A brown dwarf companion to the intermediate-mass star HR 6037*

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ABSTRACT

Context. The frequency of brown dwarf and planetary-mass companions to intermediate-mass stars is still unknown. Imaging and radial velocity surveys have revealed a small number of substellar companions to these stars.

Aims. In the course of an imaging survey we have detected a visual companion to the intermediate-mass star HR 6037. In this letter we confirm it as a co-moving substellar object.

Methods. We present two epoch adaptive optics observations of HR 6037, an A6-type star with a companion candidate at 6′′67 and position angle of 294 degrees. We also analyze near-infrared spectroscopy of the companion.

Results. Two epoch observations of HR 6037 have allowed us to confirm HR 6037 B as a co-moving companion. Its J and H band spectra suggest the object has an spectral type of M9, with a surface gravity intermediate between a 10 Myr dwarf and a field dwarf of the same spectral type. The comparison of its Ks-band photometry with evolutionary tracks allows us to derive a mass, effective temperature, and surface gravity of 62±20 M_Jup, T_e = 2330 ± 200 K, and log g = 5.1 ± 0.2, respectively. The small mass ratio of the binary, ~0.03, and its long orbital period, ~5000 yr, makes HR 6037 a rare and uncommon binary system.

Key words. -- stars: binaries: visual -- brown dwarfs -- individual: HR 6037

1. Introduction

The frequency of brown dwarfs (BDs) and planetary-mass companions around intermediate-mass main sequence (MS) stars is uncertain. BDs can be formed by several mechanisms (e.g. Padoan & Nordlund 2004; Stamatellos & Whitworth 2009), but the expected substellar fractions for B-F type primaries are uncertain. In the case of giant planets formed in the disks of primary stars, some works predict a higher frequency around AB-type stars than in solar-type stars (e.g. Kennedy & Kenyon 2008). However, Kornet et al. (2006) show an opposite result since they conclude that the percentage of stars with giant planets decreases with increasing stellar masses from 0.5 to 4 M_⊙.

To shed light on this issue, different observational programs have been focused on deriving the frequency of BDs and planet-mass objects around intermediate-mass stars. As a result, planetary mass companions have been recently detected around three A- and F-type stars through adaptive optics (AO) assisted observations (Marois et al. 2008; Kalas et al. 2008; Lagrange et al. 2010). Radial velocity (RV) studies, which are sensitive to short period companions, have also reported the presence of substellar objects around several A-F type MS stars (Galland et al. 2005, 2006; Guenther et al. 2009), with minimum masses (M_sini ) in the planetary mass regime, that is, they could also be BDs. Transit programs have also detected planetary mass companions around several F-type stars (e.g. Bakos et al. 2007; Johns-Krull et al. 2008; Joshi et al. 2009; Hellier et al. 2009), and one around an A5 star (Christian et al. 2006; Cameron et al. 2010).

In the case of BDs, direct imaging surveys have allowed to study the fraction of wide substellar companions around intermediate-mass stars. As an example, Kouwenhoven et al. (2005, 2007) studied the late-B and A-type star population with high-contrast imaging. They did not report any new BD companion. In fact, up to now there is only one BD companion to an intermediate-mass star, HR7329 B, confirmed by direct imaging and near-IR spectroscopy (Lowrance et al. 2000; Guenther et al. 2001). RV studies have also detected BD companions to A-F type MS stars (Galland et al. 2006; Hartmann et al. 2010), and transit observations have reported the presence of a BD around an F-type star, CoRoT-3 b (Deleuil et al. 2008).

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As it follows, and despite the efforts, the occurrence of planetary-mass objects and BDs around intermediate-mass stars is still unknown and deserves additional observations.

