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A posteriori detection of the planetary transit of HD 189733 b in the Hipparcos photometry

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ABSTRACT

Aims. Using observations performed at the Haute-Provence Observatory, the detection of a 2.2-day orbital period extra-solar planet that transits the disk of its parent star, HD 189733, has been recently reported. We searched in the *Hipparcos* photometry Catalogue for possible detections of those transits.

Methods. Statistic studies were performed on the *Hipparcos* data in order to detect transits of HD 189733 b and to quantify the significance of their detection.

Results. With a high level of confidence, we find that *Hipparcos* likely observed one transit of HD 189733 b in October 1991, and possibly two others in February 1991 and February 1993. Using the range of possible periods for HD 189733 b, we find that the probability that none of those events are due to planetary transits but are instead all due to artifacts is lower than 0.15%. Using the 15-year temporal baseline available, we can measure the orbital period of the planet HD 189733 b with particularly high accuracy. We obtain a period of $2.218574^{+0.000006}_{-0.000010}$ days, corresponding to an accuracy of ~1 s. Such accurate measurements might provide clues for the presence of companions.

Key words. stars: individual: HD 189733 – stars: planetary systems

1. Introduction

Bouchy et al. (2005) recently announced the detection of a 2.2-day orbital period extra-solar planet that transits the disk of its parent star, the dwarf HD 189733, which is located only 10 arcmin from the famous Dumb-Bell Nebula. This detection was performed with spectroscopic and photometric data collected at the Haute-Provence Observatory, France, as part of the ELODIE metallicity-biased search for transiting hot Jupiters (Da Silva et al. 2005). Together with radial velocity measurements, observations of transits allow the actual mass and radius of an extra-solar planet to be measured. Transiting planets also allow follow-up observations to be performed during transits (Charbonneau et al. 2002; Vidal-Madjar et al. 2003, 2004) or anti-transits (Charbonneau et al. 2005; Deming et al. 2005), yielding physical constraints on the atmospheres of these planets.

To date, HD 189733 b is only the ninth known transiting extra-solar planet (Bouchy et al. 2005), and the third transiting a star bright enough to be in the *Hipparcos* Catalogue (Perryman et al. 1997). The Epoch Photometry Annex of the *Hipparcos* Catalogue contains between ~40 and ~300 measurements performed during the 1990–1993 mission for each of the 118 204 stars of the Catalog. Transits of HD 209458 b, the first known transiting extra-solar planet (Charbonneau et al. 2000; Henry et al. 2000; Mazeh et al. 2000), were a posteriori detected in *Hipparcos* data by Robichon & Arenou (2000), Castellano et al. (2000), and Söderhjelm (1999). The transits of HD 149026 b (Sato et al. 2005) are not deep enough (0.003 mag) to be detectable with *Hipparcos* (Hébrard et al. 2005). Here we show that transits of HD 189733 b were detected by *Hipparcos*, and we quantify the signification of this a posteriori detection. The long temporal baseline available allows us to obtain an accurate orbiting period of this hot Jupiter.

2. Folding the *Hipparcos* photometric measurements

2.1. Hipparcos *photometric data of HD 189733*

The *Hipparcos* Catalogue includes HD 189733 photometry measurements at 185 different epochs. We only used in the present study the 176 measurements that are "accepted" in the Catalogue; the 9 remaining ones are flagged in the Catalogue as perturbed and not reliable. These 176 values are plotted in Fig. 1 over the 3-year observation baseline. The epochs of the measurements are given in Terrestrial Time corresponding to the Solar System Barycentric Julian Date (BJD). The difference between BJD and Heliocentric Julian Date (HJD) is negligible

