Revealing companions to nearby stars with astrometric acceleration [1]

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ABSTRACT

A subset of 51 Hipparcos astrometric binaries among FG dwarfs within 67 pc has been surveyed with the NICI adaptive optics system at Gemini-S, directly resolving for the first time 17 sub-arcsecond companions and 7 wider ones. Using these data together with published speckle interferometry of 57 stars, we compare the statistics of resolved astrometric companions with those of a simulated binary population. The fraction of resolved companions is slightly lower than expected from binary statistics. About 10% of astrometric companions could be "dark" (white dwarfs and close pairs of late M-dwarfs). To our surprise, several binaries are found with companions too wide to explain the acceleration. Re-analysis of selected intermediate astrometric data shows that some acceleration solutions in the original Hipparcos catalog are spurious.

Subject headings: stars: binaries

1. Introduction

The Hipparcos catalog (ESA 1997) contains objects with non-linear proper motions (PM) caused by binary companions; they are referred to as *acceleration* or $\dot{\mu}$ binaries. Their positions are described by 2nd (acceleration) or higher-order polynomials or, in rare cases, by full orbital solutions. In addition, accelerated motion due to companions in the so-called $\Delta\mu$ binaries can be revealed by the difference between the Hipparcos PM measured on a time base of 3.2 y and the long-term PM from the Tycho-2 (Høg et al. 2000) catalog (Makarov & Kaplan 2005, hereafter MK05), exploiting a time base of almost a century. So far little is known about both types of astrometric binary systems, yet they cover an important range of orbital periods from a few to a few hundred years where alternative detection techniques are not very efficient, especially for low-mass companions. The goal of our study is to get a better understanding of astrometric companions and their parameters and to use this information for improving binary statistics.

A thorough knowledge of binary and multiple star statistics is needed for the study of star formation, for stellar population synthesis, for predicting the frequency of supernovae, blue stragglers,

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X-ray binaries, etc. The statistical properties of binaries strongly depend on stellar mass. Only for nearby solar-mass dwarfs, however, current techniques (including Hipparcos astrometry) cover the discovery space well enough to enable statistical completeness. The classical work on G-dwarf binaries by Duquennoy & Mayor (1991) has been recently superseded by Raghavan et al. (2010) who revised the frequency of triple and higher-order hierarchies from 5% to 10% even in this well-studied sample within 25 pc. Given that there are only 56 hierarchical stellar systems in this small volume of space, we need a much larger sample for an unbiased statistical study of a multiplicity of 3 or higher.

The Hipparcos catalog is complete for dwarfs more massive than $0.8\,M_{\odot}$ with parallax larger than 15 mas (the number of objects within distance d is proportional to d^3). Hence, the sample of ∼5000 FG dwarfs within 67 pc derived from Hipparcos (hereafter FG-67pc) is ideally suited for statistical study of stellar hierarchies. The radial velocity (RV) has been measured for a large fraction of these stars by the Geneva-Copenhagen Survey of the Solar neighbourhood, GCS (Nordström et al. 2004), revealing short-period binaries. Wide companions can be retrieved by data mining (e.g. Tokovinin 2011). Unfortunately, the parameters of astrometric binaries with intermediate periods from few to few hundred years remain largely unknown. The FG-67pc sample contains $N_{\mu} = 329$ $\Delta\mu$ binaries and $N_a = 244$ acceleration binaries from MK05. These groups overlap and leave a total of $N_{\mu,a} = 343$ objects. Only half of those were also detected as spectroscopic binaries by GCS and other authors.

Many nearby dwarfs are searched for exoplanets. Dark astrometric companions do not degrade the RV precision of ongoing surveys, unlike binaries with a mass ratio ~ 1 where light of both companions is mixed in the spectrum in uncontrolled proportion due to guiding and seeing. It is known that close binaries host fewer planets than single stars, but rare exceptions to this rule give valuable insights into planet formation. Such is the case of HIP 101966 with a 72-y $\Delta\mu$ companion and a 3.6-y planet (Chauvin et al. 2011). Some other exo-planet candidates in astrometric binaries turn out to be brown dwarfs on low-inclination orbits, e.g. the outer planet in HIP 27253 (Benedict et al. 2010) or HIP 4311 (Sahlmann et al. 2011).

