A&A 417, 1031–1038 (2004)
DOI: 10.1051/0004-6361:20040008

Astronomy & Astrophysics

HD 77407 and GJ 577: Two new young stellar binaries

Detected with the Calar Alto Adaptive Optics system ALFA

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Received 16 May 2003 / Accepted 8 December 2003

Abstract. We present the first results from our search for close stellar and sub-stellar companions to young nearby stars on the northern sky. Our infrared imaging observations are obtained with the 3.5 m Calar Alto telescope and the AO system ALFA. With two epoch observations which were separated by about one year, we found two co-moving companion candidates, one close to HD 77407 and one close to GJ 577. For the companion candidate near GJ 577, we obtained an optical spectrum showing spectral type M 4.5; this candidate is a bound low-mass stellar companion confirmed by both proper motion and spectroscopy. We estimate the masses for HD 77407 B and GJ 577 B to be ∼0.3 to 0.5 $M_\odot$ and ∼0.16 to 0.2 $M_\odot$, respectively. Compared to Siess et al. (2000) models, each of the two pairs appears co-eval with HD 77407 A, B being 10 to 40 Myrs and GJ 577 A, B being ≥100 Myrs old. We also took multi-epoch high-resolution spectra of HD 77407 to search for sub-stellar companions, but did not find any with 3 $M_{\rm Jup}$ as upper mass ($m \sin i$) limit (for up to 4 year orbits); however, we detected a long-term radial velocity trend in HD 77407 A, consistent with a ∼0.3 $M_\odot$ companion at ∼50 AU separation, i.e. the one detected by the imaging. Hence, HD 77407 B is confirmed to be a bound companion to HD 77407 A. We also present limits for undetected, but detectable companions using a deep image of HD 77407 A and B, also observed with the Keck NIRC2 AO system; any brown dwarfs were detectable outside of 0.5 arcsec (17 AU at HD 77407), giant planets with masses from ∼6.5 to 12 $M_{\rm Jup}$ were detectable at ≥1.5 arcsec.

Key words. stars: low mass, brown dwarfs – stars: binaries: general

1. Introduction

Most nearby stars are quite old, so that close sub-stellar companions are too faint to be detected directly. If we consider young stars, their companions are also young and therefore self-luminous due to accretion and contraction, see e.g. Wuchterl & Tscharnuter (2003), who consider objects even younger than in our observations; other teams (e.g. Baraffe et al. 1998; Burrows et al. 1997) also show quantitatively how sub-stellar objects get fainter when they get older. However they use arbitrary initial conditions, so that their models should not be used for objects younger than ∼10 Myrs (Baraffe et al. 2002). If such young companions are also nearby, they should be well separated from their primaries. Hence, young nearby stars are most suitable for direct imaging of sub-stellar companions, see e.g. Jayawardhana & Greene (2001) for a comprehensive overview. There are ∼200 stars known with ages from ∼1 to 100 Myrs within ∼100 pc (e.g. Montes et al. 2001b; Wichmann et al. 2003), about one third of them being in the northern sky. Most of our targets still show lithium absorption and/or Ca II, H and K emission; some of them also show Hα, and/or are classified as members of young associations by Montes et al. (2001b).

The direct detection of close sub-stellar companions is currently less difficult in the near infrared, because in these wavelengths the brightness difference between companion and primary star is low and detectors work well; in the thermal infrared, the brightness difference is even lower, but the detectors

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are not yet as sensitive as in *JHK*. Nevertheless these close companions are much fainter than their host star. The application of an adaptive optics system increases the resolution to the diffraction limit and advances the dynamic range so that the detection of these faint objects becomes feasible.

The determination of the spectral type and hence companionship of faint companion candidates using *JHK* colors is difficult, because such objects are too faint and located in the PSF wing of their host star, so that colors cannot be measured well. To solve simultaneously both extinction and spectral type, three-band imaging would be indispensable. Nevertheless one needs a further observation to confirm the proper motion of a possible companion. Finally four images are necessary which makes such a photometric search inefficient. On the other hand, an astrometric survey (in one band) only needs two observations (1st and 2nd epoch), i.e. allows one to study many more targets with a minimum of observation time.

Most of the nearby stars have high proper motion and therefore they are well suited for an astrometrical survey. In this technique each star with at least one faint object nearby is observed in two epochs. Companion and primary star show the same motion relative to non-moving background stars. The proper motion of our target stars is high enough so that an epoch difference of one year is sufficient in most cases to find co-moving companions.

For a co-moving companion (candidate), spectroscopic confirmation is always necessary, either by taking a spectrum of the companion (showing its late spectral type) and/or by taking spectra of the primary (showing its secular acceleration due to the companion). We are searching for sub-stellar companions also on the southern sky, with speckle and normal imaging at the ESO NTT, and now also with AO (NAOS-CONICA at the ESO VLT). Four sub-stellar companions to young (nearby) stars have been confirmed by both proper motion and spectroscopy: The ∼12 Myrs young TWA-5 B (Lowrance et al. 1999; Neuhäuser et al. 2000), the ∼300 Myrs old Gl 569 B, C (Martín et al. 2000; Lane et al. 2001), the ∼35 Myrs young HR 7239 B (Lowrance et al. 2000; Guenther et al. 2001), and the ∼300 Myrs old HD 130948 B, C (Potter et al. 2002; Goto et al. 2002).