In 2004, we started a project aiming at deriving the binary fraction and properties among a large volume-limited sample of intermediate-mass stars in the field (hereafter, Multi-NETS Project, Ivanov et al., 2006). Thanks to the use of deep AO near infrared imaging with Naos-Conica (NACO Lenzen et al., 2003) at the Very Large Telescope (VLT), we have been able to extend our study to substellar companions that are important to understand the formation of low mass ratio binaries. In the course of our survey, we detected a faint, visual companion to the star HR 6037. In this letter, we report the discovery and the co-moving confirmation of the companion to HR 6037 based on NACO astrometric observations obtained at two different epochs. We also present ISAAC near-infrared spectroscopic data that confirms, together with the photometry, that this companion is likely to be a new and rare substellar companion to the intermediate-mass star HR 6037.

2. HR 6037 stellar properties

HR 6037 is a main sequence A-type star classified as ‘variable’ by Samus et al. (2009) although its type of variability is uncertain. Its proper motion and parallax, according to Hipparcos (Perryman et al., 1997), are \( \mu_\alpha = -44.74 \pm 0.56 \) and \( \mu_\delta = -84.65 \pm 0.43 \) mas/yr, and 18.13 \pm 0.69 mas, respectively. The latter value translates into a distance of 55 \pm 2 pc.

We have derived the physical properties of HR 6037 by analyzing high resolution (R=80,000) optical archival spectroscopy obtained with VLT/UVES (Program ID 266.D-5655(A)). The spectrum was obtained integrating a total of 70 seconds, and was centered at 8800Å.

The primary is an A6V, as derived from spectral synthesis using SYNTHE (Kurucz, 1993). Our analysis also yields [Fe/H]=0.00\pm0.05, namely solar metallicity, and provides values for the effective temperature and surface gravity (see Table 1). Using the Hipparcos parallax we derive \( M_V = 2.24 \) and \( \log(g) = 4 \pm 0.02 \), assuming no extinction. Stromgren \( H_B = 2.884 \) and b-y= 0.069 photometry (Hauck & Mermilliod, 1998) confirms HR 6037 A as an A6 dwarf with temperature and gravity in agreement with values derived from the UVES spectrum.

We have plotted the object on a Hertzsprung-Russel diagram (see Fig. 1) and compared it with the Padova evolutionary tracks for solar metallicity (Marigo et al., 2008). We have used isochrones from 100 to 500 Myr, which is a typical age range for a star of this spectral type. We estimate an age of 300\pm100 Myr and a mass of 1.8\pm0.2 M\sun.

Finally, we note that the object was included in a RV survey to look for very close BDs and planetary-mass companions, showing no significant RV variation (Lagrange et al., 2009).

3. Observations and data reduction

3.1. NACO deep imaging

HR 6037 was observed in service mode with NACO, the adaptive optics facility at the VLT on June 30, 2004 and June 9, 2006. We used the visible wavefront sensor with the primary as a reference star. We observed in the Ks-band filter with the S27 objective optics facility at the VLT on June 2004 and August 2006. The values for the two campaigns are respectively 1.5 ms and 1.0, and 1.2 ms and 1.77, during the first and second epoch, respectively.

The data were reduced using Eclipse (Devillard, 1997), and following the standard procedure: dark subtraction, flat-field division, sky subtraction, alignment and stacking. The final image from 2006 is displayed in Fig. 2. Apart from the bright primary, we detect a visual companion at a projected separation of \( \sim 6\'\)'66 and position angle of \( \sim 294 \) degrees.

In order to measure precise separations and position angles, we derived the plate scale and orientation of the detector, CONICA, using archival observations of the astrometric calibrator IDS 21506-5133 (van Dessel & Sinachopoulos, 1993) obtained on June 2004 and August 2006. The values for the two campaigns are respectively 27.01 \pm 0.05 mas/pix and 27.02 \pm 0.05 mas/pix for the plate scale, and 0.0 \pm 0.2 deg and \(-0.1 \pm 0.2 \) deg for the True North orientation.

