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Letter to the Editor

A second substellar companion in the Gliese 86 system*

A brown dwarf in an extrasolar planetary system

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Abstract. We report observations using the ESO adaptive optics system ADONIS of the known extrasolar planetary system Gliese 86. This star has a known 4 $M_{\rm Jup} \sin i$ planet in a 15.8 day orbit and exhibits an additional, large, long-period, radial velocity drift (Queloz et al. 2000). The coronographic images reveal a faint ($J = 14.7, H = 14.4, K = 13.7$) object at a projected distance of $r = 1\farcs72 \pm 0\farcs02$ and PA $= 119 \pm 1°$. Gliese 86 and the discovered object share the same proper motion, as confirmed by independent measurements at three different epochs indicating that this system is gravitationally bound. From the infrared colors and magnitudes we infer an approximate spectral type for Gliese 86B at the transition from L to T dwarfs, also called "early T dwarf" assuming the classification by Leggett et al. (2000). Although present brown dwarf evolutionary models do not cover the mass and age range probed by this objects, an upper limit of the mass of about $M_{\rm GJ86B} \leq 70\ M_{\rm Jup}$ can be inferred from the models by Baraffe et al. (1998). Dusty model atmospheres appear not to be compatible with the IR colors.

Key words. stars: individual: Gliese 86 – stars: brown dwarfs – planetary systems

1. Introduction

Among the more than 50 extrasolar planetary systems inferred so far from high precision radial velocity surveys (e.g. Marcy et al. 2000) is the signature of a planetary companion with a minimum mass of 4 $M_{\rm Jup} \sin i$ in a 15.8 days period orbit around the K dwarf Gliese 86 (or Gl 86) (see Queloz et al. 2000).

The radial velocity data measured over the last 20 years do not only show the variation due to the planetary companion, but also exhibit a large, long term, drift of about 0.3 to 0.5 ms^{-1} day^{-1}. The combination of these measurements with historical data led to the suspicion that Gl 86 has an additional companion in an orbit with a semi major axis larger than 20 AU. As the distance of Gl 86 is only 10.9 pc towards the sun, direct imaging of such a companion seems worthwhile. As reported in a poster by Sterzik, Marchis & Kürster (unpublished) the ESO adaptive optics system ADONIS was used to search for a companion close to Gl 86 but without success. Their sensitivity estimate in K band excluded any stellar companion earlier than M6 further then $1\farcs0$ from Gl 86.

In this Letter we report on new, high angular resolution, adaptive optics observations of Gl 86 leading to the detection of another substellar companion in this extrasolar planetary system.

2. Observations and data reduction

We observed the Gl 86 system with ESO's adaptive optics system ADONIS (Rousset & Beuzit 1999), mounted on the 3.6 m telescope on La Silla, Chile. The SHARP II+ near infrared camera was attached to the instrument and a pixel scale of 50 mas/pixel was used throughout all observations. In order to increase the sensitivity to detect any faint, closeby companion, the light of Gl 86 was suppressed by a pre–focal coronographic mask (Beuzit et al. 1997). For all observations a mask with a size of 1″ in diameter was chosen. Usually, we took cubes containing 60 images of Gl 86 with 6 s of integration time each. Sky emission was corrected by observing a position $1\farcm5$ north and south of Gl 86 immediately after the prime scientific target.

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* Based on observations collected with the 3.6 m Telescope of the European Southern Observatory La Silla under proposal Nos. 66.C-0333, 266.C-5621 and 266.C-5634.

A brief observing log is given in Table 1.

For further data processing we got references of the Point–Spread–Function (PSF) by observing the star HD 13424 directly before or after each integration of Gl 86 (during the observations in September we observed an additional PSF reference star, namely HD 14112).

For the observing runs in November and December, the detector pixel scale and the absolute orientation of the camera were checked observing an astrometric reference field (θ Ori). The accuracy of the absolute field orientation is found better than $0.2°$, fully consistent with systematic measurements taken over more than a year[1].

In general, the atmospheric conditions during our observations were good. Seeing conditions were always better than $1.''2$ and in average around $0.''8$. All observations were taken with an airmass of less than 1.5 except for the observations in December which were taken at an airmass of about 1.6. As photometric standard star we usually observed HR 0721. In the night of November 10, AS01 was observed as photometric standard star. The zero–points derived from the standard stars agree with the published values within 0.05 mag [2].

