic pair could perhaps be resolved by adaptive optics systems on 8 m-class telescopes, but it may need long-baseline interferometric observations if its contrast is large.

#### 3.2.2. Gl 186 (HIP 23516, SAO 170021)

7 CORAVEL radial velocities show that GL 186 is a low amplitude and long period spectroscopic binary, but they do not cover a full orbital period. The period estimated from the separation of the resolved companion, ~40 years, is compatible with the lower limit on the spectroscopic period and the two most likely coincide.

#### 3.2.3. Gl 263 (LHS 1895, HIC 34104)

28 CORAVEL radial velocities demonstrate that Gl 263 is an eccentric double-lined spectroscopic binary, with a well determined period of 1313 days (3.6 years) and a periastron on JD 2 449 171. The other orbital elements on the other hand remain poorly constrained, because observations are lacking around the critical periastron phase. Adaptive optics images obtained in February 1999 resolve it into a $0.11''$ pair with a 0.45 mag contrast in the $K$ band. This M3.5V system already provides two preliminary masses of 0.45 and 0.40, which will become excellent with better radial velocity coverage around the periastron.

#### 3.2.4. Gl 346 (BD−08 2689)

21 CORAVEL radial velocities demonstrate that Gl 346 is an eccentric long-period spectroscopic binary, but they fall short of covering one orbital period ($P > 14$ yr). An April 1999 adaptive optics image resolves the K7V system into a $0.43''$ pair with a $K$ band contrast of 0.8 mag. From this we estimate a $V$ band contrast of ~1.2, and as a result correct the 40 ± 10 mas spectro-photometric parallax (Reid et al. 1995) to 33 ± 10 mas.This nominally pushes Gl 346 beyond the 25 pc limit of the successive Gliese catalogues.

#### 3.2.5. Gl 416 (HD 97233, LHS 2370, HIC 54677)

37 CORAVEL radial velocity measurements determine an accurate 2670-day (7.3-yr) period for this new K4V spectroscopic binary, but never separate the two components. A February 2000 adaptive optics image resolves the system into a $0.14''$ pair with a $K$ band contrast of 1 mag, from which we estimate $\Delta(V) \sim 1.5$ mag. This is small enough that neglecting the secondary light biases the single-lined orbital elements, which we therefore refrain from presenting. Modern spectrographs will easily detect the two components at the next periastron in early 2005, and it will then produce two accurate masses.

#### 3.2.6. Gl 533 (HIP 67808, LHS 2821, BD+13 2721)

27 CORAVEL observations determine a fairly good 7.3 yr single-lined orbit for this new K7V system, even though the phase coverage around periastron is still somewhat sparse. An April 1999 $H$ band adaptive optics image resolves the system into a $0.23''$ pair with $\Delta(H) = 2.0$. The extrapolated contrast in the $V$ band (~3 mag) is sufficiently large that any systematic error stemming from the neglected secondary light are well below our current random errors on the orbital elements. Spectral lines from the secondary can probably be detected at the maximum radial-velocity separation ($\sim 15$ km s$^{-1}$) though, and the system would then offer excellent prospects for accurate mass measurements.

#### 3.2.7. Gl 588.1 (HIP 76202, AC +38 34548)

CORAVEL observations show that this K7V system is an eccentric single-lined spectroscopic binary, but they have yet to cover one orbital period ($P > 15$ yr). An adaptive optics image in April 1999 resolves the system into a $0.41''$ pair with $\Delta(K) = 1.0$. The expected period is consistent with the spectroscopic lower bound, strongly suggesting that the same companion was detected.

#### 3.2.8. Gl 782 (HIP 99385, HD 191391, LHS 3526)

CORAVEL observations show that the radial velocity of this well known K4 dwarf drifts by ~3 km s$^{-1}$ over 15 years. An adaptive optics image in July 2001 resolves the system into a $1''$ pair with $\Delta(K) = 3.2$. The current angular separation and the parallax indicate a very long period, consistent with the spectroscopic lower bound.

