A probable close brown dwarf companion to GJ 1046 (M 2.5V)*

M. Kürster1, M. Endl2, and S. Reffert3

1 Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
e-mail: kuerster@mpia-hd.mpg.de; kuerster@mpia.de
2 McDonald Observatory, University of Texas, Austin, TX 78712, USA
e-mail: mike@astro.as.utexas.edu
3 Zentrum für Astronomie Heidelberg, Landessternwarte, Königstuhl 12, 69117 Heidelberg, Germany
e-mail: reffert@slw.uni-heidelberg.de

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ABSTRACT

Context. Brown dwarf companions to stars at separations of a few AU or less are rare objects, and none have been found so far around early-type M dwarfs (M0V–M5V). With GJ 1046 (M 2.5V), a strong candidate for such a system with a separation of 0.42 AU is presented.

Aims. We aim at constraining the mass of the companion in order to decide whether it is a brown dwarf or a low-mass star.

Methods. We employed precision RV measurements to determine the orbital parameters and the minimum companion mass. We then derived an upper limit to the companion mass from the lack of disturbances of the RV measurements by a secondary spectrum. An even tighter upper limit is subsequently established by combining the RV-derived orbital parameters with the recent new version of the Hipparcos Intermediate Astrometric Data.

Results. For the mass of the companion, we derive $m \geq 26.9 \, M_{\text{Jup}}$ from the RV data. Based on the RV data alone, the probability that the companion exceeds the stellar mass threshold is just 6.2%. The absence of effects from the secondary spectrum lets us constrain the companion mass to $m \leq 229 \, M_{\text{Jup}}$. The combination of RV and Hipparcos data yields a 3σ upper mass limit to the companion mass of $112 \, M_{\text{Jup}}$ with a formal optimum value at $m = 47.2 \, M_{\text{Jup}}$. From the combination of RV and astrometric data, the chance probability that the companion is a star is 2.9%.

Conclusions. We have found a low-mass, close companion to an early-type M dwarf. While the most likely interpretation of this object is that it is a brown dwarf, a low-mass stellar companion is not fully excluded.

Key words. stars: low-mass, brown dwarfs – stars: binaries: spectroscopic – stars: individual: GJ 1046 – astrometry

1. Introduction

The paucity of brown dwarf companions to solar-like stars at separations of a few AU or less is a rare object, and none have been found so far around early-type M dwarfs (M0V–M5V). With GJ 1046 (M 2.5V), a strong candidate for such a system with a separation of 0.42 AU is presented.

Aims. We aim at constraining the mass of the companion in order to decide whether it is a brown dwarf or a low-mass star.

Methods. We employed precision RV measurements to determine the orbital parameters and the minimum companion mass. We then derived an upper limit to the companion mass from the lack of disturbances of the RV measurements by a secondary spectrum. An even tighter upper limit is subsequently established by combining the RV-derived orbital parameters with the recent new version of the Hipparcos Intermediate Astrometric Data.

Results. For the mass of the companion, we derive $m \geq 26.9 \, M_{\text{Jup}}$ from the RV data. Based on the RV data alone, the probability that the companion exceeds the stellar mass threshold is just 6.2%. The absence of effects from the secondary spectrum lets us constrain the companion mass to $m \leq 229 \, M_{\text{Jup}}$. The combination of RV and Hipparcos data yields a 3σ upper mass limit to the companion mass of $112 \, M_{\text{Jup}}$ with a formal optimum value at $m = 47.2 \, M_{\text{Jup}}$. From the combination of RV and astrometric data, the chance probability that the companion is a star is 2.9%.

Conclusions. We have found a low-mass, close companion to an early-type M dwarf. While the most likely interpretation of this object is that it is a brown dwarf, a low-mass stellar companion is not fully excluded.