Table 1. Observing log for Gl 86. A coronographic mask with $1.''$ in diameter was always used. For each filter setting, one data cube was acquired, except in the September night, when 5 independent measurements were performed

Date	filters used	remarks
08.09.2000	H	5 independent measurements
10.11.2000	$J\ K$	
11.11.2000	$J\ K\ K_S$	
13.11.2000	K_S	
12.12.2000	CVF	$\lambda = 1.51, 1.57$ and $1.61\ \mu$m

3. Results

After the standard reduction process (sky substraction, flatfielding and bad pixel removal), we applied an optimum PSF–substraction technique developed by Pantin et al. (2000). A faint object is located in the east direction of Gl 86 (see Fig. 1) and can already be seen in the non-PSF substracted images. But applying the PSF subtraction technique it is much easier to identify, because the residual light in the wings of the coronographic image of Gl 86 is efficiently reduced.

3.1. Astrometry

Gl 86 is a high proper motion star with $\mu_\alpha^* = 2092.7$ mas/yr and $\mu_\delta = 654.8$ mas/yr as measured by Hipparcos. We would therefore expect the object to move 9.08 mas/day in western and 1.79 mas/day in southern direction relative to Gl 86 if it is an unrelated background star. The high proper motion of this star enables therefore to check for the binding status within the relatively short time baseline of three months.

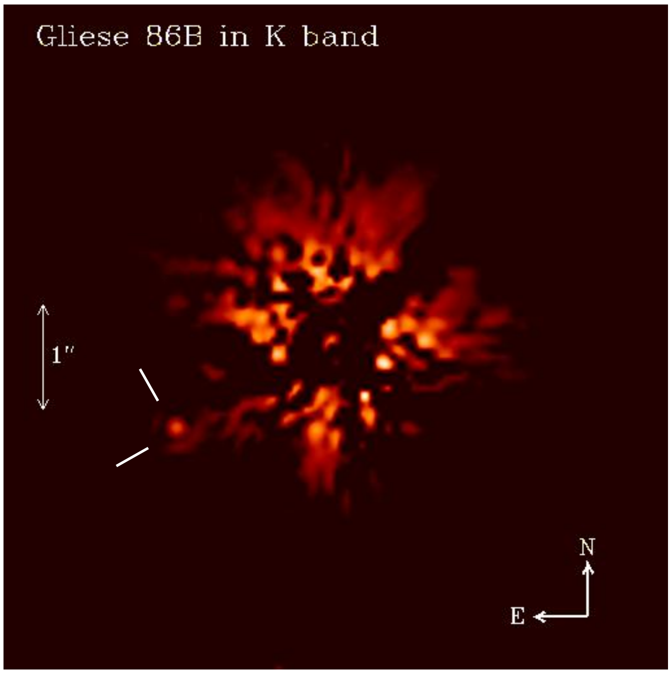

Fig. 1. Gl 86 in K band after applying the optimum PSF subtraction of Pantin et al. (2000). The PSF reference star HD 13424 was observed about 20 min after Gl 86. The total integration time on Gl 86 and on HD 13424 was 6 min each. The found companion is located between the two bars. Note also the *Airy ring* around the companion

We define the position of Gl 86 by fitting circular isophotes to the non PSF subtracted, coronographic, image. The center of the circle is determined at different isophot values, and agrees well within an error of less than about half a pixel size (i.e. $\leq 0.''025$). The position of the faint object is then easily found relative to this central position by fitting a Gaussian to it in the PSF subtracted image.

Applying this procedure to our datasets we find that the distance between Gl 86 and the faint object does not change significantly during our time baseline (see Table 2). We conclude that this object is indeed a gravitationaly bound companion to Gl 86 at a projected distance of

Table 2. Astrometric data of the detected object relative to Gl 86. The first column shows the date of observation, the $\Delta\alpha$ and $\Delta\delta$ denote the *measured* offsets in right ascention and declination of the companion relative to Gl 86. $\Delta\alpha^*$ and $\Delta\delta^*$ denote the expected relative position of the object if unrelated to Gl 86 by using its proper motion

Date	$\Delta\alpha$ [mas]	$\Delta\delta$ [mas]	$\Delta\alpha^*$ [mas]	$\Delta\delta^*$ [mas]
08.09.2000	1510 ± 25	853 ± 6	1510	853
10.11.2000	1522 ± 3	789 ± 20	929.1	962.2
12.12.2000	1508 ± 10	851 ± 13	638.6	1019.5

[1] see: `http://www.bdl.fr/priam/adonis/`

[2] see: `http://www.ls.eso.org/lasilla/Telescopes/360cat/adonis/html/Table_Photometry_SHARP.html`