Table 1. Physical properties of HR 6037 A&B derived in this work

| Name      | Sp. Type | \( T_{\text{eff}} \) [K] | \( \log g \) [cm/s\(^2\)] | Mass [M\sun] | [Fe/H] |
|-----------|---------|-----------------|-----------------|--------------|--------|
| HR6037A   | A6      | 8120\pm100      | 4.2\pm0.1       | 1.8\pm0.2    | 0.00\pm0.05 |
| HR6037B   | M9      | 2330\pm200      | 5.1\pm0.2       | 0.06\pm0.02  | -      |

Fig. 1. HR Diagram with the location of HR 6037. We have over-plotted the Marigo et al. (2008) isochrones for five different ages between 100 Myr and 500 Myr (from the left to the right). We estimate an age of \( \sim 300\pm100 \) Myr for the primary.

Fig. 2. NACO/VLT image of HR 6037. The co-moving companion is encircled.
Near-infrared spectra of the HR 6037 B were obtained in service mode with ISAAC/VLT [Moorwood et al., 1998] on 2010-06-06/07 in the J and H atmospheric windows, and on 2010-06-11/12 in the K window, in the “classical” nodding-along-the-slit observing strategy. We used the low-resolution mode and the 0.6′′ wide slit, delivering a spectral resolution of R~800. We collected six exposures for J and H, and twelve for K but one J spectrum was discarded because of a low signal. The total integration times were 1115, 2232, and 4464 sec, respectively for J, H, and K. The seeing was clear on 2010-06-06/07, and thin clouds were present on 2010-06-11/12. B-type telluric standards were observed back-to-back with the science targets with the same instrument setup. One of them showed a strong Bracket γ emission line, which was fitted with a Gaussian and subtracted from the spectrum before applying the telluric correction.

The data were reduced using IRAF and following standard steps: flat field division, sky emission removal by subtracting images from corresponding nodding pairs, and extraction and combination of the individual spectra into the final spectrum. The wavelength calibration was performed using arcs. The telluric absorption was removed by divided the target spectra by the telluric standards, and multiplied them by the corresponding spectra from the library of Pickles (1998). Some of the spectra from this library are featureless models, so artificial emission spectra from the library of Pickles (1998). Some of the spectra remained in the final product. To remove them, we went back to the telluric spectra and subtracted Gaussian fits to their intrinsic stellar features – mainly Hydrogen recombination lines. This, together with the Bracket γ emission mentioned above implies some uncertainty in the spectral regions around the strong Hydrogen lines.

4. Results

4.1. HR 6037 B, a co-moving companion

Fig. 3 shows the difference in right ascension (RA) and declination (DEC) of HR 6037 and its companion candidate as measured in 2004 and 2006. We have also overplotted the expected difference in RA and DEC of a background object taking into account the proper motion and parallax of the primary. As seen, the companion shows RA and DEC differences consistent with a co-moving object. In fact, the difference in separation and position angle between the two epochs are consistent with a bound companion within the errors (see Table 2).

4.2. Spectral characterization of HR 6037 B

The ISAAC JHK spectra of HR 6037 B were first compared to libraries of template spectra of field dwarfs (Cushing et al., 2005; Rayner et al., 2009) and moderately young dwarfs from Upper Scorpius, TW Hydrea and β Pictoris associations (Allers et al., 2009; Rice et al., 2010). The K-band spectrum of HR 6037 B is much bluer than all M and early-L type dwarfs. This is probably due to a problem of flux loss during the observation. Therefore, only the J and H-band spectra were considered for the spectral classification based on the continuum comparison with libraries of field and young dwarfs. The best matches are displayed in Fig. 4. The J and H continuum of HR 6037 B is well reproduced by the spectrum of the young M8.5 dwarf 2M1207 A from the TW Hydrae association (8 Myr) and the M9 V field dwarf (Rayner et al., 2009), so we estimate an M9±1 spectral type.