In order to improve our understanding of astrometric binaries, we conducted a "snapshot" survey using Adaptive Optics (AO) imaging. High-resolution imaging can achieve the following goals:

- Characterize targets for exo-planet search.
- Confirm or refute Hipparcos detections for nearby astrometric binaries, estimate their reliability.
- Determine companion masses from relative photometry and estimate orbital periods from projected separations. These constraints on companions are much tighter than those obtained from the astrometry alone.
- Provide first-epoch measurement of companion positions for future orbit calculation.

The results of these observations are presented in Section 2. High-resolution imaging of additional objects is retrieved from recent speckle-interferometry observations and the combined sample of 99 stars is studied in Section 3. In Section 4 we compare our findings with simulations, trying to put some constraints on the statistics of astrometric companions. The reanalysis of Hipparcos Intermediate Astrometric Data (HIAD) in Section 5 shows that some acceleration solutions of Hipparcos are spurious. We discuss the results in Section 6.

2. AO observations and results

The Near-Infrared Coronagraphic Imager, NICI, on the Gemini South telescope is an 85-element curvature adaptive optics (AO) instrument based on natural guide stars (Toomey & Ftaclas 2003; Chun et al. 2008). We used NICI in the non-coronagraphic mode, as a classical AO system with simultaneous imaging at two wavelengths. The two detectors have 1024^2 pixels of 18 mas (milliarcseconds) size, covering a square field of $18''$. To avoid saturation, we selected narrow-band filters with central wavelengths of $2.272\,\mu$m and $1.587\,\mu$m for the red and blue imaging channels.

The observations of 51 Hipparcos astrometric binaries were taken in queue mode in the period

