A&A manuscript no.
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08.04.1; 08.09.2; 08.16.2

ASTRONOMY
AND
ASTROPHYSICS
1.4.1996

Hipparcos Distances and Mass Limits for the Planetary Candidates: 47 UMa, 70 Vir, and 51 Peg ⋆

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Received:

Abstract. Distances to the recently-discovered planetary system candidates, 47 UMa, 70 Vir and 51 Peg, are presented, based on absolute trigonometric parallaxes from the global reduction of the ESA Hipparcos astrometry satellite data. Standard errors of the parallaxes are in the range 0.66–0.76 mas (milliarcsec), with resulting distances accurate to around 1 per cent. For 70 Vir, the Hipparcos parallax (55.22 ± 0.73 mas) resolves a discrepancy of almost a factor of three in published trigonometric and photometric parallaxes. The residuals of the astrometric parameters are used in combination with the radial velocity data for these orbital systems to place upper limits on the companion masses of between 7–22 and 38–65 Jupiter masses (M_J) for 47 UMa and 70 Vir respectively, with less stringent limits for 51 Peg. The Hipparcos data therefore provide confirmation of the existence of sub-stellar masses significantly below the brown dwarf limit (of about $0.08\,M_\odot$) surrounding other stars.

Key words: Hipparcos – parallaxes – planetary systems

1. Introduction

Recent interest in 47 UMa, 70 Vir and 51 Peg follows the discovery of planetary mass companions around them (Butler & Marcy 1996; Marcy & Butler 1996; and Mayor & Queloz 1995 respectively). Ground-based observations have left some uncertainty as to the distances (and therefore physical properties) of the stars, and (directly) place only lower limits on the companion masses because of the unknown orbital inclination of the systems—the small radial velocity amplitudes observed may be caused either by a very small companion mass, or by a more massive object with a very small value of $\sin i$. We present their absolute trigonometric parallaxes derived from the Hipparcos astrometry satellite data, and place corresponding constraints on the companion masses of these systems, based on upper limits to astrometric perturbations of the primary in combination with the orbital parameters derived from radial velocity observations.

2. Distances to 47 UMa, 70 Vir and 51 Peg

One of the primary scientific goals of ESA's Hipparcos space astrometry project was to provide direct distance estimates for more than 100 000 stars in the solar neighbourhood, in order to determine their physical properties, and to place theoretical studies of stellar structure and evolution on a more secure observational footing. The Hipparcos Catalogue, resulting from the project, is in the final stages of preparation.

The way in which the Hipparcos data have been reduced has recently been described by Kovalevsky et al. (1995), the general properties of the resulting catalogue by Lindegren et

⋆ Based on data from the Hipparcos astrometry satellite

Table 1. Summary of parallax determinations: parallaxes are from the General Catalogue of Trigonometric Stellar Parallaxes (GCTSP, Jenkins 1952); the Catalogue of Nearby Stars (CNS2, Gliese 1969; CNS3, Gliese & Jahreiss 1991), with both the trigonometric, CNS3(trig), and resulting, CNS3(res), values; the General Catalogue of Trigonometric Parallaxes, Fourth Edition (GCTP, van Altena et al., 1995); and from Hipparcos (HIP). The last columns give the number of 'accepted' and 'rejected' Hipparcos observations, $N_{\rm acc}$ and $N_{\rm rej}$ (combined data from both groups), and the goodness-of-fit, χ^2. The degrees of freedom, ν, is given by $N_{\rm acc} - 5$.

Name	HD	HIP	$\pi_{\rm GCTSP}$ (mas)	$\pi_{\rm CNS2}$ (mas)	$\pi_{\rm CNS3(trig)}$ (mas)	$\pi_{\rm CNS3(res)}$ (mas)	$\pi_{\rm GCTP}$ (mas)	$\pi_{\rm HIP}$ (mas)	$N_{\rm acc}$	$N_{\rm rej}$	χ^2
47 UMa	95128	53721	73 ± 7	74 ± 7	71.9 ± 13.1	71.9 ± 13.1	76.7 ± 7.8	71.04 ± 0.66	58	0	78.9
70 Vir	117176	65721	41 ± 6	53 ± 8	43.2 ± 9.6	112 ± 15	53.9 ± 6.9	55.22 ± 0.73	61	0	67.7
51 Peg	217014	113357	73 ± 6	73 ± 6	58.4 ± 8.2	58.4 ± 8.2	57.5 ± 5.1	65.10 ± 0.76	70	2	62.4

al. (1995), and the way in which the absolute trigonometric parallaxes and their standard errors have been derived and validated has been described by Perryman et al. (1995).

