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

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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 (M 0V–M 5V). 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 $m \geq 26.9\ M_{\rm Jup}$ 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 $m \leq 229\ M_{\rm Jup}$. The combination of *RV* and Hipparcos data yields a 3σ upper mass limit to the companion mass of 112 $M_{\rm Jup}$ with a formal optimum value at $m = 47.2\ M_{\rm Jup}$. 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 (a canonical value of ≲5 AU is usually quoted), was already noted by Campbell et al. (1988) in their early precision radial velocity survey. This "brown dwarf desert" is currently not well understood (see Grether & Lineweaver 2006, for an overview). Two distinctive formation mechanisms seem to be at work for planetary ($M \leq 13\ M_{\rm Jup}$) and stellar ($M \geq 0.08\ M_\odot$) companions with relatively little overlap between the two. At wide separations no "brown dwarf desert" is observed. While the frequency of brown dwarf companions separated from their host star by <3 AU is about 0.5%, it is at least a factor of 10 higher for separations >1000 AU (Gizis et al. 2001; also Neuhäuser & Guenther 2004). The fact that close-in brown dwarf companions are rare is highly significant since the commonly employed radial velocity (*RV*) method to search for sub-stellar companions to stars is very sensitive to such objects. The *RV* semi-amplitude *K* of the primary (the companion is usually not visible in the spectrum) is given by

$$K = \frac{(2\pi G/P)^{1/3}}{(1-e^2)^{1/2}}\,\frac{m \sin i}{(M+m)^{2/3}}, \qquad (1)$$

where *M* and *m* are, respectively, the mass of the star and companion, and *P*, *e* and *i* are the orbital period, eccentricity and inclination.

As can be seen from Eq. (1) the chances to detect a companion object via *RV*s increase with shorter period (and shorter separation) and higher companion mass. For example, the *RV* semi-amplitude of the stellar reflex motion caused by a 20 $M_{\rm Jup}$ brown dwarf at 1 AU from a solar-mass star is 565 m s^{-1}, if the orbit is circular and seen edge-on ($i = 90°$). This is two orders of magnitude greater than the current state-of-the-art *RV* measurement precision of a few m s^{-1}. The detectability also increases for lower-mass stars; the same 20 $M_{\rm Jup}$ at 1 AU from an 0.3 $M_\odot$ star would produce an *RV* semi-amplitude of 1009 m s^{-1}. And in fact there is observational evidence of the existence of brown dwarf companions to low-mass stars such as the prototype brown dwarf companion GJ 229B that orbits an M 1V star at a wide projected separation of 44 AU (Nakajima et al. 1995).

Few brown dwarf companion candidates in the separation regime up to a few AU are known. The first such candidate was HD 114762 (Latham et al. 1989), and a more recent example is HD 137510 (Endl et al. 2004). The masses of these candidate objects have often not been well-determined since the *RV* method just yields a minimum mass and the astrometric precision of the available Hipparcos data (ESA 1997) is mostly not sufficient to confirm brown dwarfs and exclude stellar companions (e.g. Pourbaix 2001; Pourbaix & Arenou 2001). Among the

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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 $M_{\rm Jup}$ and 34 $M_{\rm Jup}$, 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 $M_{\rm Jup}$. An example for an object with a minimum mass of 9.3 $M_{\rm Jup}$ that turned out to be a star with a mass of 142 $M_{\rm Jup}$ 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 (M 2.5V; 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 (≤5 AU) brown dwarf companion to a main-sequence star of spectral type early-M (M 0V–M 5V). Since the mass ratios of binary systems with low-mass primaries tend towards unity, brown dwarf companions to late-M dwarfs (≥M 6V) are relatively frequent (e.g. Montagnier et al. 2006). But even in these systems separations ≤5 AU are usually found only among binaries with low-mass stellar secondaries. Counterexamples are the M 8 star LHS 2397a with an L7.5 companion at a separation of 2.9 AU (Freed et al. 2003) and the young M 6 object at the star-to-brown dwarf border, Cha Hα 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 × 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 to 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 exposuremeter. 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 × 705 s) required as a template spectrum in the data modelling process (cf. Endl et al. 2000).