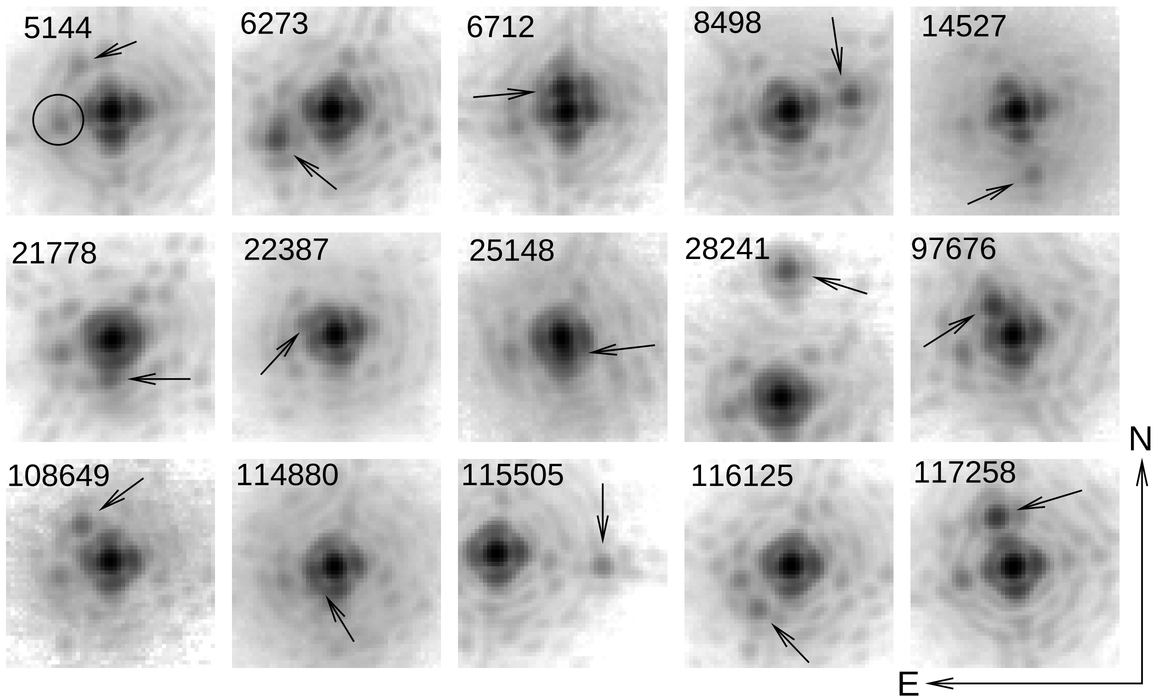

Fig. 1.— Images of some resolved close companions in the red channel (2.272 μm), marked by with the HIP numbers. Negative logarithmic intensity scale from 10^{-3} to maximum, each fragment is 50x50 pixels (0.9″). The prominent "ghost" companion to the left of each target (circled in the first image) is a reflex in the NICI optics.

from September 15 to November 8, 2011 using 11.6 h of the 14.7 h allocated time. The observing procedure and data reduction are the same as in (Tokovinin, Hartung, & Hayward 2010, hereafter THH10). The images of each target at 5 dither positions were median-combined after removing bad pixels, subtracting the median to remove the sky background, dividing by a flat field, and suitable shifts.

A complete list of the observed stars is given in the next Section. A total of 24 companions with separations from 0.″1 to 13.″8 were resolved, 17 of those are sub-arcsecond. While brighter companions are quite obvious, the faint ones (e.g. HIP 114880) are buried in the static speckle and difficult to see (Fig. 1). The speckle structure is dominated by a cross-like pattern in the first diffraction ring and by several knots along the diffraction rays (the pupil mask of NICI covers the spider with oversized stripes creating this particular diffraction pattern). The reality of detections is checked by "blinking" the red and blue images and by comparing with other stars. Some companions are better seen in the blue images where the speckle structure is less prominent and point sources are sharper. The faint "ghost" with $\Delta m \sim 4.3$ at 0.″24 to the left of each star is produced by the NICI optics.

The limiting magnitude for companion detection was determined from the intensity fluctuations in annular zones, as in THH10. Figure 2 illustrates a typical case. The detection depth depends on the AO compensation quality which was variable, reflecting the seeing variation and airmass. The median Strehl ratios and their full range are 0.36 and (0.15, 0.59) in the red channel, 0.16 and (0.08, 0.33) in the blue channel. The Strehl ratios calculated for a filled aperture are multiplied here by 1.08 to account for pupil masking in NICI. The median detection depth in the red channel is $\Delta m = 5.3^m$ at 0.″27 and $\Delta m = 7.4^m$ at 0.″90. These detection limits are only indicative because actual detections depend on companion's location and on details of the speckle structure.

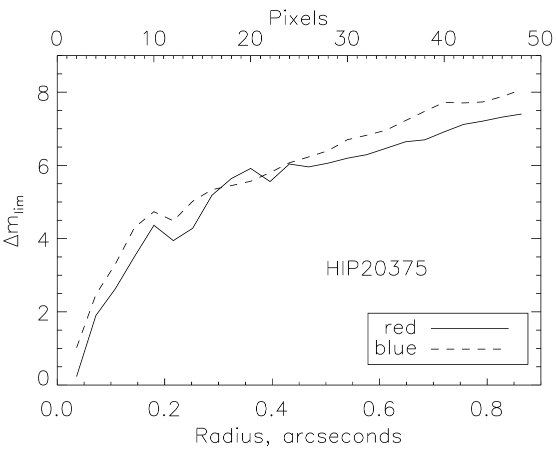

Fig. 2.— Limiting magnitude difference for companion detection in the red (full line) and blue (dashed line) channels for HIP 20375, a typical case with Strehl ratio of 0.40 in the red channel.

Table 1 lists relative astrometry and photometry of resolved pairs measured independently on the red and blue images. For well-resolved ($\rho > 0\farcs5$) companions the measure is obtained by fitting the shifted and scaled image of the main companion. For closer companions we used a blind deconvolution as described in THH10. This procedure does not produce reliable results for the faintest or closest companions near the detection limit. In such cases the difference between measures in the red and blue channels informs us of their quality. The uncertain measures of 5 pairs have question marks in the last column of Table 1.