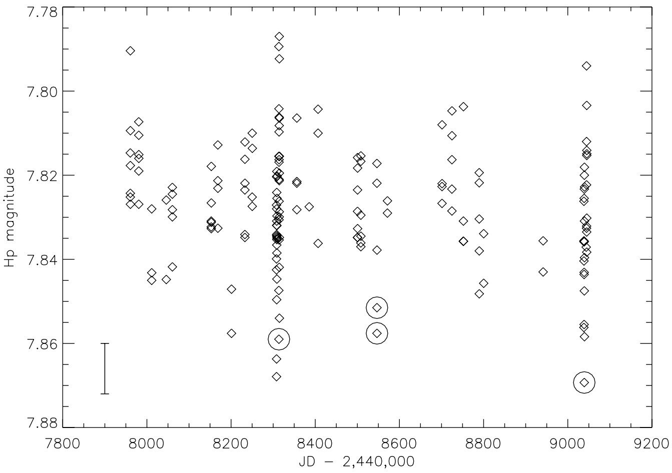

Fig. 1. The 176 reliable *Hipparcos* photometric measurements of HD 189733. The four measurements performed during planetary transits of HD 189733 are surrounded by circles. The typical error bar on H_p is represented on the bottom, left.

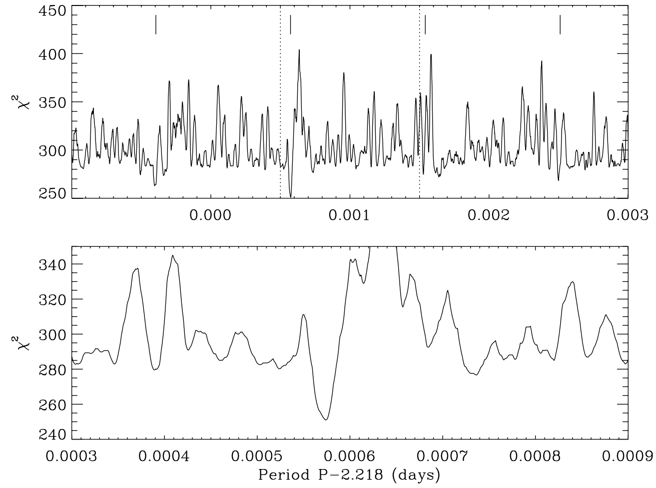

Fig. 2. *Top*: χ^2 of the fit of the *Hipparcos* magnitudes with a transit light curve, as a function of the trial period. The period interval allowed by Bouchy et al. (2005) is represented by vertical dotted lines. The ticks show the positions of the possible periods assuming that a transit occurred on 1991, Oct. 17th (see Sect. 5.1). *Bottom*: zoom around the minimum χ^2, found for a 2.218574-day period.

for our study. The *Hipparcos* measurements were performed in the specific H_p band, which is centered near 4500 Å and has a width of ~2400 Å. The estimated standard errors of each individual H_p magnitude are around 0.012 mag; this makes the ~3% deep HD 189733 planetary transit in principle detectable.

Two sets of numerous, dispersed measurements performed at two neighboring epochs are apparent in Fig. 1. Owing to the *Hipparcos* scanning law, there are actually four time intervals of about 1.5 day each (BJD – 2 440 000 = 8308.5, 8314.3, 9039.0, and 9044.7) during which numerous photometric measurements were performed. The dispersion of these measurements shows the stellar variability of HD 189733, which is classed as microvariable in the *Hipparcos* Catalogue. As we see below, the microvariability of HD 189733 does not prohibit transits detection (see also Sect. 5.3).

2.2. Period search

HD 189733 b orbits its parent star every ~2.2 days with a transit duration of ~1.6 h, so about 3% of randomly chosen observations would be expected to fall during the transit. This corresponds to about 5 measurements in the case of the 176 available *Hipparcos* values, which are however not regularly sampled in time as we described above. Nevertheless, it is likely that a few planetary transits were sampled in these 176 measurements.

