An accurate distance to 2M1207Ab *

C. Ducourant1, R. Teixeira2,1, G. Chauvin3, G. Daigne1, J.F. Le Campion1, Inseok Song4, and B. Zuckerman5

1 Observatoire Aquitain des Sciences de l’Univers, CNRS-UMR 5804, BP 89, 33270 Floirac, France.
2 Laboratoire d’Astrophysique, Observatoire de Grenoble, 414, Rue de la piscine, 38400 Saint-Martin d’Hères, France
3 Laboratoire d’Astrophysique, Observatoire de Grenoble, 414, Rue de la piscine, 38400 Saint-Martin d’Hères, France
4 Spitzer Science Center, IPAC/Caltech, MS 220-6, Pasadena, CA 91125, USA
5 Department of Physics & Astronomy and Center for Astrobiology, University of California, Los Angeles, Box 951562, CA 90095, USA

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ABSTRACT

Context. In April 2004 the first image was obtained of a planetary mass companion (now known as 2M1207b) in orbit around a self-luminous object different from our own Sun (the young brown dwarf 2MASSW J1207334-393254, hereafter 2M1207 A). 2M1207 b probably formed via fragmentation and gravitational collapse, offering proof that such a mechanism can form bodies in the planetary mass regime. However, the predicted mass, luminosity, and radius of 2M1207 b depend on its age, distance, and other observables such as effective temperature.

Aims. To refine our knowledge of the physical properties of 2M1207 b and its nature, we obtained an accurate determination of the distance to the 2M1207 A and b system by measurements of its trigonometric parallax at the milliarcsec level.

Methods. With the ESO NTT/SUSI2 telescope, in 2006 we began a campaign of photometric and astrometric observations to measure the trigonometric parallax of 2M1207 A.

Results. An accurate distance \((52.4 \pm 1.1 \text{ pc})\) to 2M1207A was measured. From distance and proper motions we derived spatial velocities fully compatible with TWA membership.

Conclusions. With this new distance estimate, we discuss three scenarios regarding the nature of 2M1207 b: (1) a cool \((1150 \pm 150 \text{ K})\) companion of mass \(4 \pm 1 \text{ M}_{\text{Jup}}\), (2) a warmer \((1600 \pm 100 \text{ K})\) and heavier \((8 \pm 2 \text{ M}_{\text{Jup}})\) companion occulted by an edge-on circumsecondary disk or (3) a hot protoplanet collision afterglow.

Key words. Extra-solar planets – Brown dwarf – mass determination – Parallax – TW Hydrael Association

1. Introduction

Since the discovery of the enigmatic classical T Tauri star TW Hya isolated from any dark cloud (Rucinski & Krautter 1983), important progress has been made with the diagnostic selection and the identification of young stars near the Sun. In addition to the members of the TW Hydrael association (Kastner et al. 1997) hereafter TWA, we count nowadays more than 200 young \((<100 \text{ Myr})\), nearby \((<100 \text{ pc})\) stars, gathered in different clusters and co-moving groups, such as \(\eta\) Chamaleonis (Mamajek et al. 1999), \(\beta\) Pictoris (Zuckerman et al. 2001), Tucana-Horologium (Torres et al. 2000, Zuckerman & Webb 2000), AB Doradus (Zuckerman et al. 2004) and the most recent identified candidates of the SACY survey (Torres et al. 2006). Their youth and proximity make these stars ideal sites for study of mechanisms of planet, brown dwarf and star formation. They also represent favorable niches for calibration of evolutionary tracks through dynamical mass measurements. With the development of direct imaging and interferometric techniques, the circumstellar environment of these young stars is now probed down to a few AU. The number of resolved disks \((\beta\) Pic, Smith and Terrille 1984; HR 4796, Schneider et al. 1999; TW Hya, Krist et al. 2000; AU Mic, Liu 2004), substellar companions (TWA5, Lowrance et al. 1999; HR7329, Lowrance et al. 2000; GSC 8048-00232, Chauvin et al. 2003 and AB Pic, Chauvin et al. 2005) and pre-main-sequence binaries with dynamically determined masses (HD 98800, Boden et al. 2005) and pre-main-sequence binaries with dynamically determined masses (HD 98800, Boden et al. 2005) and pre-main-sequence binaries with dynamically determined masses (HD 98800, Boden et al. 2005) continue to increase.