Table 1. Differential *RV* time series measurements of GJ 1046.

Date	[a] BJD – 2 450 000	*DRV* [m s^{-1}]	*RV*-error [m s^{-1}]
2004-10-03	3281.83304	–1132.0	3.2
2004-11-11	3320.62631	411.5	3.5
2005-07-27	3578.91097	–1670.6	4.8
2005-08-26	3608.77350	–1524.6	3.7
2005-09-11	3624.71807	–928.7	4.3
2005-09-19	3632.72200	–615.2	3.5
2005-10-17	3660.68277	492.3	3.5
2006-01-15	3750.60256	–1787.7	3.5
2006-09-15	3993.84856	326.4	3.3
2006-09-28	4006.77107	823.4	3.9
2006-10-05	4013.80030	1085.8	3.6
2006-10-06	4014.61077	1108.1	3.7
2006-11-02	4041.65276	1737.5	3.1
2006-11-08	4047.65399	1673.7	3.3

Note: [a] Barycentrically corrected Julian Date.

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 $f(m) = (m \sin i)^3/(M+m)^2 = 9.5\times10^{-5}\ M_\odot$ (Table 2).

Given the unknown inclination i only a minimum to the companion mass can be determined corresponding to the case i = 90°. 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 $m_{\rm min}$ = 26.9 $M_{\rm Jup}$ 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°. For a chance orientation of the orbit the probability that i is smaller than some angle θ is given by

$$p(\theta > i \geq 0°) = 1 - \cos\theta; \qquad (2)$$

hence the chance probability to have an inclination <20.3° 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

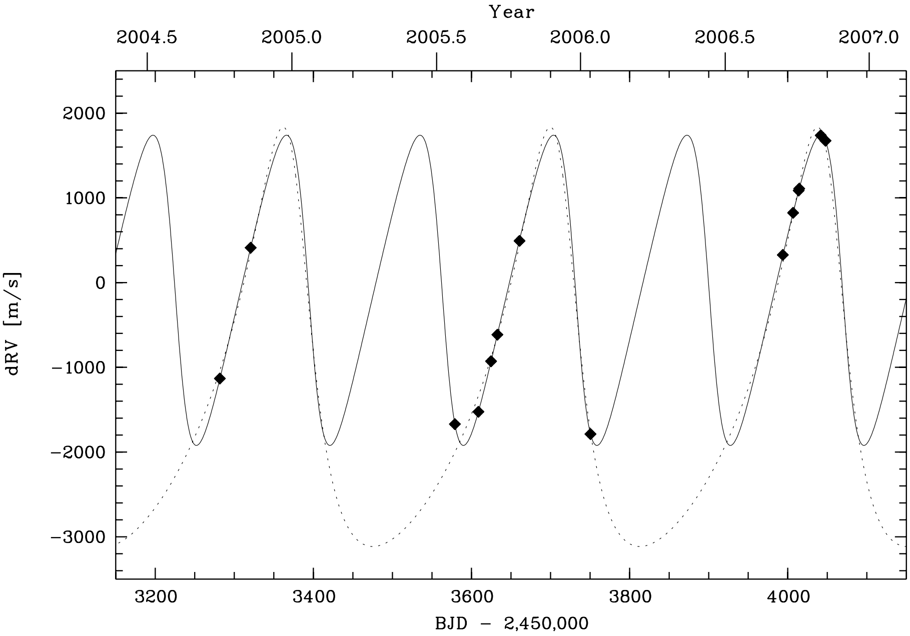

Fig. 1. *RV* time series of our UVES *RV* data for GJ 1046. The solid line corresponds to the Keplerian solution with a period of 169 d and with $\chi^2 = 12.7$, 8 degrees of freedom (d.o.f.), and $p(\chi^2) = 0.123$. The rms scatter of the measurements around the orbital solution is 3.56 m s^{-1} which 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 χ^2 value of 10 121.