Careful identification of the lines over the JHK spectral range shows the presence of broad molecular absorptions of H₂O (longward 1.33 and 1.66μm), FeH (at 1.194, 1.222, 1.239, 1.583-1.591 and 1.625 μm) as well as CO overtones longward 2.29 μm all typical of late-M dwarfs. There is also the possible presence of VO absorptions from 1.17 to 1.20 μm. In the J-band, the atomic line doublets of Na I and K I at 1.138, 1.169, 1.177, 1.243, 1.253 μm are well detected. We also detect the K I atomic line at 1.517 μm. Their strengths are intermediate between spectra of 10 Myr-old dwarfs, and those of field dwarfs with identical spectral types (see Fig. 4). This finding corroborates the age estimate of HR 6037 B A and B of a few tens to hundreds Myr (if both component are coeval).

4.3. HR 6037 B physical properties

The difference in K₁ magnitude between HR 6037 A&B in the NACO images was derived using standard packages for aperture photometry within IRAF, and is provided in Table 2. Since the
Fig. 4. Comparison of the $J$ & $H$ band ISAAC spectra of HR 6037 B companion (red) to the template spectra of the young 8 Myr-old dwarf 2M1207 A (M8.5) and the field dwarf (M9V). The spectrum of the very late type giant (IO Virginis) is also reported for comparison. All spectra have been normalized to 1.23 $\mu$m and 1.65 $\mu$m and offset.

2MASS $K_s$ value of the primary is 5.66±0.02 (Cutri et al. 2003), we estimate an average $K_s=14.1$±0.3 mag for the secondary, which translates into $M_K=10.4$±0.3 mag for a distance of 55±2 pc. We have compared this value with evolutionary tracks by Baraffe et al. (2002), assuming the age estimate derived from the UVES spectrum of the primary. According to DUSTY evolutionary tracks (Baraffe et al. 2002), a 300±100 Myr object with $M_K=10.4$±0.3 mag, corresponds to a 62±20 M$_{Jup}$ BD with $T_{eff}=2330±200$ K, and log $g=5.1±0.2$.

4.4. HR 6037 A&B: main properties of the binary system

The mass ratio of HR 6037 A&B is $q=0.034$. This mass ratio is not common for binaries with intermediate-mass stars as primaries. The projected separation of the binary components, for a distance of 55 pc, is ~366 AU. Using Kepler’s third law, we derive an orbital period of ~5000 yr. Even if imaging surveys are sensitive to these long period, small mass ratio binaries, they are uncommon (e.g. Kouwenhoven et al. 2007; Ehrenreich et al. 2010). Hence, we can conclude that HR 6037 A&B is an extremely rare binary system.

5. Conclusions

We report the detection of a BD companion to the 300 Myr old star HR 6037. Our main results can be summarized as follows:

1. HR 6037 is a binary system with a separation of 6′66 and position angle of 293.9±0.1 degrees. Two epoch observations confirm that HR 6037 B is a co-moving companion.

2. Near-IR spectroscopy reveals a spectral type of M9±1 for HR 6037 B by comparison of the $J$ and $H$ band continuum to templates. The strength of the gravity-sensitive features are consistent with a dwarf intermediate between a low-gravity young dwarf and high-gravity field dwarf of similar spectral type. This result is consistent with the age derived for the primary, 300 Myr, i.e. both objects appear to be coeval.

3. Evolutionary tracks predict a mass of $62±20$ M$_{Jup}$, an effective temperature of $T_{eff}=2330±200$ K, and a surface gravity of log $g=5.1±0.2$.

To our knowledge, HR 6037 B is the second BD companion confirmed to be bound to an intermediate-mass star by two epoch observations and spectroscopy. Its small mass ratio and long orbital period makes it a rare and uncommon binary system.