Table 1 provides a summary compilation of parallaxes for the three objects. Values are taken from the (Yale) General Catalogue of Trigonometric Stellar Parallaxes (GCTSP, Jenkins 1952), the Catalogue of Nearby Stars (CNS2, Gliese 1969; CNS3, Gliese & Jahreiss 1991), and the Fourth Edition of the General Catalogue of Trigonometric Parallaxes (GCTP, van Altena et al. 1995). Trigonometric and resulting parallaxes for CNS3 are listed separately. Particularly discrepant estimates are given in the literature in the case of 70 Vir. The GCTSP (Jenkins, 1952) values (which, for these objects, were those included in the Hipparcos Input Catalogue), were themselves a critical compilation of relative parallaxes, corrected according to observing station, galactic latitude, and combined according to a given weighting scheme. In the case of 70 Vir, the GCTSP value was derived on the basis of observations from the Allegheny (32 ± 8 mas) and McCormick (45 ± 11 mas) stations. While Gliese & Jahreiss (1991) included a trigonometric parallax of 43.2 ± 9.6 mas for the CNS3, their resulting parallax is nearly a factor of three larger, 112 ± 15 mas. For the CNS3, trigonometric and photometric or spectroscopic parallaxes were not combined, the resulting parallax being one or the other depending on the size of the respective errors. In their discussion of 47 UMa Butler & Marcy (1996) adopt a parallax of 81 mas (Heintz 1993).

The least-squares reduction of the Hipparcos data is illustrated in Fig. 1 for 47 UMa. Astrometric parameters (and covariances) derived by the two independent Hipparcos data reduction groups have been combined to produce the final astrometric results of which the parallaxes, $\pi_{\rm HIP}$, are given in Table 1, as they will be published (ESA 1997). Accuracies and limits on any possible zero-point offset of the global parallaxes have been assessed by Lindegren (1995) and Arenou et al. (1995). Together, these analyses place a limit on the global parallax zero-point offset of less than 0.1 mas, and give confidence that the published standard errors will be a reliable indication of their true external errors.

The Hipparcos parallaxes consequently resolve the disparity in the distance determinations to these stars, and in particular settle the discrepancy of more than a factor of two

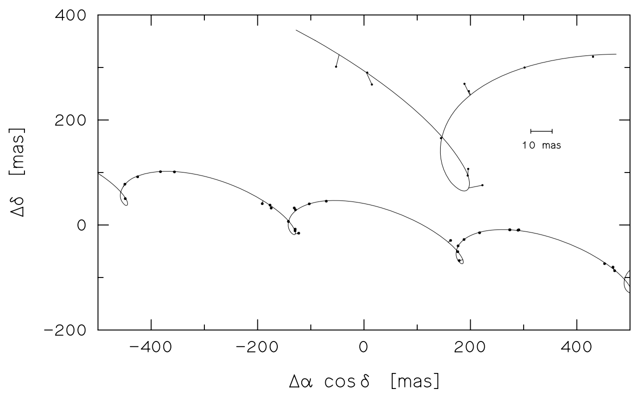

Fig. 1. The path of 47 UMa (HIP 53721) across the sky, over a period of three years, determined by the Hipparcos observations. The dots indicate the observed instantaneous position resulting from a combination of the one-dimensional measurements constrained by the model fitting. The residuals are indicated by the straight lines joining the dots to the modelled stellar path (solid line) at the corresponding epoch. The expanded region (top right) corresponds to the second 'loop', where the deviations between the elemental observations and the fitted curve are more evident. The amplitude of the oscillatory motion gives the star's parallax. The star has a proper motion of approximately −0.3 arcsec/yr in right ascension.