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best established brown dwarfs are the companions to the G4IV star HD 38529 and to the G6IV star HD 168443 with companion masses of 37 \( M_{\text{Jup}} \) and 34 \( M_{\text{Jup}} \), orbital periods of 2174.3 d and 1770 d, and separations of 3.68 AU and 2.87 AU, respectively. These masses were determined by Reffert & Quirrenbach (2006) who derived new astrometric solutions from the Hipparcos measurements given the precisely known RV-derived orbital parameters, i.e. period, time of periastron passage, eccentricity, and longitude of periastron. Another example determined in a similar fashion by Zucker & Mazeh (2000) is the G5IV star HD 10697 with a companion in a 1078 d orbit at a separation of 2.12 AU and a mass of 40 \( M_{\text{Jup}} \). An example for an object with a minimum mass of 9.3 \( M_{\text{Jup}} \) that turned out to be a star with a mass of 142 \( M_{\text{Jup}} \) is the companion to HD 33636 (Bean et al. 2007).

The present paper presents a new candidate for a brown-dwarf companion which we have found in our precision RV survey carried out with the UVES spectrograph at the ESO VLT in search for planetary and substellar companions to M dwarfs (see Kürster et al. 2003). The host star, GJ 1046 (M2.5V; \( V = 11.62 \) mag), has no entry in the Double and Multiple Systems Annex of the Hipparcos data base. Comparing its \( V \) band and \( J, H, K \) band colours (from the 2MASS catalogue; Skrutskie et al. 2006) with the mass-luminosity relationships by Delfosse et al. (2000) there is no indication of near-infrared emission in excess of the scatter found in these relations.

If the companion to GJ 1046 turns out to be a brown dwarf, then the system would be unique in that it would contain the first close-in (\( \leq 5 \) AU) brown dwarf companion to a main-sequence star of spectral type early-M (M0V–M5V). Since the mass ratios of binary systems with low-mass primaries tend towards unity, brown dwarf companions to late-M dwarfs (\( \geq 6 \) MV) are relatively frequent (e.g. Montagnier et al. 2006). But even in these systems separations \( \leq 5 \) AU are usually found only among binaries with low-mass stellar secondaries. Counterexamples are the M8 star LHS 2397a with an L7.5 companion at a separation of 2.9 AU (Freed et al. 2003) and the young M6 object at the star-to-brown dwarf border, Cha H0 8, orbited by a brown dwarf at a separation of 1AU (Joergens & Müller 2007).

### 2. Observations

GJ 1046 was observed with the VLT-UT2+UVES as one of the targets of our precision RV survey of M dwarfs in search for extrasolar planets (see Kürster et al. 2003, 2006). To attain high-precision RV measurements UVES was self-calibrated with its iodine gas absorption cell operated at a temperature of 70°C. Image slicer #3 and an 0.3” slit were chosen yielding a resolving power of \( R = 100,000–120,000 \). The central wavelength of 600 nm was selected such that the useful spectral range containing iodine (I_2) absorption lines (500–600 nm) falls entirely on the better quality CCD of the mosaic of two 4 K \( \times \) 2 K CCDs.

For a detailed description of our data modelling approach employed for the determination of high precision differential radial velocities (DRV) we refer the reader to Endl et al. (2000). A concise summary can also be found in Sect. 4 of Kürster et al. (2003).

A total of 14 spectra of GJ 1046 observed through the iodine cell were obtained in 14 nights between 3 October 2004 and 11 November 2006. See Table 1 for the journal of observations. Individual exposure time was 900 s yielding an average S/N per pixel between 39 and 58 for the various spectra (the median and mean being 51.0 and 49.1, respectively). On average our error of the individual RV measurements is 3.63 \( m \) s\(^{-1}\) for this \( V = 11.62 \) mag object. All RV data were corrected for the solar system barycenter using the JPL ephemeris DE200 (Standish 1990) for the flux-weighted temporal midpoint of the exposure as given by the UVES exposure meter. For each epoch of observation proper motion corrected stellar coordinates were used. On 19 November 2004 we also obtained a triplet of exposures without the iodine cell (exposure time 3 \( \times \) 705 s) required as a template spectrum in the data modelling process (cf. Endl et al. 2000).

