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HD 209458 planetary transits from Hipparcos photometry⋆

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Abstract. During its 39-month mission, Hipparcos observed the star HD 209458 on 89 occasions. Five of these observations are shown to correspond to epochs of planetary transits, with a 2.3 ± 0.4% mean decrease of flux in the Hp band being observed during the transits. As a result of the long temporal baseline of more than 8 years between the Hipparcos and radial velocity measurements, an accurate orbital period of $P = 3.524739 \pm 0.000014$ days can be derived from the Hipparcos photometric data.

Key words: stars: planetary systems – stars: individual: HD 209458

1. Introduction

The announcement of the photometric detection of the planetary transits for HD 209458 by Charbonneau et al. (1999) and Henry et al. (1999) represents a significant confirmation of the presence of extrasolar planets detected by radial velocity measurements, and signifies the start of a new era for extrasolar planet studies.

Compared to the orbital period (≈ 3.5 days), the transit duration (≈ 0.1 day) implies a 3% probability of observing a transit at any given epoch. On average, about a hundred individual magnitude measurements per star were obtained by Hipparcos during the mission. Although these observations are not evenly distributed in time, planetary transits for such short-period systems are nevertheless likely to be sampled by the Hipparcos epoch photometry. According to Charbonneau et al. (1999), the depth of HD 209458 transits is about 1.5% in the red, and should be larger at shorter wavelengths due to greater limb darkening. The individual Hipparcos photometric precision is about 0.01 mag making the transits in principle detectable.

Assuming that the period has not changed for 8 years, we first show that Hipparcos indeed observed a number of distinct planetary transits, then the period is refined and the transits are indicated.

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⋆ Based on observations made with the ESA Hipparcos astrometry satellite

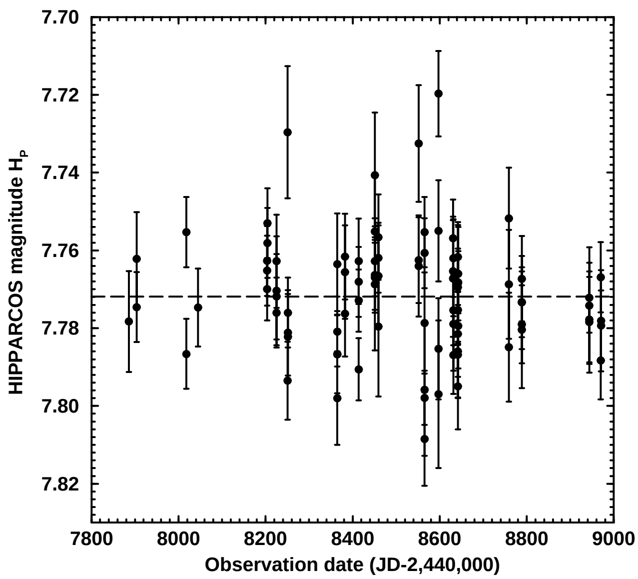

Fig. 1. Hipparcos individual photometric observations of HD 209458 as a function of the observation epoch (given in barycentric Julian Date).

2. Hipparcos photometric measurements

The Hipparcos Epoch Photometric data are part of the published Hipparcos Catalogue (ESA, 1997). It is available on CD-ROM, or via the web site of the ‘Centre de Données astronomiques de Strasbourg (CDS)’. This annex of the Hipparcos Catalogue gives: the observation epoch, in Terrestrial Time (TT) corrected to the solar system barycentre with respect to JD(TT)-2 440 000.0; the Hipparcos magnitude, Hp; its standard error σ_H; and a quality flag. The Hipparcos barycentric Julian Date, BJD, is consistent with the Heliocentric Julian Date used by Charbonneau et al. (1999) to within about 3 s.

Hipparcos observed HD 209458 (HIP 108859) on 89 occasions, with an individual mean standard error of 0.011 mag. The individual Hp magnitudes as a function of BJD are shown in Fig. 1. Six of the 89 measurements are fainter by more than $2\sigma_H$ from the median magnitude (7.7719 ± 0.002). We phased the data using the period (3.52447 ± 0.00029 days) from Mazeh et al. (2000) and the mean transit epoch (HJD 2451430.8227 ± 0.003) given by Charbonneau et al. (1999). To