In the rush to discover companions with masses below that required to burn deuterium, Chauvin et al. (2004) obtained an image of an extrasolar companion of planetary mass. This object was discovered near 2MASS J1207334-393254 (hereafter 2M1207 A), a brown dwarf (BD) member of the 8 Myr old TWA (Gizis 2002). 2M1207 A is proposed to have a near edge-on accreting disk (Gizis 2002, Mohanty et al. 2003, Sterzik et al. 2004) and to drive a bipolar resolved jet (Whelan et al. 2007). This binary system, the lightest known to drive an outflow, offers new insights in the study of mechanisms of formation and evolution of BDs, including their disk and jet properties and physical and atmospheric characteristics of objects as light as a few Jupiter masses.

Although numerous techniques have been devoted to study this binary system (imaging, spectroscopy, astrometry) at different wavelengths (X-ray, UV, visible, near-IR, mid-IR, radio), its distance remained uncertain and not well constrained. The initial distance estimate of \(~ 70 \text{ pc}\) by Chauvin et al. (2004) was improved by Mamajek (2005) who obtained an estimate of \(53 \pm 6 \text{ pc}\) based on the moving cluster method. This method relies on the
Table 1. Astrometric and Bessel photometric parameters for 2M1207 A measured with ESO NTT/Susi2.

| α   | δ   | μ_αabs | μ_δabs | π_abs | d   | V  | R  | I  |
|------|-----|--------|--------|-------|-----|----|----|----|
| (2000) | (2000) | (mas/yr) | (mas/yr) | (mas) | (pc) | (mag) | (mag) | (mag) |
| 12°07'33.460'' | -39°32'53.97'' | -64.2±0.4 | -22.6±0.4 | 19.1±0.4 | 52.4±1.1 | 20.15±0.19 | 18.08±0.17 | 15.95±0.13 |

space motion determination for the TWA and the proper motion of 2M1207A. The space motion determination for the TWA was based on the four members with known Hipparcos distance: TWA1, TWA4 TWA9 and TWA11. Song et al. (2006) suggested that significant uncertainties in the Hipparcos distance to TWA9 might affect the cluster distance estimation. They proposed a new distance estimate of 59±7 pc based on an improved proper motion determination for 2M1207A scaled with the proper motion and the Hipparcos distance to HR 4796 A (TWA11).

To determine a firm estimate for the distance to 2M1207 via measurement of its trigonometric parallax, since January 2006 we have conducted astrometric and photometric observations at the ESO NTT telescope. At the same time others observational programme were developed yielding results similar to ours (Biller and Close 2007, Gizis et al. 2007, Mamajek and Meyer 2007) and discussed below. Our observations are presented in Section 2. The data reduction and analysis and the result of this trigonometric parallax programme are given in Section 3. Finally, the physical properties and different hypotheses for the nature of 2M1207 b are discussed in Section 4.

2. Observations

2.1. Instrumental set-up and strategy

Astrometric and photometric (V, R, I) observations were performed with the ESO NTT telescope equipped with the SUSI2 camera which ensures a nice compromise between the field of view (5.5' × 5.5') and the pixel scale 80.5 mas/pixel assuring a reasonable number of field stars (113) necessary to perform accurate astrometric reductions. Seven sets of data were acquired between January 2006 and May 2007 with a total of fourteen nights of observation. All astrometric observations were realized in the ESO I#814 filter. A calibration star with known trigonometric parallax DEN 1048-3956 was also observed in order to validate our results.