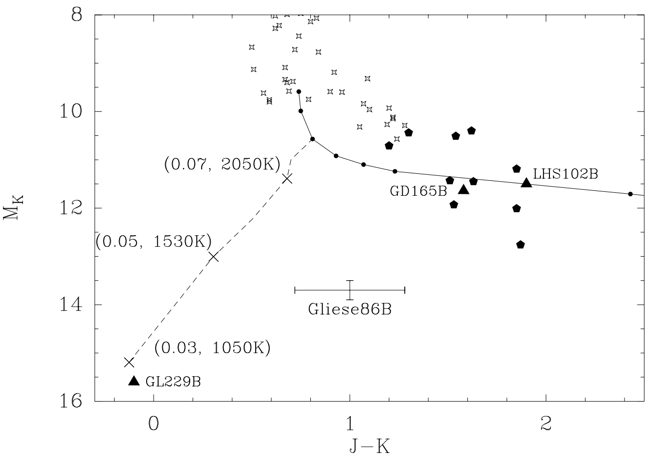

Fig. 2. Color–Magnitude diagram of Gl 86B. The DUSTY model track of a 1 Gyr old object is indicated by the solid line (dots mark from right to left the models with 0.06, 0.07, 0.072, 0.075, 0.08, 0.09 and 0.1 $M_\odot$) and the dashed line represents the COND model (from Chabrier et al. 2000) of the same age (the numbers and crosses at the COND track give the mass in $M_\odot$ and the temperature). Late M dwarfs are marked by small stars and are taken from Leggett et al. (1998). Some BD companions with known absolute photometry are marked by triangles and other BDs as polygons (data from Dahn et al. 2000; Goldman et al. 1999; Kirkpatrick et al. 1999). Gl 86B apparently falls in a region not covered by the two extreme model cases: dusty or dust free atmosphere

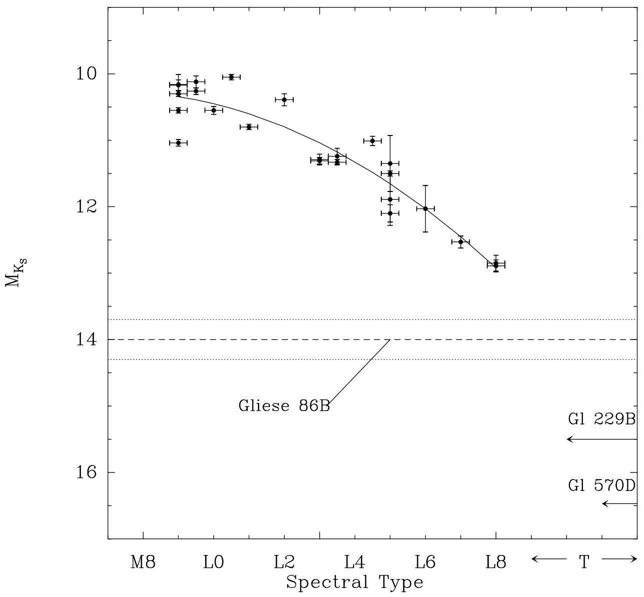

Fig. 3. Gl 86B placed into the Fig. 8 of Kirkpatrick et al. (2000). It shows that Gl 86B falls also in the K_S band between the known L and T dwarfs. The dashed line represents the measured K_S magnitude of Gl 86B with its error interval (dotted lines). The points with error bars represent known M and L dwarfs and are fitted by the solid line representing a second–order polynomial fit. The known T–dwarfs Gliese 229B and Gliese 570 D are also indicated and are more than 2.5 mag fainter than the latest L–dwarfs (after Kirkpatrick et al. 2000)

$r = 1\farcs72 \pm 0\farcs03$ and a position angle PA $= 119 \pm 1°$. From now on, we will call this object Gl 86B.