Table 2. System parameters of GJ 1046.

RV-derived parameters			
Orbital period P	168.848	±0.030	[d]
Time of periastron T_p BJD-2 450 000	3225.78	±0.32	
RV semi-amplitude K	1830.7	±2.2	[m s^{-1}]
Orbital eccentricity e	0.2792	±0.0015	
Longitude of periastron ω	92.70	±0.50	[°]
Mass function $f(m)$	9.504	±0.024	[10^{-5} $M_\odot$]
χ^2 (d.o.f. = 8)	12.7		
$p(\chi^2)$	0.123		
Scatter rms	3.56		[m s^{-1}]
Mean error $\overline{\Delta RV}$	3.63		[m s^{-1}]
Inferred parameters			
Stellar mass M	0.398	±0.007	[$M_\odot$]
Minimum companion mass $m_{\rm min}$	26.85	±0.30	[$M_{\rm Jup}$]
Semi-major axis of companion orbit a	0.421	±0.010	[AU]
Critical inclination (for $m = 0.08\ M_\odot$) $i_{\rm crit}$	20.4		[°]
^{a} Probability of $i_{\rm crit}$, $p_{i_{\rm crit}}$	6.3%	(20.4° > i ≥ 0°)	
Parameters derived from absence of companion spectrum			
Maximum companion mass $m^{\rm sp}_{\rm max}$	229		[$M_{\rm Jup}$]
Minimum inclination $i^{\rm sp}_{\rm min}$	8.7		[°]
^{a} Probability of $i^{\rm sp}_{\rm min}$, $p_{i^{\rm sp}_{\rm min}}$	1.2%	(8.7° > i ≥ 0°)	
Astrometry-derived parameters			
Ascending node Ω	97.7	formal optimum	[°]
Inclination i	125.9	formal optimum	[°]
Companion mass m	47.2	formal optimum	[$M_{\rm Jup}$]
χ^2 (d.o.f. = 202)	329.0		
Minimum inclination $i^{\rm as}_{\rm min}$	15.6	3σ limit	[°]
^{a} Probability of $i^{\rm as}_{\rm min}$, $p_{i^{\rm as}_{\rm min}}$	3.7%	(15.6° > i ≥ 0°)	
Maximum companion mass $m^{\rm as}_{\rm max}$	112	3σ limit	[$M_{\rm Jup}$]
^{b} Probability of a stellar companion p_*	2.9%		

Notes: ^{a} A priori probability based on the *RV* derived minimum mass and assuming random orientation of the orbit.
^{b} Probability derived from the astrometric model.

our data modelling approach a suitable indicator for the presence of an additional perturbing signal is the magnitude of the *RV* measurement error, because all *RV* data are obtained assuming that the modelled spectrum is that of a single-lined binary in which the light from the companion can be neglected. If this is not the case, then the light contribution from the companion manifests itself as unusually large errors of the determined *RV* values. For details of the data modelling approach and the estimation of the *RV* errors we refer the reader to Endl et al. (2000).

Briefly, the spectra are subdivided into ≈500 chunks of ≈2 Å width, each of which is modelled in order to yield an independent *RV* measurement. The mean of these values and its error are taken as the final measurements and their (internal) error estimates. If a second contaminating spectrum is present, the different spectral chunks are affected in a non-homogeneous fashion, depending on the detailed spectral line patterns within the chunk, with the effect that the derived chunk *RV* values exhibit a stronger scatter and hence combine to an increased value of the internal *RV* measurement error. By way of simulations adding faint companion spectra to the spectra of GJ 1046 we investigate the following two possibilities of obtaining information on the companion mass upper limit from the internal *RV* error.

1. A comparison of the mean internal *RV* measurement error of GJ 1046 for different added companion spectra with the distribution of mean observed errors for the sample of monitored stars.
2. A comparison of the mean internal *RV* measurement error of GJ 1046 for different added companion spectra with its original value.