in the case of 70 Vir. The absolute magnitude for 70 Vir is significantly affected by the revised distance estimate: for $V = 4.98$ mag, M_V decreases from 5.23 mag (Gliese & Jahreiss 1991) to 3.68 mag, putting 70 Vir significantly above the main sequence for $B - V = 0.71$ mag ($T_{\rm eff} = 5488$ K). This supports interpretation of its evolution towards subgiant status based on its surface gravity ($\log g = 3.8$, Blackwell & Lynas-Gray 1994). Using $T_{\rm eff}$ and [Fe/H] from Blackwell & Lynas-Gray (1994), and the theoretical isochrones of Schaller et al. (1992), we derive a revised mass of $m_1 = 1.12\,{\rm M}_\odot$ and a log(age) of 9.87 ± 0.04. This compares with a mass estimate of $0.92\,{\rm M}_\odot$ adopted by Marcy & Butler (1996) based on its assumed position on the main sequence.

3. Limits on Astrometric Perturbations

The Hipparcos observations provide a powerful indication for binary or multiple systems with separations $\varrho > 0.1$ arcsec

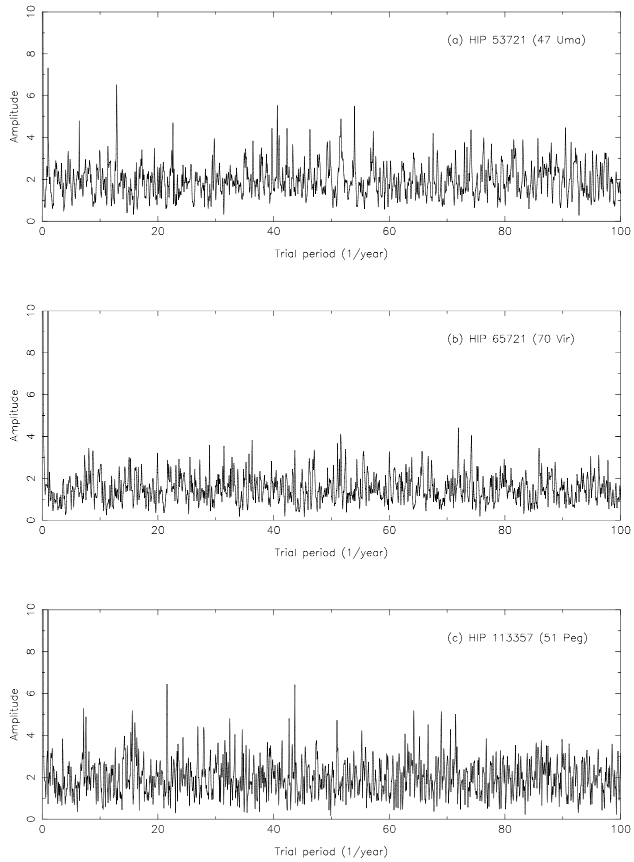

Fig. 2. Periodograms computed by fitting, for each trial period, four unknowns (the Thiele-Innes constants) in addition to the five astrometric parameters, viz. a sine and cosine term in right ascension and declination. The 'amplitude' is the root-sum-square of the four parameters, large amplitudes thus corresponding to significant perturbations. The periodograms provide no convincing evidence for binary orbits in any of the cases. The peak at 12.89 periods/yr (P = 28 days) for HIP 53721 (47 UMa), for example, with an amplitude of 6.5 mas, would correspond to a velocity of 35 km/sec (which may be ruled out from the radial velocity measurements).