3.2. Photometry

Gl 86B is faint, and to derive its photometry is not without difficulties. In order to reduce the large gradient in the local background of the object, caused by the residual wing left from the occulting mask, we used the PSF–subtracted images for aperture photometry. This method turned out to be very robust and converges at a certain aperture size where the background is still flat enough and not affected by the increasing noise residuals towards the mask. Having at least *two* data cubes per filter during different nights, we find that the measured flux of Gl 86B does not vary by more than about 20% between these images. Conservatively, we estimate our photometric error to be within 0.2–0.3 mag. We find the following magnitudes for Gl 86B: $J = 14.7$ (±0.2), $H = 14.4$ (±0.2), $K = 13.7$ (±0.2) and $K_S = 14.2$ (±0.3). As the distance of Gl 86 is measured by Hipparcos a distance modulus of 0.19 can be adopted for this object. We also observed Gl 86B using the Circular Variable Filter (CVF) mode of SHARP II+ which is a narrow–band filter system allowing to select the central wavelength thus giving a resolving power of $R = 60$. We planned to test the presence of methane absorption bands (Brandner et al. 1997), but the low count–rates, and the unavailability of PSF reference star observations did not allow us to derive reliable flux ratios for the three CFV bands chosen. Thus these observations have been used for astrometric purpose only. The magnitude difference between Gl 86 and the companion is more than 9 mag in K band. This and their small separation explain why Sterzik, Marchis & Kürster could not detect this object in their images which were taken without a coronographic mask.

4. Discussion

In the color–magnitude diagram we find that Gl 86B appears in a region well below the hydrogen burning limit (Fig. 2). It is lying between the evolutionary model tracks of COND and DUSTY (see Chabrier et al. 2000). The COND model represents an atmosphere in which a rapid grain settlement below the photosphere takes place, thus ignoring the influence of condensates on the radiative transfer but taking dust into account in the equation of state. On the other hand, DUSTY models use all condensates in the equation of state as well as in the radiative transfer equations. As pointed out in Chabrier et al. (2000), these two models represent the two extreme possible cases of a brown dwarf atmospheres. As can be seen from Fig. 2 neither the DUSTY nor the COND models seem to fit Gl 86B. Assuming coevality, an age of Gl 86 of several billion years (Queloz et al. 2000), and using the NextGen track (Baraffe et al. 1998) for 1 and 10 Gyr objects we can at least infer an upper limit for the mass of Gl 86B of about $M_{\rm GJ86B} \leq 60{-}70\ M_{\rm Jup}$. As this object seems to possess methane in its atmosphere we can follow the arguments by Leggett et al. (2000) and estimate a temperature to be about 1300 K which leads to a mass estimate of 40–70 M_{Jup} (Burrows et al. 1997).

Using the K_{S} band magnitude we infer an approximate spectral type of Gl 86B using the data of Kirkpatrick et al. (2000). Figure 3 is a reproduction of Fig. 8 from Kirkpatrick et al. (2000) including the Gl 86B data. As pointed out by these authors there is a gap of about 2.5 mag in the K_{S} band between the latest L dwarfs and the T dwarfs which is caused by the strong methane absorption features in this wavelength region. We find that Gl 86B is falling right into this gap; it seems to represent a transition object between the L and T dwarf regime. Due to the probable existance of methane it would be a so–called “early T–dwarf”, a class proposed by Leggett et al. (2000) based on their finding of three objects with similar ($J - K \approx 1$) colours and spectroscopic confirmation of the presence of methane. We speculate that Gl 86B is a (several Gyr) old transition object between the L and T dwarf regime in whose atmosphere dust has already settled below the photosphere and does not dominate the appearance of this object. Detailed spectroscopy is necessary to prove this hypothesis.

Assuming a mass of 50 M_{Jup} for Gl 86B orbiting at a distance of 18.75 AU around Gl 86 introduces a Doppler-shift amplitude of the order of about 0.5 $\mathrm{km\,s^{-1}}$, with a period of ≈100 yrs, depending on the viewing geometry. The radial velocities available might contain this additional component. However, the companion found can not account for the long term trend in the radial velocities as observed by the CORAVEL survey: CORAVEL observed a long term drift of more than about 2 $\mathrm{km\,s^{-1}}$ over more than 10 years. This companion, if real, must be fairly massive, and we should have easily spotted it, unless it is hidden by the primary. New and higher precision radial velocities could clarify this point. The Gl 86 system might contain even more components.

The detection of Gl 86B was only possible by using the high angular resolution of an adaptive optics system combined with a coronographic mask to obtain a high sensitivity close to a bright star. In the near future several such systems at 8 m class telescopes will become available thus offering the opportunity to detect the orbital motion and to do spectroscopy of this very interesting object.

The Gl 86 system is one of the few systems where a brown dwarf is found as companion to a star. In addition Gl 86 is also orbited by an extrasolar planet. It is therefore the second such system as HD 168443 (Udry et al. 2000) was found by radial velocity data to also be orbited by a planet and a brown dwarf. In view of the very small number of brown dwarfs as companions to stars, the existance of already two systems hosting a brown dwarf and a planetary companion is even more puzzling and raises the question whether star–planet–BD systems are more frequent than previously thought.

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