### 3. Results

Our RV time series for GJ 1046 is listed in Table 1 and also shown in Fig. 1 along with the best-fit Keplerian orbit yielding an orbital period of \( P = 169 \) d, an eccentricity of \( e = 0.28 \), an RV semi-amplitude of \( K = 1831 \) m s\(^{-1}\), and a mass function \( f(m) = (m \sin i)^3 / (M + m)^2 = 9.5 \times 10^{-5} M_\odot \) (Table 2).

Given the unknown inclination \( i \) only a minimum to the companion mass can be determined corresponding to the case \( i = 90^\circ \). For this we need an estimate of the stellar mass of GJ 1046 which we obtain from the K-band mass-luminosity relationship by Delfosse et al. (2000). Taking the apparent \( K \)-magnitude from the 2MASS catalogue (\( K = 7.03 \) mag) and combining it with the Hipparcos parallax (71.11 mas) we find an absolute \( K \)-magnitude of 6.29 mag. The \( K \)-band mass-luminosity relationship then yields a stellar mass of \( 0.398 \pm 0.007 M_\odot \).

We then infer a minimum companion mass of \( m_{\text{min}} = 26.9 M_{\text{Jup}} \) and, from Eq. (1), a semi-major axis of the companion orbit of \( a = 0.42 \) AU. In order for the true companion mass to exceed the stellar threshold of 0.08 \( M_\odot \) the orbital inclination \( i \) would have to be \( < 20.4^\circ \). For a chance orientation of the orbit the probability that \( i \) is smaller than some angle \( \theta \) is given by

\[
p(t > i > 0^\circ) = 1 - \cos \theta;
\]

hence the chance probability to have an inclination \( < 20.3^\circ \) is just \( 6.3% \) making it not very likely that the companion is a star (see also Table 2).

### 4. Spectroscopic companion mass upper limit

An upper limit to the mass of the companion can be determined from the spectroscopic data by exploiting the notion that with increasing mass the companion would at some point become so bright that it would noticeably affect the RV measurements. In

| Date       | BJD     | DRV       | RV-error |
|------------|---------|-----------|----------|
| 2004-10-03 | 2450000 | -1132.0   | 3.2      |
| 2004-11-11 | 2450000 | 411.5     | 3.5      |
| 2005-07-27 | 2450000 | -1670.6   | 4.8      |
| 2005-08-26 | 2450000 | 1524.6    | 3.7      |
| 2005-09-11 | 2450000 | -928.7    | 4.3      |
| 2005-09-19 | 2450000 | -615.2    | 3.5      |
| 2005-10-17 | 2450000 | 492.3     | 3.5      |
| 2006-01-15 | 2450000 | -1787.7   | 3.5      |
| 2006-09-15 | 2450000 | 824.3     | 3.9      |
| 2006-10-05 | 2450000 | 1085.8    | 3.6      |
| 2006-10-06 | 2450000 | 1108.1    | 3.7      |
| 2006-11-02 | 2450000 | 1737.5    | 3.1      |
| 2006-11-08 | 2450000 | 1673.7    | 3.3      |

Note: a Barycentrically corrected Julian Date.
Table 2. System parameters of GJ 1046.