Here, we present some first results from our ongoing imaging program at the Calar Alto observatory. We present the instrument and data reduction in Sect. 2, the astrometric results in Sect. 3, photometry in Sect. 4, and spectroscopy in Sects. 5 and 6. Finally, in Sect. 7, we present the H-R diagram to determine masses and ages of the new companions and discuss our results.

2. Imaging observations and data reduction

The observations were done in the *H*-band (1.6 μm) using the 3.5 m telescope on Calar Alto observatory in Spain. The telescope was equipped with the adaptive optics system ALFA (for Adaptive optics with a Laser guide star For Astronomy, Glindemann et al. 2000), used here without laser guide star. The IR detector used was Ω-Cass, a 1024 × 1024 HgTeCd-detector with a pixel resolution of 0.077″ per pixel. As individual integration time, we used 0.842 s, i.e. as short as possible in order to avoid saturation on the bright primary stars. In order to reach a high sensitivity (i.e. limiting magnitude for faint companions), the total integration time was almost 20 min. Therefore, many short integrated images had to be superimposed.

The jitter technique was used to take into account the high IR sky background and to observe both sky and target star in each frame. After sky subtraction, each image was flat fielded with a mean sky flat image, created out of several sky images taken in twilight. Finally all reduced images were shifted and combined to the result frame.

Up to now we have observed ∼80 stars out of our northern sample of ∼100 stars at least once. We observed 12 stars with companion candidates in two different epochs. 22 more stars with at least one faint object nearby still require a 2nd epoch image. In the following, we will present two companions found among these 12 stars observed twice. The remaining data will be presented later elsewhere.

In addition to Calar Alto, we have also observed a few stars with the Keck 2 telescope on Mauna Kea, Hawai'i. We observed HD 77407 on 28 Feb. 2002 using the Keck 2 telescope with NIRC2 and AO using an *H*-band filter and the 400 mas diameter coronograph. NIRC2 has a pixel scale of 9.942 ± 0.500 mas/pixel (NIRC2 team, Campbell, priv. comm.). The total integration time for the observations of HD 77407 was almost 7 min (23×(100×0.182 s)). We performed the data reduction using the reduction software MIDAS provided by ESO for flat fielding, background subtraction, and adding of the images.

The 400 mas coronograph has a throughput of about ∼0.1% determined by us by comparing the companion HD 77407 B outside the coronograph with the primary star A located behind the coronograph. Note that we use the 400 mas coronograph, different from the 300 mas coronograph used by König et al. (2002) for another observation obtained in the same night.

Table 1. Pixel scale and image orientation of Omega-Cass for the different observing runs. North is shifted by the orientation angle given below from the top of the image to right.

Epoch	Pixel scale [mas]	Orientation
01 Nov. 2001	77.40 ± 0.20	11.80 ± 0.30°
26 Apr. 2002	77.60 ± 0.30	22.27 ± 0.05°
23 Dec. 2002	77.46 ± 0.05	18.60 ± 0.10°

3. Astrometric results

The first step in the astrometric analysis of the images is the measurement of the pixel scale and the orientation of the images. In order to determine these important values, we need to observe visual binary stars with well-known separations and orientations (position angles), e.g. from Hipparcos, namely HD 79210, HD 82159, HD 108574, HD 112733, HD 218738, HIP 63322. The result of the calibration for the different epochs is shown in Table 1.

The second step is the position measurement of the target star and all faint objects in the images, all of which may be regarded as companion candidates. The position measurement is done with ESO-MIDAS using Gaussian centering.

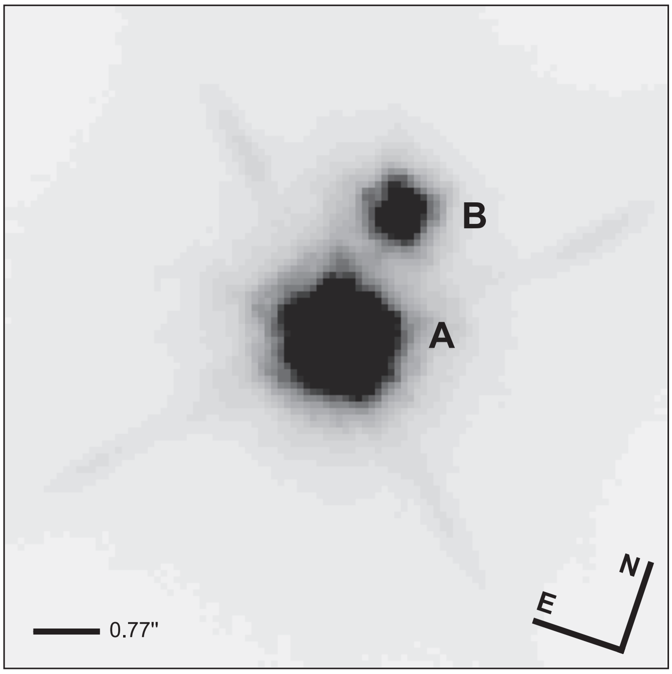

Fig. 1. HD 77407: H-band image taken in epoch Dec. 2002 with the 3.5 m Calar Alto + ALFA + Ω-Cass with a total integration time of 16.5 min.

We have observed 12 stars with companion candidates twice, i.e. at two different epochs separated by about one year (see below for details). In the case that a companion candidate is a non-moving background object, we should see only the (known and fast) motion of the star, i.e. the separation changes from 1st to 2nd epoch. This motion includes the proper motion and the parallactic motion. Moreover, for close companions, orbital motion may be detectable. If the separations measured in 1st and 2nd epoch in both right ascension and declination are identical (within the errors and taken into account possible orbital motion), then a faint object can be regarded as co-moving companion – unless the proper motion of the primary star is too slow: the motion of the primary star between the two images (according to its proper motion and the epoch difference) should be significantly larger than the astrometric precision achieved, in order to obtain significant astrometric results. A follow-up spectrum is always useful to confirm the companionship.