3. Speckle interferometry and combined data

To improve statistics we invoke the results of speckle interferometry obtained with the 4m telescopes Blanco and SOAR between 2008 and 2011 and published in (Tokovinin, Mason, Hartkopf 2010) and (Hartkopf, Tokovinin, Mason 2012). These papers contain data on 57 astrometric binaries from the FG-67pc sample, 9 of which were also observed with NICI. There are 99 stars combined. Most observations were done in the I or Strömgren y bands. The detection limits $\Delta m(\rho)$ for the unresolved stars are published. They are not as deep as with NICI since the data were obtained at shorter wavelength and with half the telescope size. Nevertheless, 21 astrometric binaries were resolved with speckle. The speckle sample compiled *a posteriori* from existing publications can be biased towards more resolved binaries. Note that we removed known binaries from the NICI program.

The merged AO and speckle interferometry results on the 99 stars are presented in Table 2 followed by comments on the individual targets. It contains the Hipparcos number and the rounded values of parallax $p_{\rm HIP}$, $\Delta\mu$ and acceleration $\dot{\mu}$ (zero indicates non-detection of astrometric perturbations in MK05). If the RV variability is found in GCS, the amplitude in km/s is given in the next column. Otherwise it contains flags **C** (constant RV), **SB** (known spectroscopic orbit) or **-** (no RV data). The mass of each star is listed in the next column. It is estimated from the absolute magnitude in K band using photometry from 2MASS (Cutri et al. 2003), Hipparcos parallax, and the standard relation from Henry & McCarthy (1993). The light of companions is taken into account where necessary. For resolved pairs we estimate the mass ratio $q = M_2/M_1$ from the magnitude difference using the K-band standard relation (for binaries resolved with NICI) or stellar models of Baraffe et al. (1998) in the appropriate color (for speckle pairs). The separation ρ in arcseconds also is given. Then we list order-of-magnitude estimates of orbital periods from the third Kepler law $P^* = [\rho^3\, p_{\rm HIP}^{-3} M_1(1+q)]^{1/2}$, assuming that the separation equals the semi-major axis. The flags in the next column show whether the object was observed with NICI (**n** for unresolved, **N** for resolved, **-** if not observed), speckle (**s**, **S**, **-**), and if it is listed as resolved binary in the Washington Double Star Catalog (WDS) (Mason et al. 2001, flag **W**). The remarks in the last column indicate spectroscopic and astrometric binaries with known orbits (in these cases the true period is listed instead of P^*) or binary-star designations of known pairs in the WDS.

The fraction of directly resolved astrometric binaries is 21/51=0.41 for NICI (3 companions wider that 3″ are not counted) and 21/57=0.37 for speckle. These numbers should be taken with caution because some resolved companions may belong to triple systems where the close inner pair is responsible for the astrometric acceleration. Note that our speckle data contain a substantial num-

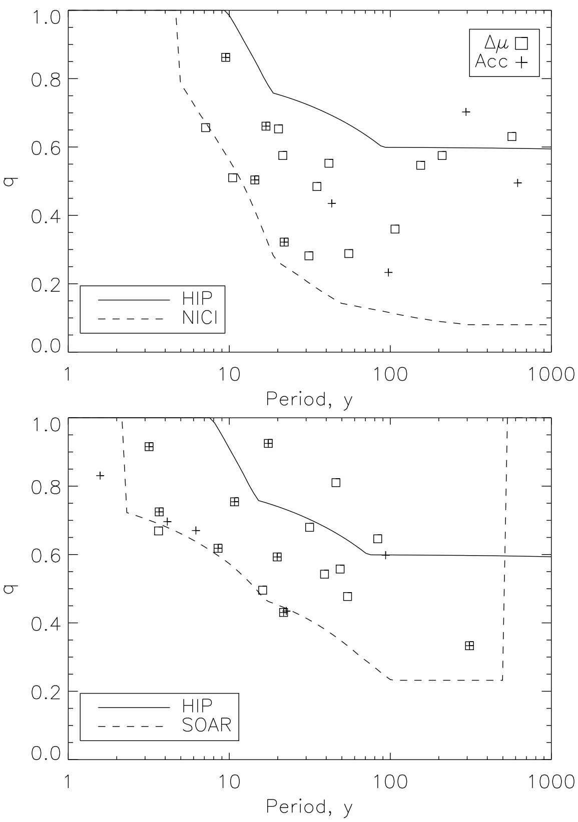

Fig. 3.— Astrometric binaries from FG-67pc actually resolved with NICI (top) and speckle (bottom) in the (P, q) plane. Squares and pluses mark $\Delta\mu$ and $\dot{\mu}$ binaries from MK05, respectively. The curves indicate approximate detection limits at 50 pc distance.