We performed a χ^2 analysis to detect transits. We scanned the possible periods around the period of 2.2190 days given by Bouchy et al. (2005) with steps of 5×10^{-7} day (or about 0.04 s), in the range [2.217–2.221] days, that is four times the uncertainties given by Bouchy et al. (2005). A broader search was also performed (see Sect. 5.2). The phase of the transit within the *Hipparcos* data is a function of the assumed period. Indeed, for a given period, the phase is strongly constrained by the mean transit epoch, T_0, as determined by the ground-based discovery and follow-up observations. As, for a given period, there are integer numbers of HD 189733 b orbits between the transits observed by Bouchy et al. (2005) and the ones possibly detected by *Hipparcos*, the accuracy of the phase is exactly the accuracy of T_0. Bouchy et al. (2005) reported T_0 = 2 453 629.3890 ± 0.0004 (HJD) so the uncertainty on the phase in the *Hipparcos* data is 0.000018, corresponding to 0.0004 day. This assumes that the period is constant, or at least that if any, the variations of the period are small, with a constant average value.

For each of the 8000 periods tested, we computed the χ^2, i.e. the quadratic sum of the weighted difference between the observed magnitudes and a transit model. The transit model is an approximation of the light curve presented by Bouchy et al. (2005). It assumes a 2.7% deep transit, and durations from the 1st to the 4th contacts and from the 2nd to the 3rd contacts of 1.60 h and 0.66 h, respectively.

Figure 2 shows the χ^2 as a function of the trial period, which is the only free parameter. A clear minimum is seen for the period $P_{\rm Hipp}$ = 2.218574 days. The minimum is χ^2 = 251.0. We attribute this high χ^2, considering the 175 degrees of freedom, to the microvariability of HD 189733 (Sect. 5.3). The value of the orbital period which we found, $P_{\rm Hipp}$, is in agreement with the one reported by Bouchy et al. (2005), 2.2190 ± 0.0005 days. The *Hipparcos* data folded with the period $P_{\rm Hipp}$ are plotted in Fig. 3.

The median value for H_p is 7.827. Assuming that $P_{\rm Hipp}$ is the orbital period of HD 189733 b, the weighted average value of the four H_p measurements obtained during the planetary transit is 7.859 ± 0.006 whereas the weighted average of the 172 remaining points is 7.8261 ± 0.0009. Thus, the depth of the transit light curve as measured with *Hipparcos* is (0.033 ± 0.006) mag or (3.1 ± 0.6)% in flux. This agrees with the light curve reported by Bouchy et al. (2005) from accurate and well sampled ground-based observations of the transit. The *Hipparcos* data of HD 209458, the host of the first known transiting planet (Charbonneau et al. 2000; Henry et al. 2000), yield a transit marginally deeper than the actual one, which