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References

Allers, K. N., Liu, M. C., Shkolnik, E., et al. 2009, ApJ, 697, 824
Bakos, G. A., Kovács, G., Torres, G., et al. 2007, ApJ, 670, 826
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, A&A, 382, 563
Cameron, A. C., Guenther, E., Smalley, B., et al. 2010, MNRAS, 407, 507
Christian, D. J., Pollacco, D. L., Skillen, I., et al. 2006, MNRAS, 372, 1173
Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005, ApJ, 623, 1115
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, 2246, 0
Deleuil, M., Deeg, H. J., Alonso, R., et al. 2008, A&A, 491, 889
Devillers, N. 1997, The Messenger, 87, 19
Ehrenreich, D., Lagrange, A., Montagnier, G., et al. 2010, ArXiv e-prints
Galland, F., Lagrange, A., Udry, S., et al. 2006, A&A, 452, 709
Galland, F., Lagrange, A., Udry, S., et al. 2005, A&A, 444, L21
Guenther, E. W., Hartmann, M., Esposito, M., et al. 2009, A&A, 507, 1659
Guenther, E. W., Neuhäuser, R., Huélamo, N., Brandner, W., & Alves, J. 2001, A&A, 365, 514
Hartmann, M., Guenther, E. W., & Hatzes, A. P. 2010, ApJ, 717, 348
Hauck, B. & Mermilliod, M. 1998, A&AS, 129, 431
Hellier, C., Anderson, D. R., Cameron, A. C., et al. 2009, Nature, 460, 1098
Ivanov, V. D., Chauvin, G., Focardi, S., et al. 2006, Ap&SS, 304, 247
Johns-Krull, C. M., McCullough, P. R., Burke, C. J., et al. 2008, ApJ, 677, 657
Joshi, Y. C., Pollacco, D., Cameron, A. C., et al. 2009, MNRAS, 392, 1532
Kalas, P., Graham, J. R., Chiang, E., et al. 2008, Science, 322, 1345
Kennedy, G. M. & Kenyon, S. J. 2008, ApJ, 682, 1264
Kornet, K., Wolf, S., & Różycka, M. 2006, A&A, 458, 661
Kouwenhoven, M. B. N., Brown, A. G. A., Portegies Zwart, S. F., & Kaper, L. 2007, A&A, 474, 77
Kouwenhoven, M. B. N., Brown, A. G. A., Zinnecker, H., Kaper, L., & Portegies Zwart, S. F. 2005, A&A, 430, 137
Kurucz, R. 1993, SYNTHE Spectrum Synthesis Programs and Line Data. Kurucz CD-ROM No. 18. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993, 18
Lagrange, A., Bonnefoy, M., Chauvin, G., et al. 2010, Science, 329, 57
Lagrange, A., Desert, M., Galland, F., Udry, S., & Mayor, M. 2009, A&A, 495, 335
Lenzen, R., Hartung, M., Brandner, W., et al. 2003, in Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, Vol. 4841, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. M. Iye & A. F. M. Moorwood, 944–952
Lowrance, P. J., Schneider, G. K., Kirkpatrick, J. D., et al. 2000, ApJ, 541, 390
Marigo, P., Girardi, L., Bressan, A., et al. 2008, A&A, 482, 883
Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348
Moorwood, A., Cuby, J., Bierich, P., et al. 1998, The Messenger, 94, 7
Padoan, P. & Nordlund, A. 2004, ApJ, 617, 559
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Pickles, A. J. 1998, PASP, 110, 863
Rayner, J. T., Cushing, M. C., & Vacca, W. D. 2009, ApJS, 185, 289
Rice, E. L., Faherty, J. K., & Cruz, K. L. 2010, ApJ, 715, L165
Samus, N. N., Durlevich, O. V., & et al. 2009, VizieR Online Data Catalog, 1, 2025
Stamatellos, D. & Whitworth, A. P. 2009, MNRAS, 392, 413
van Dessel, E. & Sinachopoulos, D. 1993, A&AS, 100, 517