2.2. Differential colour refraction

Atmospheric refraction will affect differently our target brown dwarf and the background reference stars (typically main-sequence G or K stars) when observed through a given filter bandpass because of their difference in effective wavelength. This is called differential colour refraction (DCR) (Ducourant et al. 2007) which is a major source of systematic errors in parallax programs. To minimize DCR all measurements were performed near transit of the target (projected tangent of the zenith distance in R.A. ≤ 20'). Following Monet et al. 1992, we performed observations at small and large hour angle during an observing night to empirically calibrate the difference of refraction between the target and the reference stars. We present this calibration in Figure 2. All measurements of the target were corrected for DCR. The difference of slope between 2M1207A and background stars is $\Delta F = -0.004 ± 0.001$ pix/deg. One can evaluate the accuracy of DCR correction as $\sigma_{DCR} = \sigma_{\Delta F} < Z_a >= 0.38$ mas (with $<Z_a> = 11.8^\circ$, mean projected tangent of the zenith distance in right ascension of observations).

3. Data reduction and analysis

3.1. Astrometry

Images were measured using the DAOPHOT – II package (Stetson 1987) fitting a PSF to the images. The astrometric reduction of the whole dataset (261 images) was performed iteratively through a global central overlap procedure (see Ducourant et al. 2007) in order to determine simultaneously the position, the proper motion and the parallax of each object in the field. Each valid observation of each well-measured object in the field participates in the final solution (error on instrumental magnitude $\leq 0.07$ (as given by DAOPHOT), $\text{Imag} \leq 21.5$). We present in Figure 2 the observations of 2M1207 A together with the fitted path (relative parallax and proper motions).

3.2. Conversion from relative to absolute parallax

As a consequence of the least-square treatment, the parallax and proper motion of the target is relative to reference stars (that are supposed to reside at infinite distance). The correction from this relative parallax to the absolute value is performed using a statistical evaluation of the distance of the 113 reference stars (13.5 ≤ $I \leq 21.5$), using the Besançon Galaxy model (Robin et al. 2003, 2004). This correction is $\Delta \pi = +0.58 ± 0.01$ mas. Same method is used to convert the relative proper motion of...
2M1207A to absolute proper motion. We derive the corrections: \( \Delta \mu_a = -57.5 \pm 0.4 \) mas/yr, \( \mu_b = -22.5 \pm 0.4 \) mas/yr.

3.3. Space motion

With our measured absolute parallax, together with a radial velocity of \(+11.2\pm2.0\) km s\(^{-1}\) from Mohanty et al. (2003) and absolute proper motion, we calculate the Galactic space velocity \((U,V,W)\) of 2M1207A as \((-7.9\pm0.8,-18.3\pm1.7,-3.5\pm0.8)\) km s\(^{-1}\).

The comparison of our results with the data from Reid (2003) \((-10.0\pm2.6,-17.8\pm2.1, -4.6\pm1.1)\) confirms the compatibility of 2M1207A motion with TW A membership.

3.4. Control star

Our parallax solution for DEN 1048-3956 is \( \pi_{\text{abs}} = 251.5 \pm 0.7 \) mas and \( (\mu_a^*, \mu_b^*)=(-1170.0,-996.0)\pm(0.6,0.6)\) mas/yr which is in good agreement with Costa et al. 2005 \( (\pi_{\text{abs}} = 249.8 \pm 1.8 \) mas, \( (\mu_a^*, \mu_b^*)=(-1175.3,-993.2)\pm(2.2,2.2)\) mas/yr.

We present in Table 2 astrometric and photometric parameters for 2M1207A.

4. Discussion

Since the discovery in 2004 of the planetary mass companion 2M1207 b, several groups have worked at its distance determination (see table 2). Chauvin et al. (2004) first estimated a distance to and mass for 2M1207 b of 70 pc and 5 \( \pm 2 \) M\(_{\text{Jup}}\), and an associated effective temperature of 1250 \( \pm 200 \) K. A low signal-to-noise spectrum in H-band enabled them to suggest a mid to late-L dwarf spectral type for 2M1207 b. Mamajek (2005) re-estimated the mass of 2M1207 b. Converting the \( K_s \) absolute magnitude into luminosity using a bolometric correction appropriate for mid and late-L dwarfs (Golimowski et al. 2004), based on his nearer distance estimate, he derived a mass of \( 3 - 4 \) M\(_{\text{Jup}}\) from both DUSTY and COND evolutionary models (Baraffe et al 2003).