| Parameter | Value |
|-----------|-------|
| **RV-derived parameters** |       |
| Orbital period $P$ | 168.848 ±0.030 [d] |
| Time of periastron $T_p$ | 3225.78 ±0.32 |
| BJD-2450000 | 1830.7 ±2.2 [m s$^{-1}$] |
| RV semi-amplitude $K$ | 0.2792 ±0.0015 |
| Orbital eccentricity $e$ | 92.70 ±0.50 [°] |
| Longitude of periastron $\omega$ | 9.504 ±0.024 [10$^{-5}$ M$_\odot$] |
| Minimum inclination $i$ | 12.7 |
| Mass function $f(m)$ | 0.123 |
| Probability of $\chi^2$ (d.o.f. = 8) | 3.63 |
| Stellar mass $M$ | 0.398 ±0.007 [M$_\odot$] |
| Minimum companion mass $m_{\text{min}}$ | 26.85 ±0.30 [M$_{\text{Jup}}$] |
| Semi-major axis of companion orbit $a$ | 0.421 ±0.010 [AU] |
| Critical inclination (for $m = 0.08$ M$_\odot$, $i_{\text{crit}}$) | 20.4 [°] |
| Probability of $i_{\text{min}}$, $P_{\text{min}}$ | 6.3% (20.4° $i$ $\geq$ 0°) |
| Probability of $i_{\text{max}}$, $P_{\text{max}}$ | 1.2% (8.7° $i$ $\geq$ 0°) |
| **Inferred parameters** |       |
| Maximum companion mass $m_{\text{max}}$ | 229 [M$_{\text{Jup}}$] |
| Minimum inclination $i_{\text{min}}$ | 8.7 [°] |
| Probability of $i_{\text{max}}$, $P_{\text{max}}$ | 3.7% (15.6° $i$ $\geq$ 0°) |
| **Astrometry-derived parameters** |       |
| Ascending node $\Omega$ | 97.7 formal optimum [°] |
| Inclination $i$ | 125.9 formal optimum [°] |
| Companion mass $m$ | 47.2 formal optimum [M$_{\text{Jup}}$] |
| $\chi^2$ (d.o.f. = 202) | 329.0 |
| Minimum inclination $i_{\text{min}}$ | 15.6 3σ limit [°] |
| Probability of $i_{\text{max}}$, $P_{\text{max}}$ | 3.7% (15.6° $i$ $\geq$ 0°) |
| Maximum companion mass $m_{\text{max}}$ | 112 [M$_{\text{Jup}}$] |
| Probability of a stellar companion $p_c$ | 2.9% |

Notes: 

- A priori probability based on the RV derived minimum mass and assuming random orientation of the orbit.
- Probability derived from the astrometric model.

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Fig. 1. RV time series of our UVES RV data for GJ 1046. The solid line corresponds to the Keplerian solution with a period of 169 d and with $\chi^2 = 12.7$, 8 degrees of freedom (d.o.f.), and $p(\chi^2) = 0.123$. The rms scatter of the measurements around the orbital solution is 3.56 m s$^{-1}$ which compares well with the average measurement error of 3.63 m s$^{-1}$ which is much smaller than the plot symbols. For comparison the second best solution with a period of 338 d is shown as a dashed line. While being the second best, the latter solution is clearly excluded due to its extremely large $\chi^2$ value of 10.121.
The employed single-lined spectrum model fails. Six stars have abnormally strong contributions from the secondaries that displayed error range. They are newly discovered double-lined spectroscopic binaries with large errors (79, 81, and 92 m s\(^{-1}\)). Of the total sample of 41 stars only 38 are displayed, because three stars were not detected. Applying a \(\kappa\) rejection of values exceeding the mean plus 2\(\sigma\) (for a Gaussian distribution the chance probability of exceeding this value in one iteration is 0.5\%) we reject all stars with mean \(\Delta RV\) errors in excess of 6.5 m s\(^{-1}\). Of the total sample of 41 stars only 38 are displayed, because three stars with large errors (79, 81, and 92 m s\(^{-1}\), respectively) lie far outside the displayed error range. They are newly discovered double-lined spectroscopic binaries with such strong contributions from the secondaries that the employed single-lined spectrum model fails. Six stars have abnormally high mean errors between 7 and 16 m s\(^{-1}\) which, in one case, is the result of very low signal-to-noise ratio, but in the other cases could also be due to spectral contamination from a companion. The remaining bulk of the distribution (mean error <6.5 m s\(^{-1}\)) has a mean of 3.91 m s\(^{-1}\) and a width of \(\sigma = 1.02\) m s\(^{-1}\).