3.1. HD 77407

We have included HD 77407 in our sample of young nearby stars after the Cool Stars Workshop in 1999 on Tenerife, where it was listed as a young star in the poster by Wichmann & Schmitt (2001), see also Montes et al. (2001a) and Wichmann et al. (2003). In our own optical spectrum (see Sect. 6) we measure EW(Li) = 170 mÅ i.e. the star is clearly young.

HD 77407 is located at a distance of 30.1 ± 0.8 pc. The proper motion of this star is −86.26 ± 1.24 mas in right ascension and −168.79 ± 0.59 mas in declination.

The ALFA image is shown in Fig. 1. There is a close object (B) north of the primary target star (A) at a separation of only 1.689 ± 0.005″ with a position angle of 353.7 ± 0.5°. The star was observed in epoch Nov. 2001 and Dec. 2002. The separation between B and A for the two epochs is shown in Table 2.

Table 2. Separation between HD 77407 A and B.

Epoch	RA [arcsec]	Dec [arcsec]
Nov. 2001	0.197 ± 0.009	−1.644 ± 0.005
Dec. 2002	0.174 ± 0.004	−1.680 ± 0.002

Table 3. Relative motion between HD 77407 A and B.

	RA [arcsec]	Dec [arcsec]
Result of astrometry (observed)	−0.023 ± 0.010	−0.034 ± 0.005
If B is non-moving (calculated)	−0.109	−0.180

If this candidate is a non-moving background star, we should see only the proper and parallactic motion of the star between the two observing epochs. This motion can be calculated using Hipparcos data. Table 3 shows the measured relative motion between the star and the companion candidate which can be computed with the values from Table 2. The relative motion between the star and its companion candidate – as observed – is significantly smaller than expected for a non-moving background star. Therefore, it appears likely that object B is a real companion of HD 77407. We do not include the Keck image in this analysis, because it has a different pixel scale. Precise relative astrometry should be done only by using the same telescope and instrument.

There is some relative motion between the two objects larger than 5 σ in declination. How can we explain this? A separation of 1.689 ± 0.005″ corresponds to a projected separation of 50 ± 2 AU at a distance of 30.1 ± 0.8 pc. We assume the mass of the barycenter to be ~1 $M_{\odot}$ (this is reasonable because the primary has spectral type G0 and lies in an H-R diagram close to the main sequence). Using Keplers's third law, we can estimate the orbital motion of the companion. The predicted separation is 31.5 mas at the second epoch observations. This is consistent with the observed relative motion between HD 77407 A and B (41 ± 11 mas, Table 3). According to Fig. 2, we can clearly distinguish between a non-moving background object and a co-moving companion (allowing for orbital motion). Hence, the pair appears to be bound and we see first hints for orbital motion.

3.2. GJ 577

GJ 577 is included in our sample since 2001, because it is listed as young star in Montes et al. (2001a,b).

GJ 577 is located at a distance of 44.3 ± 1.3 pc. Its proper motion is −121.47 ± 0.73 mas in right ascension and 112.21 ± 0.63 mas in declination. The ALFA image is shown in Fig. 3. There is an object (B) to the west of the star (A) in a separation of 5.39 ± 0.02″ with a position angle of 260.9 ± 0.2°.

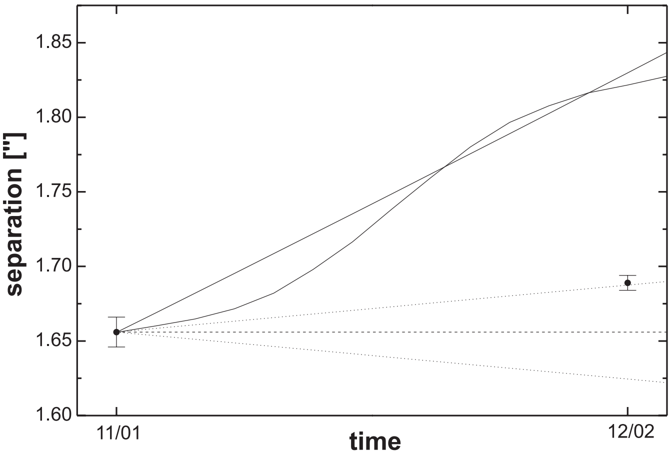

Fig. 2. Separation of HD 77407B from its host star at the two observations. The straight solid line is the expected separation if B is a non-moving background star; the curved solid line takes into account parallactic motion of the primary. The dotted line (±the calculated orbital motion of B) is expected for a co-moving companion. The 2nd epoch observation is 27σ deviant from the background hypothesis and fully consistent with being a co-moving companion.