In the case of considerable contamination the average *RV* error for the spectra of the star in question stands out from the distribution of *RV* errors for the sample of monitored stars which is shown in Fig. 2. If only the bulk of the distribution is considered, i.e. stars with a mean *RV* error <7 m s^{-1}, this distribution is nearly Gaussian with a mean value of 3.91 m s^{-1} and a width of $\sigma = 1.02$ m s^{-1}.

The average *RV* measurement error for GJ 1046 is 3.63 m s^{-1} with the errors of the 14 individual GJ 1046 spectra ranging

Table 3. Simulations for the determination of an upper limit to the companion mass.

Mass $[M_\odot]$	Mass $[M_{\rm Jup}]$	V-band flux ratio	Model spectrum	Mean error $[{\rm m\,s^{-1}}]$	Excess error $[{\rm m\,s^{-1}}]$	Chance probability from sample comparison a)	Chance probability from sample comparison b)	Chance probability from excess error criterion
0.00	0	–	none	3.63	0.00	0.56	0.61	1
0.16	167	18.30	GJ 699	3.79	1.07	0.50	0.55	0.70
0.17	177	14.85	GJ 699	3.92	1.49	0.47	0.50	0.59
0.18	188	12.26	GJ 699	4.04	1.77	0.47	0.45	0.51
0.19	198	10.27	GJ 699	4.22	2.16	0.34	0.38	0.40
0.20	209	8.69	GJ 699	4.47	2.61	0.25	0.29	0.28
0.20	209	8.69	GJ 682	4.41	2.51	0.31	0.31	0.31
0.21	219	7.43	GJ 682	4.79	3.12	0.17	0.20	0.14
0.22	230	6.41	GJ 682	5.16	3.67	0.13	0.11	0
0.23	240	5.57	GJ 682	5.61	4.28	0.094	0.048	0
0.24	250	4.87	GJ 682	6.10	4.90	0.031	0.016	0
0.25	261	4.29	GJ 682	6.70	5.63	0	0.0032	0
0.26	271	3.79	GJ 682	7.40	6.45	0	0.00032	0

Notes: a) Fraction of stars in the distribution with larger mean errors.
b) Areal fraction of Gaussian fitted to the distribution exceeding the mean error.

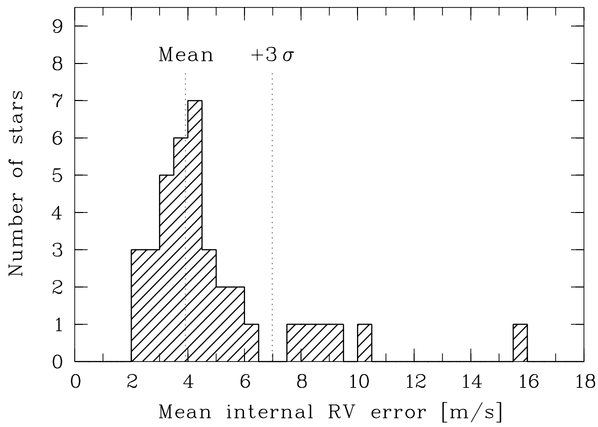

Fig. 2. Histogram of the mean internal *RV* measurement errors for our sample of stars. Applying a κ-σ clipping procedure with an iterative rejection of values exceeding the mean plus 2.6 σ (for a Gaussian distribution the chance probability of exceeding this value in one iteration is 0.5%) we reject all stars with mean *RV* errors in excess of 6.5 ${\rm m\,s^{-1}}$. Of the total sample of 41 stars only 38 are displayed, because three stars with large errors (79, 81, and 92 ${\rm m\,s^{-1}}$, 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 ${\rm m\,s^{-1}}$ 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 ${\rm m\,s^{-1}}$) has a mean of 3.91 ${\rm m\,s^{-1}}$ and a width of σ = 1.02 ${\rm m\,s^{-1}}$.

from 3.07 to 4.84 ${\rm m\,s^{-1}}$. These values are typical of the range of signal-to-noise values of our spectra (between 39 and 58 for GJ 1046) and well inside the distribution of errors in our sample of stars (Fig. 3). We also note that the *RV* errors increase with decreasing signal-to-noise ratio of the GJ 1046 spectra which would not be the case, if the errors were dominated by a perturbing signal.