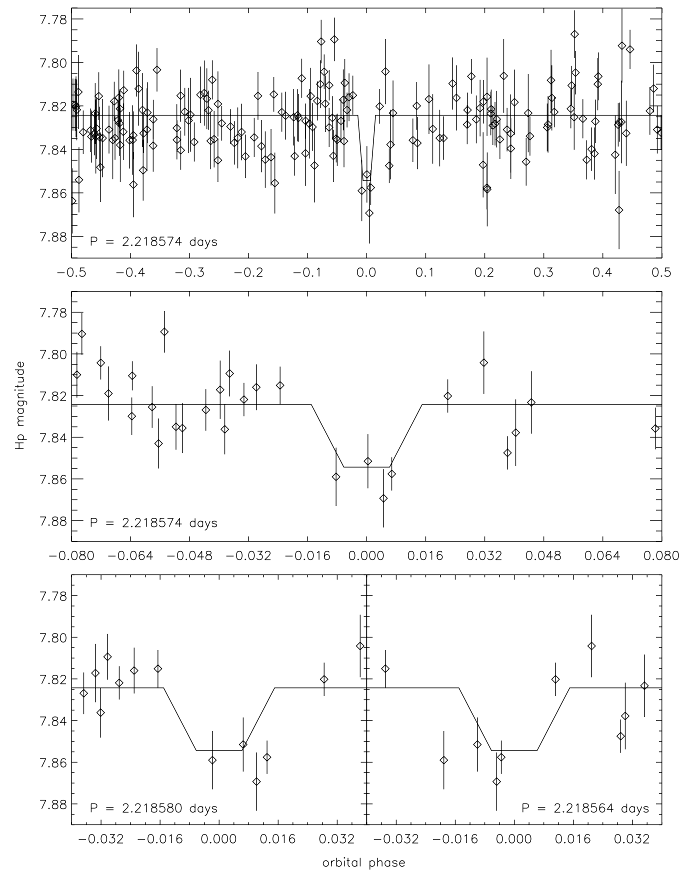

Fig. 3. *Top*: *Hipparcos* photometric measurements folded with a period $P_{\rm Hipp}$ = 2.218574 days. We found this period from χ^2 analysis of the *Hipparcos* measurements. It agrees with the value reported by Bouchy et al. (2005). The approximation of the transit curve from Bouchy et al. (2005) used for the χ^2 computation is over-plotted. *Middle*: zoom on the measurements around the transit (phase = 0). *Bottom*: same plots, but for the two extreme values of the error bar on $P_{\rm Hipp}$ (see Sect. 4).

favored its detection in the *Hipparcos* photometry (Robichon & Arenou 2000; Castellano et al. 2000). This is not the case for HD 189733.

2.3. Transits observations

Assuming $P_{\rm Hipp}$, four *Hipparcos* photometric measurements are clearly located within the planetary transit (see Fig. 3). They sample three different transits, which are surrounded by circles in Fig. 1. The transits occurred on 1991, Feb. 26th (BJD 2 448 313.68), 1991, Oct. 17th (BJD 2 448 546.63), and 1993, Feb. 20th (BJD 2 449 039.16). The *Hipparcos* measurements performed around these three dates are plotted in Fig. 4. Between these three transits observed by *Hipparcos* and that observed by Bouchy et al. (2005) on 2005, Sept. 15th at the Haute-Provence Observatory, there were exactly 2396, 2291, and 2069 orbits of the planet HD 189733 b around its host star.

3. Significance of the detection

Hipparcos measurements have a poor time coverage. In addition, the errors on each measurement are of the same order of magnitude than the expected transit effect. Moreover, HD 189733 seems to exhibit an actual stellar microvariability (see Sect. 2.1). Due to these causes, various periods might be found such that the HD 189733 *Hipparcos* photometric measurements are consistent with a transit light curve and agree with the period and T_0 given by Bouchy et al. (2005). The question is to know whether the period $P_{\rm Hipp}$ we report above produces a solution that is significantly better than those obtained with other periods. Three arguments allow us to answer this question in the affirmative: χ^2 variations, fits with an inverse light curve, and a bootstrap test.

First, as seen in Fig. 2, the χ^2 of the solution with $P_{\rm Hipp}$ is significantly lower than those obtained with other periods. Some χ^2 local minima are found for other periods in the range [2.217–2.221] days; however, the lowest ones present a χ^2 at least greater by ~11 than the minimum χ^2 found for $P_{\rm Hipp}$. A $\Delta\chi^2$ of 11 is significant. This is seen in Fig. 5 that plots the χ^2 histogram of the fits performed with the 8000 different planetary orbital periods chosen in the range [2.217–2.221] days (see Sect. 2.2). As expected, if no signal is present, there is a continuous distribution of χ^2, with fewer solutions with lower χ^2; this is seen in the tail of the χ^2 distribution. However, there is a solution that emerges from this distribution, at $\Delta\chi^2 \simeq$ 11 from the end of the distribution tail, namely $P_{\rm Hipp}$. This detection is thus significant.