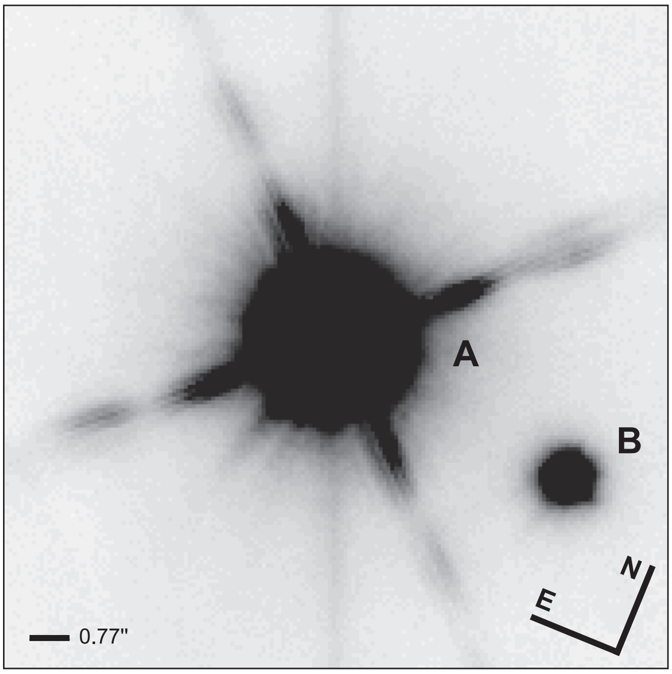

Fig. 3. GJ 577: H-band image taken in epoch April 2002 with the 3.5 m Calar Alto + ALFA + Ω-Cass with a total integration time of 17.9 min.

The star was observed in epoch April and Dec. 2002. The separation between B and GJ 577 is shown in Table 4. We can again calculate the relative motion between the star and its companion candidate. With the Hipparcos data, we determine the motion of the star between the two epochs. The results are shown in Table 5. The computed relative motion for a non-moving background star is listed below. In both axis the relative motion between the two objects is negligible if we consider the uncertainty in the astrometry. In declination the observed relative movement is 10 times smaller as the value expected for a non-moving background object. Therefore, we can conclude that object B is a companion of GJ 577. A separation of 5.39″ (at 44.3 ± 1.3 pc) corresponds to a semi-major axis of 239 ± 7 AU. Therefore, the orbital motion of the companion can be calculated with the third Kepler law. We again assume a mass of barycenter of 1 $M_{\odot}$ because the primary has a spectral type G5 and lies close to the main sequence in an H-R diagram. We then expect an orbital motion of about 7 mas within the time passed between the first and second observation in April and December 2002. The prediction is consistent with the measured orbital motion of the primary and secondary, see Fig. 4.

Table 4. Separation between GJ 577 A and B.

Epoch	RA [arcsec]	Dec [arcsec]
April 2002	5.332 ± 0.018	0.865 ± 0.012
Dec. 2002	5.325 ± 0.003	0.836 ± 0.009

Table 5. Relative motion between GJ 577 A and B.

	RA [arcsec]	Dec [arcsec]
Result of astrometry (observed)	−0.007 ± 0.018	−0.029 ± 0.015
If B is non-moving (calculated)	−0.071	0.036

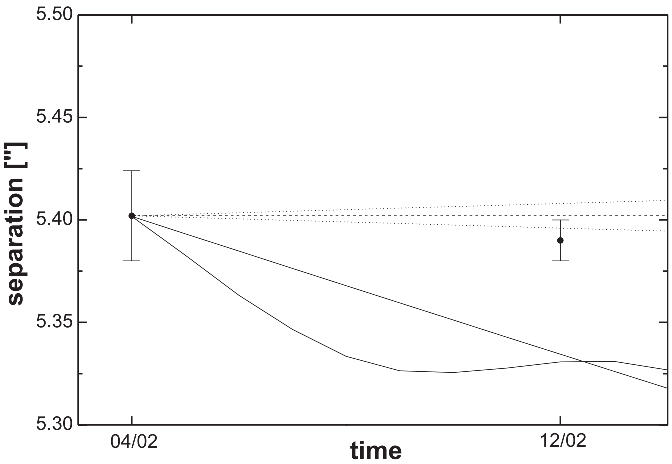

Fig. 4. Separation of GJ 577 B from its host star at the two observations. The straight solid line is the expected separation if B is a non-moving background star; the curved solid line takes into account parallactic motion of the primary. The dotted line (±orbital motion as expected) is expected, if B is co-moving with A.

4. Photometry

Due to the small field of view of an adaptive optical system, it is not possible to find many 2MASS reference stars for relative photometry. Therefore we determine the magnitude difference between the star and the companion. With the H-band magnitude for star A as published in 2MASS, and having assured that the primary stars are not saturated in our images, we can derive the H-band magnitude of the companions. The results are shown in Table 6.

Table 6. Photometry of HD 77407 A, B and GJ 577 A, B apparent magnitudes (from 2MASS for the primaries A, from our images for the companions B by differential photometry).

Name	m_H(A)	m_H(B)
HD 77407	5.54 ± 0.03	7.68 ± 0.07
GJ 577	6.89 ± 0.02	10.84 ± 0.05

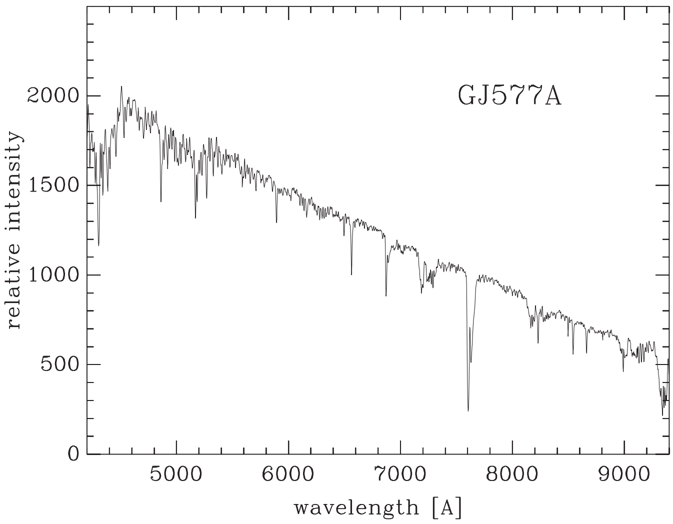

Fig. 5. Optical spectrum of GJ 577 A, the primary, G5.