In the performed simulations we added spectra of faint low-mass stars to the original GJ 1046 spectra. As summarised in Table 3 these simulations explored the companion mass regime 0.16–0.26 $M_\odot$ (first two table columns) which, according to the V-band mass-luminosity relation by Delfosse et al. (2000), corresponds to companions that are factors of 18–4 fainter than the 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; M 4V; mean S/N per pixel: 300) and GJ 682 (M 3.5V; mean S/N per pixel: 230) for masses ≤0.20 $M_\odot$ and ≥0.20 $M_\odot$, respectively (fourth column). For each simulated spectrum the companion spectrum was shifted to the appropriate companion *RV* for the probed mass value as well as scaled in flux corresponding to the brightness predicted by the V-band mass-luminosity relation.

We find that a companion with a mass ≥0.254 $M_\odot$ or 265 $M_{\rm Jup}$ and a factor of 4.1 fainter in the V-band than its primary would increase the internal error (fifth column in Table 3) to ≥7 ${\rm m\,s^{-1}}$ 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 *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 introduces an additional *RV* error (6th column in Table 3) of the same magnitude, i.e. it doubles the square of the errors. With an original value of 3.63 ${\rm m\,s^{-1}}$ we search in the simulated data for the companion mass and brightness that leads to a mean intrinsic error a factor of $\sqrt{2}$ larger, i.e. 5.13 ${\rm m\,s^{-1}}$. (We note in passing that this value is in the 88.4% percentile of the distribution of the stellar sample truncated at 7 ${\rm m\,s^{-1}}$; see Fig. 2.) The 9th column of Table 3 lists the chance probability of obtaining the excess error value listed in the 6th column.

For this increased error value we find a companion mass of ≥0.219 $M_\odot$ or 229 $M_{\rm Jup}$ and a primary-to-secondary V-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 $M_{\rm Jup}$ as the spectroscopic upper limit to the mass of the companion to GJ 1046. This value corresponds to an orbital inclination of 8.7°. The probability for an inclination as small