![Histogram of the mean internal RV measurement errors for our sample of stars.](image)

Fig. 2. Histogram of the mean internal RV measurement errors for our sample of stars. Applying a \(\kappa\)-\(\sigma\) clipping procedure with an iterative rejection of values exceeding the mean plus 2\(\sigma\) (for a Gaussian distribution the chance probability of exceeding this value in one iteration is 0.5\%\) we reject all stars with mean \(\Delta RV\) errors in excess of 6.5 m s\(^{-1}\). Of the total sample of 41 stars only 38 are displayed, because three stars with large errors (79, 81, and 92 m s\(^{-1}\), respectively) lie far outside the displayed error range. They are newly discovered double-lined spectroscopic binaries with such strong contributions from the secondaries that the employed single-lined spectrum model fails. Six stars have abnormally high mean errors between 7 and 16 m s\(^{-1}\) which, in one case, is the result of very low signal-to-noise ratio, but in the other cases could also be due to spectral contamination from a companion. The remaining bulk of the distribution (mean error <6.5 m s\(^{-1}\)) has a mean of 3.91 m s\(^{-1}\) and a width of \(\sigma = 1.02\) m s\(^{-1}\).

stellar primary (third column). We have used the high-signal-to-noise template spectra (observed without the iodine cell) of two other M dwarfs of this survey, GJ 699 (Barnard’s star; M4V; mean S/N per pixel: 300) and GJ 682 (M3.5V; mean S/N per pixel: 230) for masses \(\geq 0.20\ M_\odot\) and \(\geq 0.20\ M_\odot\), respectively (fourth column). For each simulated spectrum the companion spectrum was shifted to the appropriate companion \(\Delta RV\) for the probed mass value as well as scaled in flux corresponding to the brightness predicted by the \(\Delta RV\)-band mass-luminosity relation.

We find that a companion with a mass \(\geq 0.254\ M_\odot\) or \(\geq 265\ M_\text{Jup}\) and a factor of 4 fainter in the \(\Delta RV\)-band than its primary would increase the internal error (fifth column in Table 3) to \(\geq 7\) m s\(^{-1}\) which would make this star stick out from the bulk of the sample (Fig. 2) indicating a contamination of the spectrum. The 7th and 8th columns of Table 3 list the chance probabilities of the obtained mean errors (fifth column) from a comparison with the total sample of observed stars.

For the second possibility of determining the mass upper limit of the companion we assume (conservatively) that the mean original \(\Delta RV\) error is entirely caused by contributions from the companion spectrum and not attributable to photon noise or to effects of instrumental nature or intrinsic to the star. We then search for the companion spectrum (as a function of companion mass and brightness) whose addition to the observed spectra increases the \(\Delta RV\) error (6th column in Table 3) to \(\geq 7\) m s\(^{-1}\) (cf. Table 3). We find that a companion with a mass \(\geq 0.254\ M_\odot\) or \(\geq 265\ M_\text{Jup}\) and a factor of 4 fainter in the \(\Delta RV\)-band than its primary would increase the internal error (fifth column in Table 3) to \(\geq 7\) m s\(^{-1}\) which would make this star stick out from the bulk of the sample (Fig. 2) indicating a contamination of the spectrum. The 7th and 8th columns of Table 3 list the chance probabilities of the obtained mean errors (fifth column) from a comparison with the total sample of observed stars.

For this increased error value we find a companion mass of \(\geq 0.219\ M_\odot\) or \(229\ M_\text{Jup}\) and a primary-to-secondary \(\Delta RV\)-band flux ratio of 6.5 (cf. Table 3).

As the mass value derived with the criterion to double the square of the mean internal error is lower than the one derived from the comparison with the star sample, we will adopt the value of \(229\ M_\text{Jup}\) as the spectroscopic upper limit to the mass of the companion to GJ 1046. This value corresponds to an orbital inclination of 8\(^\circ\). The probability for an inclination as small as 5\(^\circ\) is 0.13 (cf. Table 3).
as (or smaller than) this value is 1.2%, again assuming random orientation of the orbit (see also Table 2).