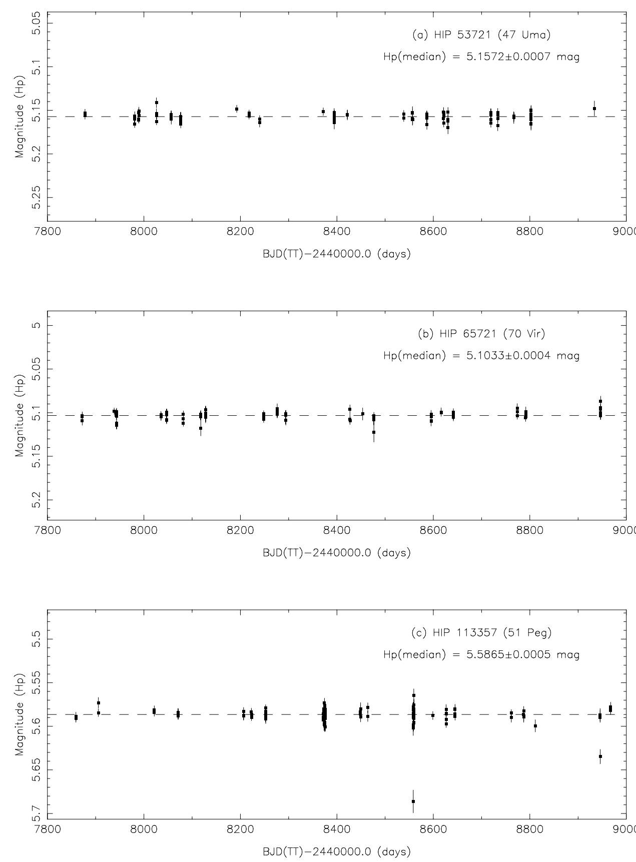

Fig. 3. Calibrated Hipparcos Hp (broad-band) magnitudes, with $\pm 1\sigma$ standard errors, are shown for each epoch of observation. Median magnitudes are indicated by the dashed horizontal lines (and given with their standard errors).

and $\Delta m \leq 3-4$ mag (Mignard et al. 1995). Some 20 000 double systems, roughly half of them newly discovered, will be classified in the published catalogue. None of the three stars considered here have been identified as binaries by the criteria adopted for double star detection for the routine Hipparcos data processing. Additional evidence that a Hipparcos star may be non-single is derived from the number of observations rejected in the construction of the 5-parameter astrometric solution, or from the solution's goodness-of-fit (see Table 1). In the case of 47 UMa and 70 Vir, there were no rejected observations, and in the case of 51 Peg, two observations were rejected, which is not, however, exceptional. The large goodness-of-fit statistic for 47 UMa suggests the presence of some unmodelled perturbations for this star.

Non-linear motion of a Hipparcos star due to an invisible companion may still be present at levels below which the star is clearly identifiable as double. Milliarcsec astrometry does not reach the sensitivity of radial velocity measurements for inclined orbits and for secondaries of order 1–10 M_J. While smaller orbital inclinations lead to smaller radial velocities, the astrometric signature due to the primary's reflex motion is present at all inclinations. This provides a method for constraining the upper limit of the secondary's mass.

Systematic detection of possible astrometric binaries due to the reflex motion of the primary along a Keplerian ellipse has been attempted within the Hipparcos reductions by Bernstein & Bastian (1995). While all unseen companions detected by Hipparcos up to now have stellar masses, the astrometric sensitivity of Hipparcos is just sufficient to determine orbits for brown dwarf companions of nearby stars, if they exist.

In this approach, the orbital elements are derived from the data by a least-squares adjustment, using a large number of trial periods (see Fig. 2). The analysis has been extended up to f = 100 periods per year in order to include the 4-day period of 51 Peg, although the most interesting frequency interval for astrometric detection is for f below a few per year (where, for a given mass ratio, the radial velocity amplitudes ($\propto f^{1/3}$) are smaller and the astrometric signature ($\propto f^{-2/3}$) larger). Application to the three objects confirms that the Hipparcos

Table 2. Parameter determinations. The orbital parameters m_1, P, a_0 (AU), $a_1 \sin i$ (AU), and $m_2 \sin i$ are taken from the respective radial velocity references (47 UMa: Butler & Marcy 1996; 70 Vir: Marcy & Butler 1996; 51 Peg: Mayor & Queloz 1995). a_0 and $a_1 \sin i$ are converted to angles using the Hipparcos parallaxes. Limits on a_1 (mas) are inferred from the Hipparcos astrometric residuals: the lower value is the amplitude of the periodogram (Fig. 2) at the specific period given by the radial velocity determinations; the more conservative value (in parentheses) corresponds to a 90 per cent confidence limit. Limits on $\sin i$ and m_2 follow directly, or from $m_2 = m_1 a_1/a_2 \sim m_1 a_1/a_0$.