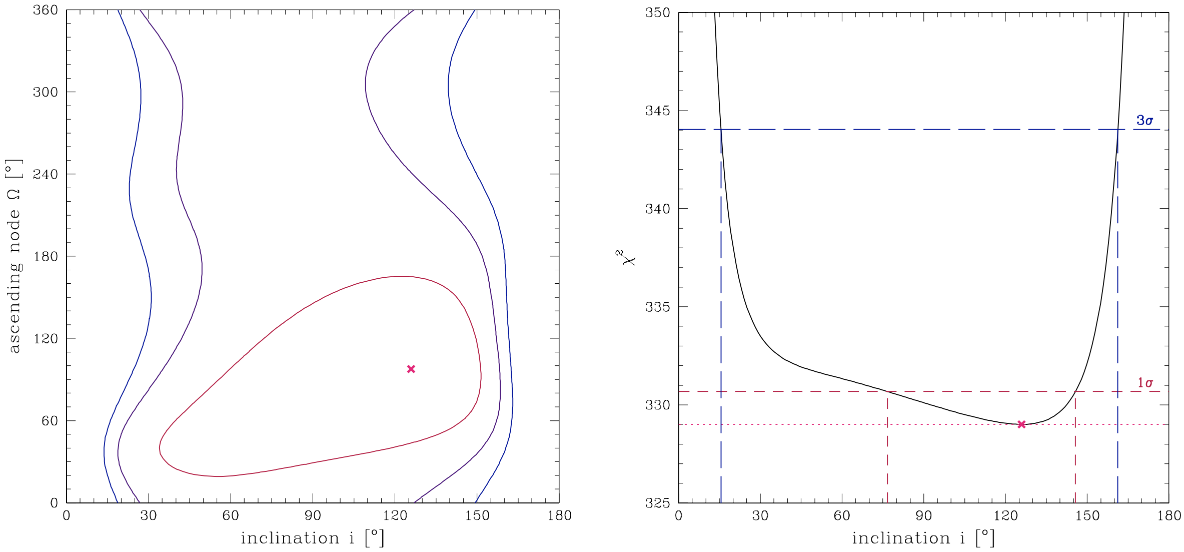

Fig. 3. *Left*: χ^2 contours for fitting a substellar companion with fixed spectroscopic parameters to the Hipparcos Intermediate Astrometric Data of GJ 1046. The inclination i and the ascending node Ω were free parameters of the fit, as were corrections to the standard five astrometric parameters in the Hipparcos Catalogue. The contours represent two-parameter joint confidence levels with probabilities of 68.3% (1σ), 95.4% (2σ), and 99.7% (3σ). The best fit solution is indicated by a cross. *Right*: the χ^2 of the astrometric orbit as a function of inclination only. In this case the 1σ and 3σ confidence levels indicated by the horizontal dashed lines correspond only to the single parameter i treating Ω as an uninteresting parameter. Again the best fit solution is indicated by a cross.

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 (71.11 mas) together with the orbital parameters derived from the *RV* measurements we can predict the minimum astrometric signal of the stellar reflex motion to be 3.7 mas peak-to-peak. This corresponds to the full minor axis of the orbit. Since the Keplerian fit to the *RV* data only permits the determination of the projected orbit of the stellar reflex motion, the true astrometric effect could be considerably higher. For the limiting inclination of 20.4° the full minor axis of the stellar orbit would extend 10.6 mas on the sky.

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 *RV*s 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 $M_{\rm Jup}$ 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 χ^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 $M_{\rm Jup}$.

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 $M_{\rm Jup}$ 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 $m = 229$ $M_{\rm Jup}$.

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 $M_{\rm Jup}$, 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 $M_{\rm Jup}$ 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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References

Bean, J. L., McArthur, B. E., Benedict, G. F., et al. 2007, AJ, 134, 749
Campbell, B., Walker, G. A. H., & Yang, S. 1988, ApJ, 331, 902
Delfosse, X., Forveille, T., Ségransan, D., et al. 2000, A&A, 364, 217
Endl, M., Kürster, M., & Els, S. 2000, A&A, 362, 585
Endl, M., Hatzes, A. P., Cochran, W. D., et al. 2004, ApJ, 611, 1121
ESA 1997, ESA SP-1200
Freed, M., Close, L. M., & Siegler, N. 2003, ApJ, 584, 453
Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., et al. 2001, ApJ, 551, L163
Grether, D., & Lineweaver, C. H. 2006, ApJ, 640, 1051
Joergens, V., & Müller, A. 2007, ApJ, 666, L113
Kürster, M., Endl, M., Rouesnel, F., et al. 2003, A&A, 403, 1077
Kürster, M., Endl, M., & Rodler, F. 2006, The Messenger, 123, 21
Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G. 1989, Nature, 339, 38
Montagnier, G., Ségransan, D., Beuzit, J.-L., et al. 2006, A&A, 460, L19
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., et al. 1996, Nature, 378, 463
Neuhäuser, R., & Guenther, E. W. 2004, A&A, 420, 647
Pourbaix, D. 2001, A&A, 369, L22
Pourbaix, D., & Arenou, F. 2001, A&A, 372, 935
Reffert, S., & Quirrenbach, A. 2006, A&A, 449, 699
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Standish, E. M. 1990, A&A, 233, 252
van Leeuwen, F. 2007a, Hipparcos, the New Reduction of the raw data (Dordrecht: Springer)
van Leeuwen, F. 2007b, A&A, 474, 653
Zucker, S., & Mazeh, T. 2000, ApJ, 531, L67