Second, we performed the same χ^2 scan as that presented in Sect. 2.2, but with an inverse model light curve, i.e. an increase of the star brightness of 2.7% instead of a decrease. If the signal we report is just an artifact due to the noise present in the data and the high number of folding possibilities, the chance of finding a false absorption light curve should be roughly the same as that of finding a false emission light curve. However, the lowest χ^2 found in the case of these inverse light curves are around 266.7, which is larger by at least $\Delta\chi^2 \simeq 15.7$ than the lowest χ^2 reported in Sect. 2.2 for the normal light curve with $P_{\rm Hipp}$. The χ^2 histogram performed in the case of the inverse light curve shows a decreasing tail toward lower χ^2 values, but without any solutions emerging from this tail (see Fig. 5). Thus, inverse light curves do not show any significant solution within the period range defined by Bouchy et al. (2005).

Finally, we performed a bootstrap experiment to quantify the significance of our detection and the probability that the three transits apparently detected in the period range [2.217–2.221] days can be all due to noise. We generated 20 000 random sets of data from the original *Hipparcos* data by redistribution of the times of observation (we kept the times of observation the same, but scrambled the photometric values). This method includes all sources of noise in the real data, including the observed microvariability of the star. From these 20 000 trials, only 30 give a detection of a period in the range of acceptable values and a lower χ^2. With a false-alarm probability of less than 0.15%, this gives us confidence that the transit detections we report in Sect. 2 in the *Hipparcos* data is real.

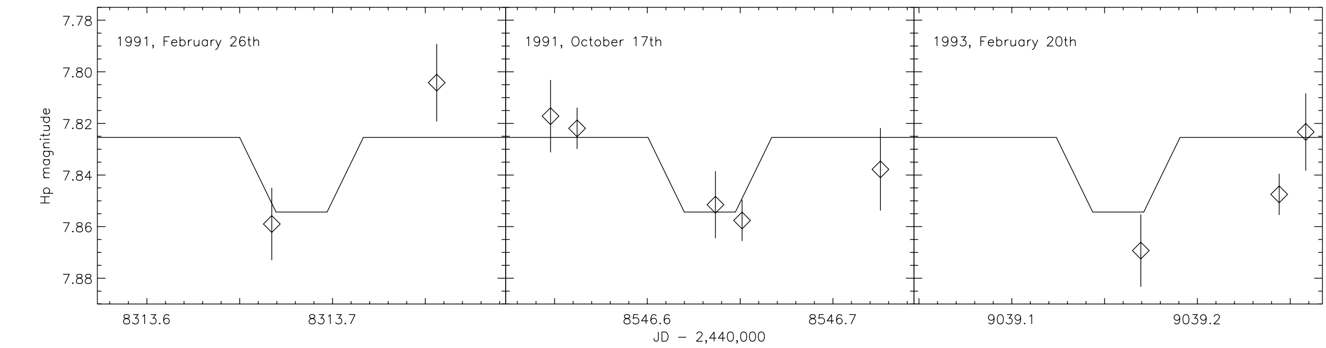

Fig. 4. Photometry around the epochs of the three planetary transits of HD 189733 observed by *Hipparcos*. The model of the transit assuming a planetary orbital period $P_{\mathrm{Hipp}} = 2.218574$ days is over-plotted.

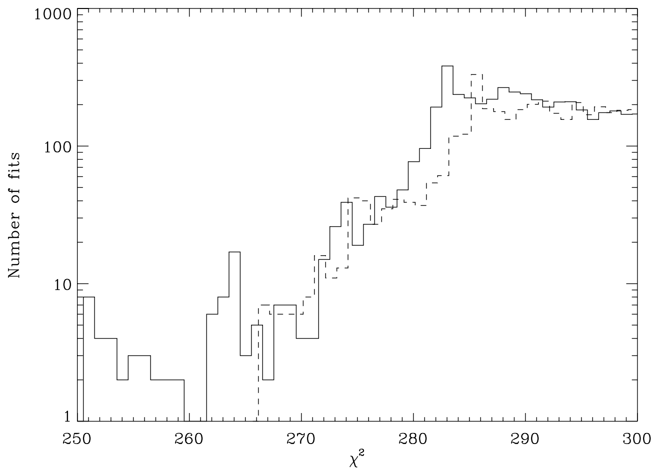

Fig. 5. χ^2 histogram (solid line) of the fits performed with 8000 different planetary orbital periods chosen in the range [2.217−2.221] days. The solution with P_{Hipp} clearly emerge from the χ^2 distribution, at $\chi^2 = 251.0$. The dotted line shows the corresponding histogram in the case of fits with an inverse light curve; no solutions emerge in that case, where no signal is present (see Sect. 3).