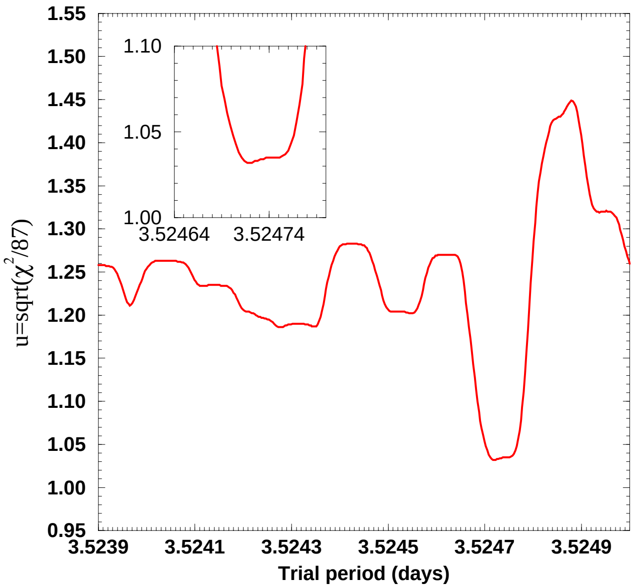

Fig. 2. Unit-weight error of normalised magnitude residuals as a function of trial transit period.

Table 1. Hipparcos individual magnitudes within one day of the transits. Observations occurring during the transits are in bold type.

transit #	epoch	BJD	H_P	σ_{H_P}
	$\mathbf{t_{11}}$	**8364.30120**	**7.7980**	**0.012**
	$\mathbf{t_{12}}$	**8364.31557**	**7.7867**	**0.010**
1	t_{13}	8364.56789	7.7635	0.013
	t_{14}	8364.58223	7.7809	0.009
	t_{15}	8364.65680	7.7866	0.011
	t_{21}	8413.44502	7.7729	0.008
2	t_{22}	8413.53390	7.7681	0.009
	t_{23}	8413.54821	7.7628	0.011
	$\mathbf{t_{24}}$	**8413.62280**	**7.7906**	**0.008**
	t_{31}	8565.11988	7.7607	0.009
	t_{32}	8565.13421	7.7553	0.009
3	$\mathbf{t_{33}}$	**8565.20876**	**7.8085**	**0.012**
	$\mathbf{t_{34}}$	**8565.22306**	**7.7979**	**0.007**
	t_{35}	8565.29764	7.7958	0.017
	t_{36}	8565.31196	7.7787	0.013

our surprise, 4 of these 6 discrepant Hipparcos measurements occurred very close to the predicted transit times, with the remaining two discrepant measurements consistent with what can be expected randomly in such a sample. For the subsequent analysis, we removed one 'bright' observation at $-4\sigma_H$ from the median which occurred on BJD 8597.20329.

The first question is whether the 4 statistically fainter observations are normal outliers, or whether they represent transit signatures. Due to the scanning law of the satellite, the distribution of observations is not uniform. The phases of the 4 candidate transit measurements are within 0.072 (0.25 days) from zero phase, and 11% of the measurements fall in this 0.25 day interval for the sample as a whole. With no planetary transit, 0.68 such outliers are expected on average in the quoted interval; the probability of getting 4 or more such observations is about 5×10^{-3}, or even smaller if we now consider the short phase span (0.014) of these 4 observations. Thus these measurements are not normal outliers, and it can be inferred that Hipparcos did observe the planet transit on at least these 4 occasions. This is however a lower limit, since other transit observations under the adopted $2\sigma_H$ threshold may have occurred.

3. Period analysis

The ≈ 0.1 day transit duration from Charbonneau et al. (1999), together with the mean eclipse epoch from Torres (1999) ($T_{c0} = 2451430.8238 \pm 0.0033$ using a simultaneous solution of the radial velocities and the transit observations) are evidently much more accurately known than from the Hipparcos data. These values have thus been adopted in what follows, and we then tried to estimate the period given by the Hipparcos photometry. For this purpose, we approximated the magnitude curve given by Charbonneau et al. (1999) by an analytical function, scaled to obtain a 0.025 mag dimming during transits, and we minimised the χ^2 of the difference between predicted and observed magnitudes, weighted by σ_H, as a function of period. The adopted 0.025 mag, a rough average of early observations indicated in the IAU circulars, is not critical; using either 0.017 or 0.03 mag does not change significantly the following results, other than slightly increasing the χ^2.

The unit-weight error $u = \sqrt{\chi^2/87}$ versus trial period is shown in Fig. 2. A clear minimum occurs in the period interval $[3.52471, 3.52476]$ days, the minimum being formally at $P = 3.524718^{+.000039}_{-.000010}$ days. Given the 87 degrees of freedom, the $u = 1.03$ minimum value is compatible with the expectation ($=1$) if the magnitude errors are Gaussian and the standard errors correctly estimated; outside of the minimum range, $u > 1.17$, i.e. a probability of less than 1% of occurring by chance.