With HST/NICMOS multi-band (0.9 to 1.6 \( \mu \)m) photometry and a distance estimate of 59\( \pm 7 \) pc, Song et al. (2006) derived a mass of \( 5 \pm 3 \) M\(_{\text{Jup}}\) for 2M1207 b, due to its brighter flux than expected from model predictions at shorter wavelengths (for a given mass and age) and to the scatter in the emergent flux predicted by the DUSTY and COND03 evolutionary models at wavelengths less than \( 2 \mu \)m (and shown in Fig. 3).

In addition to J-band photometry, Mohanty et al. (2007) obtained an HK spectrum of 2M1207 b at low-resolution \( (R_s = 100)\). Comparison with synthetic spectra DUSTY, COND and SETTLE yielded an effective spectroscopic temperature of \( 1600 \pm 100 \) K, leading Mohanty et al. (2007) to suggest a mass of \( 8 \pm 2 \) M\(_{\text{Jup}}\) for 2M1207 b. However, this mass and temperature are inconsistent with that expected from model predictions based on absolute magnitudes spanning \( f \) to \( L^\prime\)-band photometry. This discrepancy is explained by Mohanty et al. (2007) by a gray extinction of \( \sim 2.5 \) mag between 0.9 and \( 3.8 \mu \)m caused by the occultation of a circum-secondary edge-on disk. This hypothesis is illustrated in Fig. 3.

Gizis et al. (2007) note that the hypothesis of a lighter and cooler 2M1207 b cannot be ruled out by the current photometric, spectroscopic and parallax observations. Synthetic atmosphere models clearly encounter difficulties in describing faithfully the late-L to mid-T dwarfs transition \( (\sim 1400 \) K for field L/T dwarfs\). This transition corresponds to the process of cloud clearing, that is, an intermediate state between two extreme cases of cool atmospheres: saturated in dust (DUSTY) and where dust grains have sunk below the photosphere (COND03). It is therefore probable that synthetic spectra fail for the moment to properly model the spectroscopic and physical characteristics of young L and T dwarfs. Comparison of absolute fluxes of 2M1207 b with DUSTY and CON03 model predictions for
the age of the TWA illustrates this possible intermediate state. In such a scenario, absolute magnitude and luminosity based on the $K_{s}$-band photometry indicate a mass of $4 \pm 1 M_{Jup}$ and an effective temperature of $1150 \pm 150$ K. Such low temperatures for a young mid to late-L dwarf would corroborate the observations of HD 203030 B (Metchev & Hillenbrand 2006) and TN Peg (Luhman et al. 2007) indicating that the L/T transition is possibly gravity dependent and appearing for temperatures as low as $\sim 1200$ K. Our current accurate parallax measurement ($52.4 \pm 1.1$ pc) slightly changes the absolute magnitudes and errors from ones given by Mamajek (2005), Song et al. (2006), Mohanty et al. (2007) and Gizis et al. (2007), but does not modify their conclusions. The predicted physical properties (mass, luminosities, effective temperature and gravity) are summarized in Table 3 for the two models described above. An alternative hypothesis has been proposed by Mamajek & Meyer (2007) to explain the subluminosity of 2M1207 b. Their explanation is that the apparent flux is produced by a hot protoplanet collision afterglow. Mamajek & Meyer (2007) suggest several ways to test this hypothesis, for example a lower surface gravity ($\log(g) \sim 3$) and a rich metallicity for the protoplanetary collision remnant. In addition, potential observables such as polarized emission, infrared excess, resolved scattered light or a proposed 10 $\mu$m silicate absorption feature (predicted if 2M1207b is occulted by a circum-secondary edge-on disk), should help to clarify the nature of 2M1207 b.

5. Conclusion
Motivated by the need to have an accurate distance determination of the 2M1207 A and b system to better refine the properties of 2M1207b, we measured the trigonometric parallax of the unresolved system with a precision better than 2%. This parallax puts 2M1207 A and b at 52.4+1.1 pc from our Sun and, along with our accurately measured proper motion, lends substantial support to the notion that this binary is a member of the young TW Hydrae Association and, thus, that the mass of 2M1207b lies clearly in the planetary mass range.

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