### *3.3. Newly resolved spectroscopic and astrometric binaries*

#### 3.3.1. Gl 120.1 (HIP 13769, HD 18445 C)

The Gl 120.1 system associates Gl 120.1AB, a $P \sim 150$ yrs visual pair of K1/K2 dwarfs, with Gl 120.1C, a K2 dwarf, at a projected distance of $\sim 30''$. Duquennoy & Mayor (1991) found the C component to be a spectroscopic binary and derived a 1.5-yr single-lined orbit. The minimum mass of the secondary, for this orbit, is $M_2 \times \sin i = 0.042\, M_\odot$ and well below the limit for stable hydrogen nuclear burning. Gl 120.1C therefore contributes to the statistical excess of such companions that Duquennoy & Mayor (1991) found over the numbers expected for distributions of companion masses that include no brown dwarfs. As such it has been discussed in a number of the papers (e.g. Mazeh 1987; Heacox 1999) which examine the significance of the apparent dearth of close brown-dwarf companions around solar-type stars (the "brown dwarf desert"), compared with the larger number of stellar and planetary companion detections.

Halbwachs et al. (2000) recently obtained an astrometric orbit from the HIPPARCOS intermediate data, which demonstrates that the pair is in fact fairly close to face-on, with $\sin i \sim 0.25$. Using the Duquennoy & Mayor (1991) radial-velocity amplitude, they derive a mass of $0.18\ M_\odot$ for the spectroscopic companion. This is well over the maximum mass of a brown dwarf, but still only one quarter of the primary mass.

From Mass-Luminosity relations (e.g. Delfosse et al. 2000) such a star is over three magnitudes fainter in the near-IR than a K2 dwarf. It was therefore a surprise when adaptive optics images resolved the system with approximately the expected separation, but showed that it has a very low contrast (Fig. 2). Because the pair is not completely separated in Fig. 2, the (zero) magnitude difference in Table 2 is slightly correlated with the measured separation. Any contrast above ~0.3 mag would however produce images that are very obviously incompatible with the observation. The Gl 120.1CD pair therefore consists of a pair of early K dwarfs, rather than of a K dwarf and a mid/late M dwarf. With this additional information, it is now clear that Gl 120.1C is not a true single-lined system: the Duquennoy & Mayor (1991) orbit actually underestimates the actual velocity amplitude of the primary, because both components of this low-inclination system contribute a significant fraction of its integrated light, and yet they are never perceptibly separated at the $R \sim 28\,000$ resolution of the CORAVEL instruments. It therefore doesn't truly belong to a sample of single-lined systems with minimum companion masses in the brown-dwarf range. Its removal obviously weakens the statistical significance of an excess of such companions, which to date represents most of the possible evidence for a population continuity across the "brown-dwarf desert". One should note in addition that Halbwachs et al. (2003) exclude a continuity between stellar and planetary companions to solar-type stars, through an analysis of a sample that includes the Duquennoy & Mayor (1991) objects but benefits from additional CORAVEL observations and from a larger and cleaner sample. The case for a population in the "brown-dwarf desert" would be further weakened if the Duquennoy & Mayor (1991) sample and its Halbwachs et al. (2003) update turned out to still contain a small number of unrecognized double-lined systems, as could conceivably be the case. We are currently obtaining data with the ELODIE and CORALIE spectrographs to settle this issue.

### 3.3.2. Gl 268.3 (HIP 35191, BD +27 1348)

Gl 268.3 was found to be a 304-day double-lined spectroscopic binary by Delfosse et al. (1999b). They also presented marginally resolved CFHT adaptive optics images but could not determine quantitative parameters. The pair is well resolved in a February 2000 Keck adaptive optics image, with $\Delta(H) = 0.57$, $\rho = 0.054''$ and $\theta = 123.5$ deg. Preliminary masses of 0.49 and 0.33 solar masses can be derived from the presently available data, and a few additional adaptive optics observations should pinpoint them with excellent accuracy.

### 3.3.3. Gl 494 (DT Vir, LHS 2665, HIP 63510, BD+13 2618)

Gl 494A is a magnetically very active M0.5 dwarf, as a result of its fast rotation ($v \sin i = 9.6$ km s$^{-1}$, determined with ELODIE). It is not a tidally-locked short-period binary, and the age–rotation relation therefore implies that it is fairly young, most likely younger than 1 Gyr. Heintz (1990, 1994) obtained a convincing 14.5-yr astrometric orbit for Gl 494, which established that the M0.5V primary has a much lower-mass companion. 26 CORAVEL radial-velocity measurements show $\pm 1.5$ km s$^{-1}$ variations at approximately this orbital period, and therefore validate the astrometric detection. Heintz asserted the companion to be substellar, based however on an estimated mass of 0.4 $M_\odot$ for an M2V primary. Gl 494A has since been reclassified as M0.5V (Reid et al. 1995), so that 0.6 $M_\odot$ is now a more appropriate guess for its mass. This rescaling brings the Heintz companion mass close to the substellar limit.