5. Companion mass upper limit from a combination of the RV data with Hipparcos measurements

Even if the astrometric signature of the companion is not seen in the Hipparcos data, Hipparcos astrometry can yield stringent upper mass limits on companions detected via the radial velocity method.

Using the Hipparcos parallax (71.1 mas) together with the orbital parameters derived from the RV measurements we can predict the minimum astrometric signal of the stellar reflex motion, the true astrometric eccentricity, and the ascending node while fitting an astrometric orbit to the abscissa residuals. Additional free parameters in the fit were a correction to the mean position, mean proper motion and parallax of the star.

The result is shown in Fig. 3 (left panel).

We have analysed the Hipparcos Intermediate Astrometric Data for GJ 1046 (HIP 10812) using the new reduction of the raw data (van Leeuwen 2007a,b). We followed the approach described in Reffert & Quirrenbach (2006) by keeping those of the orbital parameters that are known from the analysis of the RVs fixed and varying only the inclination and the ascending node while fitting an astrometric orbit to the abscissa residuals. Additional free parameters in the fit were a correction to the mean position, mean proper motion and parallax of the star. The result is shown in Fig. 3 (left panel).

The formally best fit to the Hipparcos data is achieved with an inclination \(i = 125.9°(i−90° = 35.9°)\) corresponding to a true companion mass of \(47.2 \ M_{\text{Jup}}\) pointing at a brown dwarf companion (Table 2)\(^1\). However, an F-test measuring the variance improvement yields a probability of 17\% for the detection of the astrometric orbit implying that is has not been detected with significance. This can also be seen in Fig. 3 (left panel), where the ascending node is completely undetermined since the 2 and 3σ confidence contour levels span the entire parameter range.

In the right panel of Fig. 3, the \(\chi^2\) value is shown as a function of inclination only, together with the 1σ and 3σ confidence regions for the inclination. The 3σ (99.73\% confidence) lower limit to the inclination is \(i = 15.6°\) implying a 3σ upper mass limit for the companion of \(112 \ M_{\text{Jup}}\).

Therefore, a stellar companion cannot be fully excluded, even though it is unlikely. From the astrometric solution the chance probability for the companion to have a stellar mass, or equivalently, for its inclination to be either \(i < 20.3°\) or \(>159.7°\), is 2.2\% and 0.7\%, respectively, corresponding to a combined chance probability of 2.9\% (see also Table 2)\(^2\).

6. Conclusions

We have presented the discovery of a probable brown dwarf companion to an M dwarf with an orbital period of just under 1/2 year and a star-companion separation of 0.42 AU. Our RV measurements provide a lower limit to the true companion mass of \(26.9 \ M_{\text{Jup}}\) and a chance probability of just 6.2\% that the companion is actually a star. From the absence of any indications of a secondary spectrum in our data we can place an upper limit to the companion mass of \(m = 229 \ M_{\text{Jup}}\).

Combining our RV measurements with the Hipparcos Intermediate Astrometric Data from the recent new reduction by van Leeuwen (2007a,b) we find a formal best-fit companion mass value of \(47.2 \ M_{\text{Jup}}\), but pertinent to a model that is not significant. However, the same data allows us to place a much tighter companion mass upper limit of 112 \(M_{\text{Jup}}\) at 99.73\% confidence. This mass upper limit still allows a stellar companion, but with a low probability. From the astrometric analysis the

\(^1\) Varying the RV derived parameters within their errors leads to minute changes in the formal best-fit solution indicating that the uncertainties of the latter are absolutely dominated by the astrometric data.

\(^2\) The combined chance probability is given by one minus the product of the confidences: \(1−(1−2.2\%)(1−0.7\%) = 2.88\%\).
chance probability that the companion mass exceeds the stellar mass threshold is 2.9%.

If the brown dwarf nature of this object can be fully established, e.g. from future astrometric measurements, it would be the first genuine brown dwarf desert object orbiting an early-M dwarf.

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