Note that if we restrict the period search to the exact range allowed by Bouchy et al. (2005), the false-alarm probability decreases to 7/20 000, or 0.035%.

The false-alarm probability is actually even lower. Indeed, as these four points appear to be real transit measurements, they will favor false solutions (i.e. with other periods) to be found in the bootstrap test since these four low points allow transits curves to be fitted.

Thus, we conclude that the orbital period presented in Sect. 2 results from an actual detection with *Hipparcos* of transits of HD 189733 b in front of its parent star.

4. Accuracy of the planetary orbital period

We quantify here the accuracy of the HD 189733 b orbital period we obtained, which is computed from χ^2 variations. $\Delta\chi^2 = 11$ appears to be a reasonable confidence interval, as the local minima reported in Sect. 3 have at least this $\Delta\chi^2$ with our best solution. According to Fig. 2, an interval with $\Delta\chi^2 = 11$ implies an error bar on P_{Hipp} of $^{+0.000006}_{-0.000010}$ day, corresponding to about $^{+0.5}_{-0.9}$ s. The *Hipparcos* data folded with the two extreme periods of this interval are plotted in the lower panel of Fig. 3. Thanks to the 15-year baseline, this error bar is almost 100 times smaller than that obtained by Bouchy et al. (2005) on a one-week baseline.

There are two other causes of uncertainties on P_{Hipp} that are not included in this χ^2 study. However, they are negligible. The first one is due to the uncertainty in the mean transit epoch T_0. If T_0 is sooner or later, the obtained period would be respectively shorter or longer. This error on P_{Hipp} is equal to the uncertainty on T_0 divided by the largest number of planetary orbits between two observed transits, namely 2396 (see Sect. 2.3). Bouchy et al. (2005) reported a 0.0004-day error in T_0, which thus translates into an error of 1.7×10^{-7} day on P_{Hipp}; this is about 40 times lower than the error bar reported above.

The second extra uncertainty, which is due to the shape and the duration of the transit, is even lower, as those parameters are well known from the photometric observations of Bouchy et al. (2005). We note that fitting the transit with a box-shaped approximation might lead to an erroneous solution as the impact parameter of HD 189733 b is relatively high. However this has no effect on our solution, as the four points we identified in the transits are located in the central part of the transit, and none is located near the beginning or the end of them.

Finally, we also performed all the tests described in the present paper using the detection statistic l as described by Castellano et al. (2000). All the results in terms of period determination, error bars, and significance of the detection are identical to those obtained using the χ^2.

5. Discussion

5.1. Periods from the October 1991 transit

The period determination and the deep minimum of the χ^2 are mainly based on the detection of a transit on 1991, October 17th. In that case, two measurements were obtained just before the transit, two other during it, and a last one just after the transit (Fig. 4, middle panel). The observations of the two other transits have only one point during the transit and lower quality flags (Sect. 5.4). However, using this single transit of October 1991, an accurate period can also be estimated. If n is the number of periods between this transit and the transit observed by Bouchy et al. (2005) on 2005, Sept. 15th, the period must be $P_n = 5082.75/n \pm 9 \times 10^{-6}$ days. These possible periods are represented by ticks in Fig. 2, upper panel (for n = 2290, 2291, 2292, and 2293). The best period $P_{\rm Hipp} = P_{n=2291}$ given the lowest $\chi^2 = 251.0$ is found in the Bouchy et al. (2005) range of possible periods. For other values of n around 2291, we find significantly higher χ^2 values, in most cases because other data points are obviously incompatible with the observation of a transit if they are folded with the corresponding periods. We note that $P_{n=2287}$, $P_{n=2292}$, and $P_{n=2293}$ (respectively 2.22245, 2.21760, and 2.21664 days) give low values of χ^2 (but still higher than 263). These periods correspond to the situation where the only transit observed by *Hipparcos* would be the one of 1991, October 17th; they can be eliminated only because they are beyond the error bars given by Bouchy et al. (2005). The period $P_{n=2294}$ corresponds to the situation where *Hipparcos* would have observed during two other transits; for the first one, two measurements are consistent with the transit light curve, while for the second one, one low quality flagged measurement is not consistent with the transit light curve. Again, this period can be eliminated only because it is well beyond the error bars given by Bouchy et al. (2005).