From the known spectral types of the primaries and, hence, their expected intrinsic *JHK* colors and their published *JHK* magnitudes (from 2MASS), we find that interstellar absorption is negligible, as expected for nearby stars. Hence, the absolute *H*-band magnitudes for the companions are 5.3 ± 0.1 for HD 77407 B and 7.6 ± 0.1 for GJ 577 B. We do not use the Keck image of HD 77407 for photometry here, because star A is located behind a (semi-transparent) coronograph and star B is located partially behind one of the spiders.

5. Spectroscopy of GJ 577 B

Spectra of GJ 577 A and B were taken with the MOSCA faint-object spectrograph on the Calar Alto 3.5 m telescope at the end of Dec. 2002. We use the green500 grism which covers the wavelength range from 4200 to 8200 Å. The dispersion is about 2.9 Å per pixel with Site-CCD which has 2048 × 4096 15 μm pixel. We used a slit-width of one arcsec which gives a resolving power $\lambda/\Delta\lambda \simeq 700$. In order to calibrate the relative fluxes in the spectra, we also observed Feige 56. Standard IRAF routines were used to flat field, wavelength and flux-calibrate the spectra using frames taken with the standard flat field and Hg-Ar and Ne lamps.

Figure 5 shows the resulting spectrum of GJ 577 A and Fig. 6 the spectrum of GJ 577 B. As pointed out by Reid et al. (1995), the ratio of the fluxes in the 7042 to 7046 Å-band versus the flux in the 7126 to 7135 Å band can be used for determining the temperatures of very late-type objects. We derive TiO-2, TiO-4 and TiO-5 values of 0.508, 0.587 and 0.340 respectively. Using these values and the information given in Reid et al. (1995) and Hawley et al. (1996), we derive spectral types in the

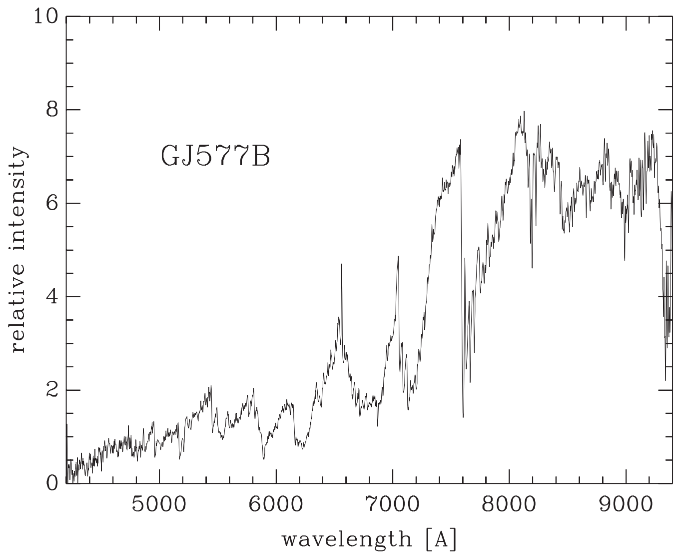

Fig. 6. Optical spectrum of GJ 577 B, the companion, M 4.5, showing strong H_α emission, deep TiO and VO molecular absorbtion bands and red continuum.

range M 4 to M 5. We also used the PC3 (1.02) and PC6 (2.05) coefficients from Martín et al. (1999) yielding M 3.1 and M 3 to M 4, respectively; for the PC6 index, used for L-dwarfs only in Martín et al. (1999), we used data of early M dwarfs given in that paper and a linear regression to early M. The spectrum also shows that the Hα-line is in emission. The equivalent width is −4.7 Å, which implies that $\log(H_\alpha/L_{bol})$ is about −4.0. These values are fairly typical for an object of this spectral type, and we thus conclude that the level of chromospheric activity of GJ 577 B is normal. The equivalent width of the Na I doublet around 8190 Å is 5.8 Å, partly affected by telluric absorption. It appears deeper (stronger) than in ~10 Myrs young M-types objects of the TW Hya association (Neuhäuser et al. 2000), pointing to an older age for GJ 577 B compared to TW Hya stars.

Given the observed magnitude difference between primary and secondary, and the known spectral type G5 for the primary, the spectral type M 4 to M 5 for the fainter object is as expected for a bound companion, i.e. being at the same age, distance, and metallicity.