No smaller minimum was found for periods in the range 1–100 days, for 10^{-5} day steps, so that the agreement with what has been found by radial velocity measurements is not a coincidence. This also means that the Hipparcos photometric data may be used for the detection of planetary transits across other stars. In this respect, one may note that, using the Hipparcos data only, the mean transit epoch T_{c0} of HD 209458 would be recovered to within 8 hours.

4. Transits observations

The reality of the transit observations by Hipparcos being established, the period may be computed more precisely. The flat χ^2 minimum is due to the fact that Hipparcos did not cover entirely the observed transits, so that each observation must be studied individually.

Three distinct transits were found. Table 1 is a collection of all the Hipparcos observations close to the predicted transits. For each transit i ($1 \leq i \leq 3$), an estimate of the central epoch T_{ci} of the transit has been computed assuming a transit duration of 0.1 day according to Fig. 5 of Charbonneau et al. (1999). Each Hipparcos observation (Table 1 and Fig. 4) is considered to have

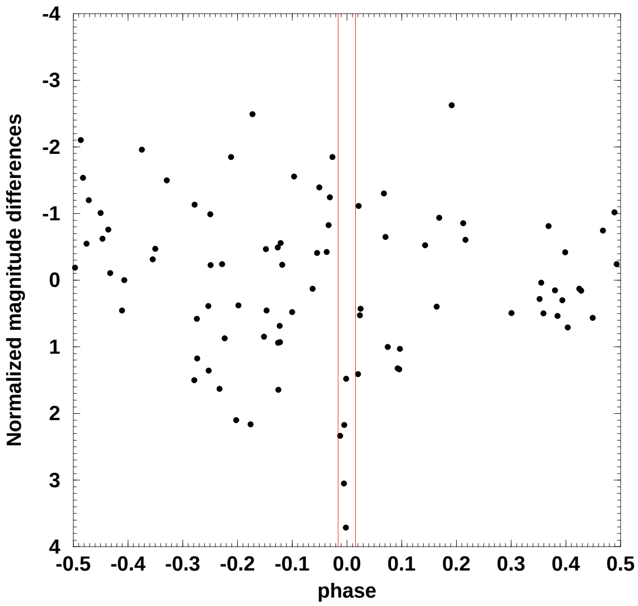

Fig. 3. Normalised magnitude residuals (formal error = 1) versus phase, using T_{c0} from Torres (1999) and the period obtained in Sect. 3. The transit duration is indicated.

occurred during the 0.1 day transit if the magnitude is faint enough, and this gives constraints on the transit centre value. Let t be the date of a Hipparcos observation; if t occurs during a transit, then T_{ci} lies in the interval $[t - 0.1/2, t + 0.1/2]$; if t does not, one has $T_{ci} \leq t - 0.1/2$ or $T_{ci} \geq t + 0.1/2$. Each observation around a transit then gives constraints on the interval in which T_{ci} lies. Assuming a uniform distribution, an estimate of T_{ci} is the centre of this interval, and its formal error is the interval duration divided by $\sqrt{12}$. Once T_{ci} is estimated, the period is $\frac{T_{ci}-T_{c0}}{n_i}$ where $T_{c0} = 2451430.8238 \pm 0.0033$ from Torres (1999) and n_i is the integer number of periods between these two central epochs (known without error from the period obtained in Sect. 3).

The successive transits then give the following periods:

- on BJD 8364: t_{11} and t_{12} occur during the transit, while subsequent observations do not. Thus $t_{12} - 0.1/2 \leq T_{c1} \leq t_{11} + 0.1/2$, which gives $T_{c1} = 8364.308 \pm 0.025$ and $P_1 = 3.524730 \pm 0.000028$.
- on BJD 8413: t_{24} occurs during the transit, the previous observations do not: $t_{23}+0.1/2 \leq T_{c2} \leq t_{24}+0.1/2$, which gives $T_{c2} = 8413.6355 \pm 0.022$ and $P_2 = 3.524753 \pm 0.000025$.
- on BJD 8565: first hypothesis: t_{33} and t_{34} occur during the transit, the other observations do not: $t_{32} + 0.1/2 \leq T_{c3} \leq t_{35} - 0.1/2$, which gives $T_{c3} = 8565.216 \pm 0.018$ and $P_3 = 3.524733 \pm 0.000023$.
  However a second hypothesis could be considered: t_{33}, t_{34} and t_{35} occur during the transit, the other observations do not. Then $t_{35} - 0.1/2 \leq T_{c3} \leq t_{33} + 0.1/2$, which would imply $T_{c3} = 8565.253 \pm 0.003$ and $P_3 = 3.524685 \pm 0.000006$. This hypothesis is however rejected, since it is incompatible with P_1 and P_2.