5.2. Large period range scan

In Sect. 2.2, we found the best period by searching for the period giving a relatively deep minimum for the χ^2 over four times the period range given by Bouchy et al. (2005). To check if such a deep minimum is frequent with the actual *Hipparcos* measurements, we extend the period range and find that such a minimum can also be found if we consider periods down to 2.0822 days or up to 3.4909 days. These periods are far from the Bouchy et al. (2005) acceptable values by more than 100 times their error bar. This strengthens the case that the 2.518574-day period is peculiar and not simply the best period among statistical variations of the χ^2.

This 2.0822-day period has a deep minimum in χ^2 mainly because of the data of 1991, Oct. 17th. Therefore, it corresponds to folding the data with n = 2441 orbital periods between this transit observations and the transit observations at the Haute-Provence Observatory performed by Bouchy et al. (2005) at $T_0 = 2\,453\,629.3890$. This shows that it is unlikely that the data can be folded by a period inside the limited period range of Bouchy et al. (2005) to fit the transit light curve only because of the statistical noise; this gives us confidence that we really detected HD 189733 b transits.

5.3. Stellar microvariability

HD 189733 is known to be microvariable. We therefore have to address if this variability can mimic a transit light curve. We performed tests on the long term and short term variability which indicate that this variability is unlikely to reproduce the observed transit signature.

First, on the long term, we searched for periodicity and found that HD 189733 presents significant periods of 13.3, 11.8, 8.8 and 4.6 days (for the method, see Lecavelier des Etangs et al. 2005). By removing these periods, we found that the χ^2 is significantly reduced to $\chi^2 = 193.2$ if we fit the data with a sinusoid and a period of 11.8 days. This period is similar to the stellar rotational period of ~11 days reported by Bouchy et al. (2005). This confirms that the large χ^2 for 175 degrees of freedom is effectively due to the variability of the star (Sect. 2.2). However, using the data corrected for these periodic variations, we do not find any significant change in the period of the planet, its uncertainties and the significance of the detection.

It is also desirable to estimate the risk that short term microvariability (on a time scale of hours) can mimic the transit light curve. The bootstrap test presented in Sect. 3 shows that short-term stellar variations are extremely unlikely to be responsible for our signal. However, this test assumes that there are no correlations between the different measurements, which can be incorrect in the case of stellar variations. We performed two tests in order to take any correlations into account.

First, we searched for the pairs of measurements separated by less than 0.66 h and estimated their difference with the mean brightness of the star. We found 77 such pairs and among them only two pairs show differences above 0.025 mag, including the October 1991 measurements for which the difference is believed to be due to a real transit. If we correct for the 11.8 day periodic variations, the October 1991 pair of measurements is the only one presenting a difference with the mean brightness above 0.02 mag. This demonstrates that the microvariability is unlikely to produce on a short time scale two subsequent measurements reproducing an apparent light decrease similar to the transit signature.

As a second test, we search for the groups of four measurements that are separated by less that 5 h and estimated the difference between the mean of the two first measurements and the mean of the two last. We found 74 such groups and among them only three groups show differences above 0.025 mag, including two groups of measurements for which the difference is believed to be due to a real transit (October 1991 and February 1993). This again demonstrates that the microvariability is unlikely to produce in a short time four subsequent measurements reproducing an apparent light decrease similar to the transit signature of October 1991.