6. Spectroscopy of HD 77407 A

We have started a program to search for close, low-mass companions around young nearby stars using precise stellar radial velocity (*RV*) measurements taken with the 2 m-Alfred-Jensch telescope of the Thüringer Landessternwarte Tautenburg (TLS). Young stars have been largely excluded from *RV* planet searches due to their high level of intrinsic *RV* variability. Magnetic activity in the form of spots, plage, changes in the convection pattern, etc. can cause significant *RV jitter* of several tens of m s^{-1} (Saar & Donahue 1997; Saar & Fischer 2000; Hatzes 2002). This additional source of noise can obscure the signal due to the presence of a planetary companion. In spite of this large intrinsic noise planetary companions can be detected around young stars as long as one has enough measurements to average out the activity noise (e.g. Hatzes et al. 2000). The TLS Program

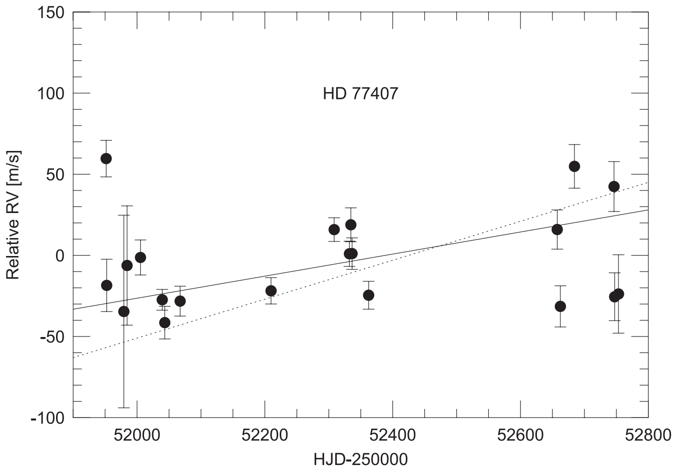

Fig. 7. Radial velocity measurements of HD 77407 (nightly averages) showing some scatter consistent with an active spotted star. The lines show the expected *RV* change for an 0.3 and 0.6 $M_\odot$ companion at 50 AU separation. The lower mass is consistent with a long-term trend seen in the *RV* data, and is also consistent with the imaging observations.

may be the first *RV* planet search program to search for planets around a sample of young stars and HD 77407 is among the targets.

Using the cross-dispersed coudé echelle spectrograph, we obtained 32 *RV* measurements of HD 77407 in 20 separate nights covering a time span of roughly two years. This spectrograph is especially optimized for high-precision *RV* work, located in a temperature stabilized coudé room with a temperature stabilized iodine I_2 gas absorption cell placed in front of the entrance slit. The use of an I_2 cell allows modelling of temporal and spatial variations of the instrumental point-spread function. Temperature sensors on the iodine cell, close to the grating, and close to the grism allow us to monitor any possible change in temperature. With the 1.2″ slit used the resolving power $\lambda/\Delta\lambda$ is 67 000. The cross-dispersing grism gives a wavelength coverage of 4630 to 7370 Å which encompasses the full wavelength region of the iodine absorption lines (5000 to 6000 Å). The *RV* analysis procedure largely follows the data modelling outlined by Butler et al. (1996) and the instrumental point spread function reconstruction techniques of Valenti et al. (1995). A template spectrum of the Tautenburg I_2 cell was taken at the McMath telescope, and template stellar spectra taken without the cell were obtained with the TLS echelle spectrograph.

Figure 7 shows the *RV* measurements for HD 77407 (nightly averages). The error bars represent *internal* errors determined by the mean rms scatter of the *RV* computed using individual spectral chunks (typically several hundred). This does not include any systematic errors which may be present in the data and which are difficult to assess given the short time span of our measurements. The rms scatter of the *RV* measurements in Fig. 7 is about 30 m/s, or more than a factor of 2 greater than the internal errors. These variations could easily be caused by activity noise. The Hipparcos photometry shows significant scatter of ≈0.015 mag (after subtracting the mean error in quadrature). This yields a spot filling factor of 1.4% assuming these are the source of the photometric variations. Hatzes (2002) presented an empirical relationship between *RV* amplitude due to spots, the $v \sin i$ of the star, and the spot filling factor. Assuming $v \sin i \simeq 7$ km s^{-1} yields an *RV* amplitude from spots of about 80 m s^{-1}. Thus cool spots on HD 77407 can easily account for the observed *RV* scatter of this star. Our *RV* measurements, however, can exclude the presence of any companion with $m \sin i$ greater than ∼3 $M_{\rm Jup}$ and periods of less than 4 years. Such companions would cause peak-to-peak variations in excess of 140 m/s which would have been clearly visible in our data.

The acceleration induced by a 0.3 $M_\odot$ and 0.6 $M_\odot$ companion in a circular orbit 50 AU from the star is 22.3 and 43.9 m s^{-1} yr^{-1}, respectively. This expected motion is shown in Fig. 7 as solid (22.3 m s^{-1} yr^{-1}) and dashed lines (43.9 m s^{-1} yr^{-1}). The acceleration expected from the lower mass companion is consistent with any long term *RV* variations for HD 77407 given the large scatter of the individual measurements; such a lower-mass companion (0.2 to 0.4 $M_\odot$) at ∼50 AU projected separation is detected in the imaging, (see above). Tentatively, the acceleration due to a higher mass companion seems to produce too large of an *RV* change. However, we measure only the radial component of total stellar orbital velocity, so we cannot exclude a higher mass for the stellar companion. The long-term *RV* trend seen in HD 77407 A with an amplitude consistent with the mass estimate for component B – as detected in the imaging – confirms that B is a bound companion to A.

Nidever et al. (2002) also included this star in their *RV* planet search program, but did not find any variability within their time base of only 23 days consistent with our data.