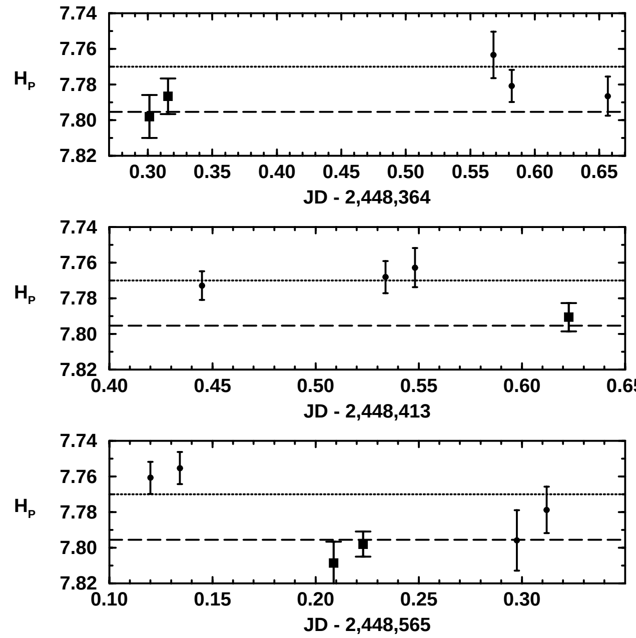

Fig. 4. Hipparcos individual photometric observations of HD 209458 as a function of the observation epoch around the three inferred planetary transits. Observations occurring during the transits are indicated by squares. The two lines are the average magnitude during and outside the transits. The distribution of observations is resulting from the ≈ 20 minute interval between the preceding and following Hipparcos fields of view, and the ≈ 2 hours between two successive great circles.

The three periods P_1, P_2 and P_3 are in excellent agreement, with a negligible correlation, and a mean value of $P = 3.524739 \pm 0.000014$ days. This value is also compatible with, but much more accurately determined than, the periods 3.52433 ± 0.00027 quoted by Torres (1999) and 3.52447 ± 0.00029 obtained by Mazeh et al. (2000).

Excluding the 5 points, the normality hypothesis for the 83 remaining normalised magnitude errors is not rejected, using a Kolmogorov (Lilliefors) test, with a 42% confidence, and the resulting median magnitude is 7.77 mag (dotted line in Fig. 4).

The five relevant transit observations are indicated in bold in Table 1 and in Fig. 4. During these transit observations, the weighted mean magnitude is 7.795 ± 0.004 (dashed line in Fig. 4), corresponding to a $2.3 \pm 0.4\%$ mean decrease in flux. This is consistent with, but slightly greater than, the 1.6% decrease found by Charbonneau et al. (1999).

5. Conclusion

Although the Hipparcos astrometric data have proven to be useful for the study of orbital motions of astrometric binaries, the precision is generally insufficient for the astrometric detection of extrasolar planets, and certainly for planets with small periods and correspondingly small semi-major axes. However, future space astrometric missions, such as GAIA, will greatly improve the detection statistics of extrasolar planets, since the presence of Jupiter-like planets will be screened for all solar-like stars out to distances of about 200–300 pc. Simulations suggest the probable detection of some 30 000 or so Jupiter-mass planets based on our present knowledge of the occurrence of these systems from ongoing radial velocity surveys (Lattanzi et al., 1999).

The availability of the Hipparcos epoch photometry data has however, turned out to have an unexpected impact on extrasolar planet research, and proves to be a valuable tool for the detection of planetary transits. For HD 209458, the long time span between the Hipparcos Catalogue mean epoch and the recent radial velocity and ground-based photometry observations has allowed us to improve by a factor ≈ 20 the current precision on the period given by the radial velocity measurements. Such an improvement will follow for other extrasolar planets detected in the Hipparcos photometric data in the same way.

The ESA Astrophysics Division at ESTEC has provided a Web facility (`http://astro.estec.esa.nl/Hipparcos/research.html#epoch`) which allows period searches for each star in the Hipparcos Catalogue, a facility which should be of further use for the transit studies of future planetary candidates. We also note that, upon submitting this paper, we were informed that our colleague Steffan Söderjhelm obtained independently a result very similar to ours.

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