5.4. Quality flags

The analysis we report above was performed on the 176 HD 189733 measurements "accepted" in the *Hipparcos* Catalogue. This includes the values with the Quality flags "0", "1", and "2"; the 9 remaining HD 189733 *Hipparcos* measurements have higher Quality flags, meaning they are perturbed and unreliable. 17 of the 176 reliable measurements are flagged "1" or "2", which means that one of the two consortia that reduced the data, namely NDAC and FAST, rejected it. Two of the four measurements located within transits (those of February 1991 and February 1993) present such flags. This makes them possibly unreliable. We thus performed all the tests described above using only the 159 *Hipparcos* measurements of HD 189733 that are are flagged "0". We found the same value for $P_{\rm Hipp}$ within the period range allowed by

Bouchy et al. (2005), but of course, only one transit was detected (that of October 1991). This makes us confident that our result is not due to unreliable points.

Interesting enough, a broad scan with only these 159 points allow another period to be found, far from the Bouchy et al. (2005) range, namely 2.217675 days. This solution presents a lower χ^2 than the solution at 2.218574 days. Two transits are detected in that case, that of October 1991 and apparently another on 1990, November 5th. The bootstrap test similar to that presented in Sect. 3 indicates that there is less than 1.5% probability that no transits are detected in that case, and that this solution is only due to noise. As this solution is not allowed by Bouchy et al. (2005), it cannot be adopted, except if a second planet is present in the system, implying a smooth oscillation of the observed transit period (indeed, radial velocity measurements show motions of the star around the center of mass of the whole system, whereas transits show motion of the planet with respect to the central star only). However this seems unlikely to us. More probably, the low brightness observed on 1990, November 5th is due to the stellar microvariability. Indeed, these low points are not low if the 11.8-day stellar oscillation is removed (see Sect. 5.3). This second bootstrap test reinforces the significance of the *Hipparcos* detection of the October 1991 HD 189733 b transit.

6. Conclusion

We report the a posteriori detection with *Hipparcos* of three transits of HD 189733 b in front of its parent star. This allows an accurate orbital period of this extra-solar planet to be measured.

One important question is to know whether an a priori detection of HD 189733 b would have been possible. Searching for planetary candidates in the *Hipparcos* data is difficult due to the poor time coverage and the accuracy of the photometry. Laughlin (2000) and Jenkins et al. (2002) concluded that the *Hipparcos* Catalog does not represent a likely place to detect planets in the absence of other information, even if it might provide planetary transit candidates for follow-up observations. Hébrard et al. (2005) made radial-velocity measurements on transiting candidates selected in the *Hipparcos* Photometry Annex but did not report any detections.

The identification of HD 189733 b transits within *Hipparcos* data was not obvious. However, the allowed period range was small and the mean time of the transits as well as their shape and duration were well known, reducing the number of possible solutions. Searching for planetary transits without a priori knowledge of period would require one to explore a period range of several days, with numerous, small steps. As the time of the potential transits are not known, all the phases should be explored, here again with a small enough step. Finally, since the impact parameter is not known, as is the stellar size relative to the planetary companion or the limb darketing, several shapes and durations of the transits should be looked for. This makes the number of solutions huge in folding the data. Because of the poor time coverage and the accuracy of the photometry, the *Hipparcos* Photometry Annex does not seem a promising and efficient tool for transits searches without a priori information. However, it probably will be a valuable database for the studies of the transits that are discovered in the future. It would allow them to be quickly confirmed, and their period to be accurately determined, which is useful for follow-up observations. It may also reveal long-term period oscillations, yielding clues to the presence of companions.

Shortly before the submission of this paper, we became aware that Bouchy et al. (2005) also report detection of HD 189733 b within the *Hipparcos* data. Although their reported error bar on the period is smaller than ours, their folding solution and period are in good agreement with ours, which confirms our results.

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