7. Discussion

HD 77407 is a slow rotating ($v \sin i \simeq 7$ km s^{-1}) G0 star with a notable chromospheric excess emission in the Hα, Hβ and Ca II lines. It is detected as radio source with a flux of 1.67 mJy at 20 cm and also as EUV source (Wichmann et al. 2003). Montes et al. (2001a) and Wichmann et al. (2003) report *EW*(Li I) = 170...183 mÅ, consistent with our own measurement *EW*(Li I) = 170 mÅ, indicating that it is a very young star. It is identified as a member of the local association (20 to 150 Myrs) due to its galactic space motion (Montes et al. 2001a). Our *RV* monitoring revealed no sub-stellar spectroscopic companion to HD 77407, but some scatter probably due to stellar activity (typical for young stars), and also a long-term trend consistent with the mass estimate of the co-moving companion detected in the imaging.

GJ 577 is a G5 V star with high levels of photospheric magnetic activity and a photometrically determined rotation period of around 4 days (Messina & Guinan 1998; Messina et al. 1999). Based on the kinematic criteria this star can be considered as a member of the Hyades supercluster with an age of 600 Myrs. A moderate Ca II H and K emission is observed in the spectra as well as an *EW*(Li I) of 145 mÅ. This lithium absorption is too strong for a member of the Hyades supercluster and is close to the weakest Li-lines of the local association with an age of 20 to 150 Myrs (Montes et al. 2001a,b).

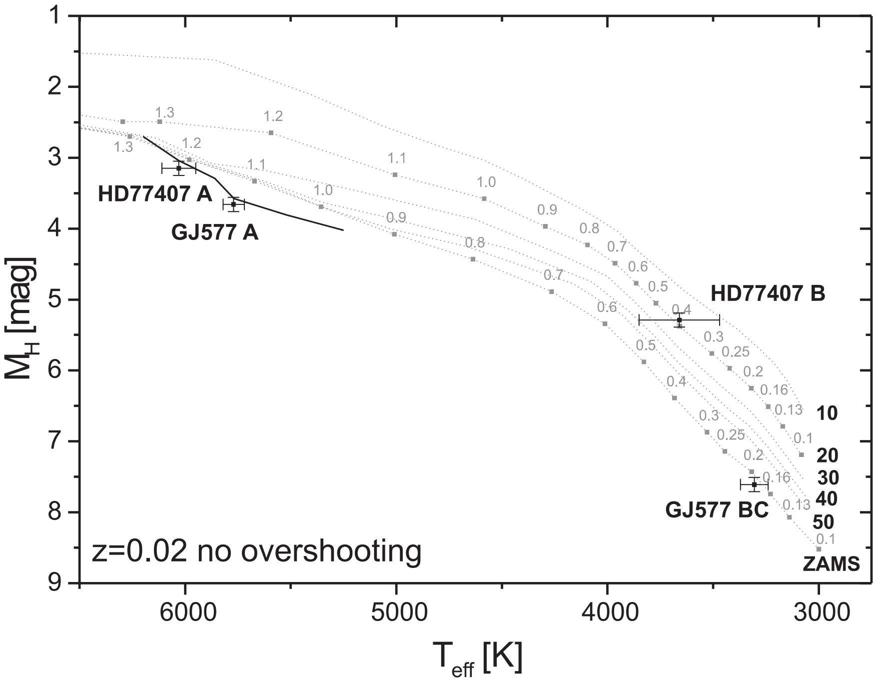

Fig. 8. H-R diagram with Siess et al. (2000) models with ($z = 0.02$ no overshooting) for HD 77407 and GJ 577 primary and secondary, our observed M_H value versus the temperature obtained from our observed (or derived) spectral type. The isochrones (dotted lines) are labeled by ages in Myrs. The object mass is given in units of solar mass. Furthermore we have plotted data for main-sequence stars (solid black line) from Schmidt-Kaler (M_V) and Kenyon-Hartmann ($H - V$ and $T_{\rm eff}$) for spectral types F8V to K0V. GJ 577 A lies on that main-sequence for spectral type G5V as observed, inconsistent with the ZAMS by Siess et al. by ~500 K.

Halbwachs et al. (2003) included GJ 577 in their spectroscopic observing program, but did not find any close low mass companion, nor any long-term trend, consistent with our data.

If we use the measured absolute H-band magnitudes of HD 77407 B and GJ 577 B as well as the stellar age given above, we can determine the companion mass and its effective temperature by using the evolutionary models for low-mass stars from Siess et al. (2000). The spectral type is converted to effective temperature using the scale for main-sequence dwarf stars by Kenyon & Hartmann (1995).

In Fig. 8, we show the H-R diagram for both new visual pairs and compare their locations with tracks and isochrones by Siess et al. (2000) with a metallicity $z = 0.02$ and no overshooting.

GJ 577 B appears to be older than 100 Myrs or already on the zero-age MS (ZAMS), also consistent with the 20 to 150 Myrs given by Montes et al. (2001a,b). Here, it is not possible to determine the age better from the companion alone, because the isochrones lie very close together at its location in the H-R diagram.

We used Siess et al. (2000) models as well as Baraffe et al. (1998) models. We took those sets of models which were available for low-mass objects down to 0.1 $M_\odot$. For Baraffe et al. (1998) models (mixing length parameter $\alpha = 1.0$, He abundance $Y = 0.275$ and solar metallicity [M/H] = 0) and for the Siess et al. (2000) models (with metallicity $z = 0.02$ no overshooting and with Kenyon-Hartmann conversion) the primaries lie below the main sequence, which is unphysical and may indicate problems with that particular set of models. We note that the primary stars are not saturated in the 2MASS images and that the Hipparcos parallaxes of the primaries should not be affected by the much fainter companions. Furthermore we used M_V data from Schmidt-Kaler and converted them to M_H using $(V - H)$ from Kenyon-Hartmann (1995). Those data are consistent with the 2MASS photometry and lie also under the Siess et al. ZAMS (see Fig. 8). For a metallicity [M/H] = −0.5, mixing length parameter $\alpha = 1$ and He abundance Y = 0.25 for Baraffe models and metallicity $z = 0.01$ for Siess models, each of the two pairs appears to be co-eval. However it is extremely unlikely that these two young stars are that metal-poor. Hence we do not show those models here.