Henry et al. (1999) did not detect the companion in either of two *HST* observations with FGS3 used in TRANS mode. At the ~0.4″ separation, expected from the astrometric orbit and an estimated 0.6 $M_\odot$ mass for the M0.5V primary, this implies a $V$ band contrast of at least 3.5 mag and confirms that the companion is indeed rather faint. $K$ band adaptive optics images in February 2000 resolve the system into a 0.48″ pair, with $\Delta(K) = 4.4$. With $M_K = 9.7$, its spectral type is approximately M7V (Leggett 1992). The extrapolated contrast in the $V$ band is very large, and does explain why the FGS observations could not detect the companion. It should on the other hand be within reach of *HST* imaging observations.

From the orbital elements of the astrometric orbit of Heinz (1994) and the observed separation in April 1999, we can in principle determine a scale factor between the astrometric and relative orbits of 10.8. From this a semi-major axis of 0.55″ immediately follows for the relative orbit. Together with the HIPPARCOS parallax this results in a system mass of 1.19 $M_\odot$, which the scale factor then splits into 1.08 $M_\odot$ for the M0.5V primary and 0.11 $M_\odot$ for the faint secondary. The elements of the Heintz (1994) astrometric orbit are quoted without standard errors, so that we are not in a position to evaluate precise confidence intervals. Still, 1.08 $M_\odot$ cannot possibly be the mass of a single M 0.5 dwarf, and we also note an 80 degrees discrepancy for the predicted position angle. We therefore suspect that either the actual confidence intervals are so wide as to be of little use, or perhaps there is a problem in the Heintz elements, for instance because they force a circular orbit for a system which may have some small eccentricity.

For the time being we therefore prefer to turn to its absolute magnitude to evaluate the position of the secondary relative to the substellar limit. From the Baraffe et al. (1998) models, an object of $M_K = 9.7$ has to be younger than 300 Myr to be a brown dwarf. If it has instead reached the main sequence, its mass for the same models would be 0.09 $M_\odot$. The age range that can be inferred from the characteristics of its primary is at present insufficiently constrained to presently ascertain whether Gl 494B is a brown dwarf or a star, but whatever its status it will clearly play an important role in characterizing the substellar transition. Together with the Gl 569 (Martín et al. 2000) and GJ 2005 (Leinert et al. 1994) systems, Gl 494 contains one of the faintest known objects for which dynamical masses can be obtained on realistic timescales. Continued observations with adaptive optics, astrometric satellites, and radial-velocity spectrographs, have together the potential to determine its mass from first principles and with excellent accuracy.

### 3.3.4. Gl 563.4 ($\alpha$1 Lib, FK5 1387, HIP 72603, HD 130819)

Gl563.4, a $V = 5.1$ F3 dwarf, forms a common proper motion system with the brighter ($V = 2.8$) A3-dwarf Gl 564.1. The Hipparcos proper motions of the two stars are mildly discrepant ((−0.136, −0.059) vs. (−0.106, −0.069)), but at a level that is consistent with the orbital motion of the Gl 563.4 photocenter over the Hipparcos mission. Duquennoy & Mayor (1991) found it to be a single-lined spectroscopic binary and derived a preliminary orbit. With additional CORAVEL measurements obtained since 1991, the orbit is now definitive and has $P = 5870$ days. Adaptive optics images obtained in February 1999 resolve Gl 563.4 into a 0.38″ pair, with $\Delta(H) = 3.4$. It most likely coincides with the spectroscopic system and offers good prospects of determining reasonably accurate masses.

### 3.3.5. Gl 609.2 (HD 144287, HIP 78709, BD+25 3020)

Duquennoy & Mayor (1991) found Gl 609.2, a G8 dwarf, to be a spectroscopic binary and determined a 12-yr single-lined spectroscopic orbit. Multiple speckle observations with large telescopes failed to resolve this pair (Bonneau et al. 1986; Mason et al. 1999), in retrospect because of its large contrast in visible bands. Adaptive optics images obtained in april 1999 easily resolve the system into a 0.21″ pair, but with a $\Delta(H) = 2.2$ infrared contrast. This translates into values for visible bands that are somewhat beyond the typical dynamic range of speckle observations. The Gl 609.2 system will provide accurate masses if spectral lines from the faint secundary can be detected, as might be possible with improved analysis tools (e.g. Zucker et al. 2003).

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