Name	m_1	P	a_0		$a_1 \sin i$		$m_2 \sin i$	a_1	$\sin i$	m_2
	($M_\odot$)	(days)	(AU)	(mas)	(AU)	(mas)	(M_J)	(mas)		(M_J)
47 UMa	1.05	1088	2.10	149	0.0047	0.334	2.46	$< 1.0\,(3.0)$	$> 0.33\,(0.11)$	$< 7\,(22)$
70 Vir	0.92	116.7	0.43	23.7	0.0031	0.167	6.5	$< 1.0\,(1.7)$	$> 0.17\,(0.10)$	$< 38\,(65)$
51 Peg	1.00	4.229	0.05	3.3	$2.26\,10^{-5}$	$1.5\,10^{-3}$	0.47	$< 1.5\,(3.5)$	$> 10^{-3}\,(4\,10^{-4})$	$< 500\,(1100)$

observations of 51 Peg and 70 Vir are consistent with the stars being single. In the case of 47 UMa the method indicates that, although χ^2 is large, there is no unambiguous binary solution in the period range 30–2 000 days. Furthermore, the addition of (quadratic or cubic) acceleration terms to the astrometric solution, as may be required for long-period astrometric binaries, does not significantly improve the fit.

Constraints on the amplitudes of any unmodelled motion have been derived from the astrometric residuals, as indicated in Fig. 2. Confidence levels have been derived using a χ^2 statistic taking into account the covariance of the trigonometric terms for each frequency. The resulting 90 per cent confidence limits on a possible astrometric perturbation of the primary, a_1, are given in Table 2. For a 95 per cent confidence level the a_1 limits must be multiplied by 1.104, and for a 99 per cent level, by 1.306. That these are reasonable may be seen from the 90th percentiles of the periodogram amplitudes, which give the typical amplitudes for a single arbitary frequency (2.9 mas for 47 UMa, 2.3 mas for 70 Vir, and 3.0 mas for 51 Peg). Amplitudes of the periodograms at the specific orbital frequency are also given in Table 2.

The high-precision Hipparcos photometry is shown in Fig. 3. Although 51 Peg is a known variable (NSV 14374), classified as a long-period chromospheric variable by Baliunas et al. (1995), the photometry for all three objects is largely consistent with non-variability—the errors on the medians are around 0.4–0.7 millimag, with the scatter of individual observations around 5–6 millimag. For 51 Peg, the observation at BJD(TT)= 2 448 558.29297 (7σ fainter than the median) and three other observations more than 3σ fainter than the median, are incompatible with the $P = 4.2293 \pm 0.0011$ day period published by Mayor & Queloz (1995). Although, presumably by chance, they fit a 4.213 ± 0.003 day periodicity, we are unable to confirm that they arise from planetary occultation at the orbital period. Sinusoidal variations at the respective orbital periods are also insignificant.

4. Upper Limits on Companion Masses

Table 2 summarises the orbital parameters, including $a_1 \sin i$ and $m_2 \sin i$ from the radial velocity determinations. The unknown orbital inclination, i, yields only lower limits on m_2. In contrast an orbital radius (or upper limit), combined with the distance, places an upper limit on m_2, with only weak dependence on the initial assumptions on m_1 and m_2/m_1. For 51 Peg, better limits on a_1 are needed to constrain $\sin i$, and thus to distinguish between the possibility that the companion is above or below the brown dwarf limit. In contrast, the limit of $m_2 \leq 38 - 65 M_J$ for 70 Vir confirms the inferences made by Marcy & Butler (1996) that the companion is a massive planet or brown dwarf below 0.08 $M_\odot$.

While for 47 UMa a value of $m_2 \leq 5 - 10\,M_J$ has been argued on statistical grounds by Butler & Marcy (1996), we conclude that the Hipparcos astrometric residuals imply an observational limit of $m_2 \leq 7 - 22\,M_J$. With $m_1 \sim 1 M_\odot$, $e \sim 0$, $a_0 \sim 2.1$ AU, the companion to 47 UMa satisfies the semantic criterion for classification as a massive planet. Our results therefore provide confirmation of the existence of planetary masses surrounding other stars.

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