Table 7. Stellar properties of HD 77407 B and GJ 577 B.

	HD 77407 B	GJ 577 B
Age [Myrs]	10 ... 40	>100
Mass [$M_\odot$]	0.3 ... 0.5	0.16 ... 0.2
Spec type	M 0 ... M 3	M 4 ... M 5
$T_{\rm eff}$ [K]	3850 ... 3470	3370 ... 3240

GJ 577 B was also detected by McCarthy et al. (2001) and Lowrance et al. (2003). The former show their J-band image having resolved A and B. They give $J = 11.15 \pm 0.15$ mag and $I \simeq 13$ mag, consistent with spectral type mid-M. Furthermore, McCarthy et al. (2001) quote Lowrance (2001) as having measured the proper motion of GJ 577 B to be consistent with A. McCarthy et al. (2001) do not show nor mention a spectrum, and the dissertation of Lowrance (2001) is not available to us. Lowrance et al. (2003) show that GJ 577 B is actually a double star and is called GJ 577 B and C. The components B and C are both close to the sub-stellar limit or brown dwarfs. They have a combined spectral type of M 5 to M 6 which is marginally consistent with our results.

We can use the ALFA and Keck images to obtain limits for undetected, but detectable faint companion candidates, i.e. for determining the limiting dynamic range achieved in terms of magnitude difference versus separation. We measure the 3σ flux level (for HD 77407 for both Keck and ALFA, so that we can compare them), and ratio it to the primary to determine the curves shown in Fig. 9.

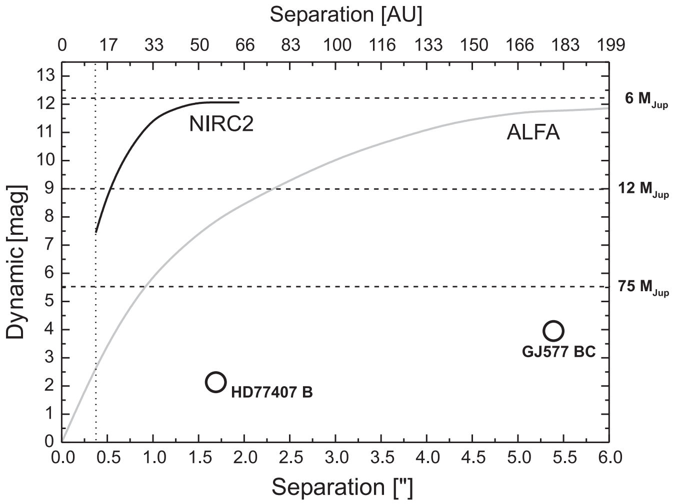

Fig. 9. Dynamic ranges achieved with ALFA and Keck AO for HD 77407, magnitude difference in H between primary and companions versus separation in arcsec. The two companions detected are indicated by circles. The Keck system is obviously much more sensitive than ALFA. We also indicate magnitude differences expected for companions at the upper mass limits for planets and brown dwarfs – computed for an age of 50 Myrs using Baraffe et al. (2003). Any brown dwarf should have been detected outside of 0.5 arcsec (17 AU), and any giant planet above ~6.5 $M_{\rm Jup}$ would have been detected outside of 1.5 arcsec. The upper x-axis scale in AU is given for the distance of HD 77407.

Any additional stellar companion (above ~75 $M_{\rm Jup}$ for 50 Myrs following Baraffe et al. 2003) should have been detected at a separation of ≥0.4 arcsec, the radius of the semi-transparent coronograph used. Also, any brown dwarf companion above ~40 $M_{\rm Jup}$ would have been detected outside of 0.4 arcsec. Brown dwarfs of any mass ranging from ~12 to ~75 $M_{\rm Jup}$ were detectable outside of 0.5 arcsec, which is 17 AU at the distance of HD 77407. We reached a magnitude difference of $\Delta H = 9$ mag at 0.5 arcsec separation. Giant planets with masses from ~6.5 to 12 $M_{\rm Jup}$ were detectable outside of 1.5 arcsec (50 AU), where we reached $\Delta H = 12$ mag.

We will report other detected companion candidates (both background objects as well as possibly bound secondaries) as well as other possibly negative (null) results (i.e. primaries without any detected companion candidates) elsewhere.

Acknowledgements. We are grateful to our referee, Eduardo Martín, for several useful comments and the Calar Alto Time Allocation committee for continuous support. R.J. acknowledges support from NASA Origins grant NAG5-11905. The German-Spanish Astronomical Centre Calar Alto is operated by the Max-Planck-Institute for Astronomy, Heidelberg, jointly with the Spanish National Commission for Astronomy. We thank the technical staff of the TLS in Tautenburg for all their help and assistance in carrying out the observations. We thank Jens Woitas, Sebastian Els, and Martin Kürster for taking some of the spectra of HD 77407. We made use of the 2MASS public data releases and of the Simbad database operated at the Observatoire Strassburg. Some of the data presented herein were obtained at the W. M. Keck Observatory, operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautic and Space Administration. We thank Randy Campbell and David LeMignant for help during the observing run.

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