ber of previously known binaries. About 10% of the Hipparcos astrometric binaries from MK05 are listed in the WDS as resolved; such objects were removed from the NICI program. Figure 3 compares parameters of systems resolved here with NICI and speckle with estimated detection limits.

Table 2 lists 67 spectroscopic binaries (SB) including 11 with known orbits (we do not count here two short-period sub-systems), 13 stars without RV data and 17 stars with constant RV. Overall, the detection rate of astrometric binaries by RV is high, 67/87=77%. However, some of those SBs were missed by the GCS.

Frankowski et al. (2007) used a slightly different approach to detecting astrometric binaries than MK05 (total acceleration and $\Delta\mu$ instead of their components along coordinate axes and a different statistical criterion). They do not confirm long-term $\Delta\mu$ acceleration in seven systems from Table 2, namely HIP 20524, 25180, 31480, 48072, 88648, 108649, 109067 (all but HIP 88648 have $\Delta\mu < 10$ mas y^{-1}). However, HIP 108649 was resolved with NICI at $0\farcs812$, HIP 109067 is a 4.6-y SB, and two more stars have variable RV. Therefore we cannot affirm that their analysis is better than that of MK05.

The new Hipparcos reduction, HIP2 (van Leeuwen 2007), contains fewer acceleration binaries than the original catalog, HIP. Of 2403 stars with non-zero $\dot{\mu}$ and $p_{\rm HIP} > 15$ mas in MK05, half (1244) have standard 5-parameter solutions in HIP2 (no acceleration), the rest are divided equally between acceleration (7- and 9-parameter) or stochastic solutions (large residuals without polynomial or orbital fits). On the other hand, some new acceleration binaries appear in HIP2. We are not in a position to compare treatment of astrometric binaries in HIP and HIP2 and focus here only on the 99 objects in Table 2, for which HIP2 gives 52 standard 5-parameter solutions, 24 accelerations (which agree well with HIP), and 23 stochastic solutions. There are 15 stars with non-zero $\dot{\mu}$ in HIP but standard 5-parameter solutions in HIP2 (the HIP numbers 493, 5697, 8653, 12425, 13350, 17478, 24336, 25905, 28083, 38134, 45995, 49767, 103260, 112052, 114313). Of those 15, 7 are spectroscopic binaries, three more are resolved with NICI, while other 5 stars with small $\dot{\mu}$ may have spurious accelerations in HIP (see Sect. 5).

It is perplexing that several acceleration binaries have companions with separations on the order of $1''$. Nine pairs (HIP 11072, 11537, 12145, 16853, 21543, 24336, 103260, 109443, 116125) are acceleration binaries without detectable $\Delta\mu$ yet with relatively large separations (hence long periods). Some of those may owe their acceleration to unresolved inner sub-systems, for example HIP 21543 with a 2.2 y inner SB (which however should not produce detectable acceleration according to our simulations).

The case of HIP 11072 (κ For) deserves special comment. The joint analysis of astrometric (Gontcharov & Kiyaeva 2002), spectroscopic (Abt & Willmarth 2006) and visual (Hartkopf, Tokovinin, Mason 2012) orbits, to be presented elsewhere, leads to the firm conclusion that the astrometric companion is as massive as the primary, while it is ∼100 times fainter at optical wavelengths and has a red color index $V - I \sim 2$. Most likely it is a close pair of M-dwarfs. This explains the large acceleration of 19 mas y^{-2} measured by Hipparcos and the PM difference $\Delta\mu$ of 58 mas y^{-1} between Hipparcos and FK5. The star is not listed as $\Delta\mu$ binary by MK05 simply because it is missed in Tycho-2.

4. Simulations

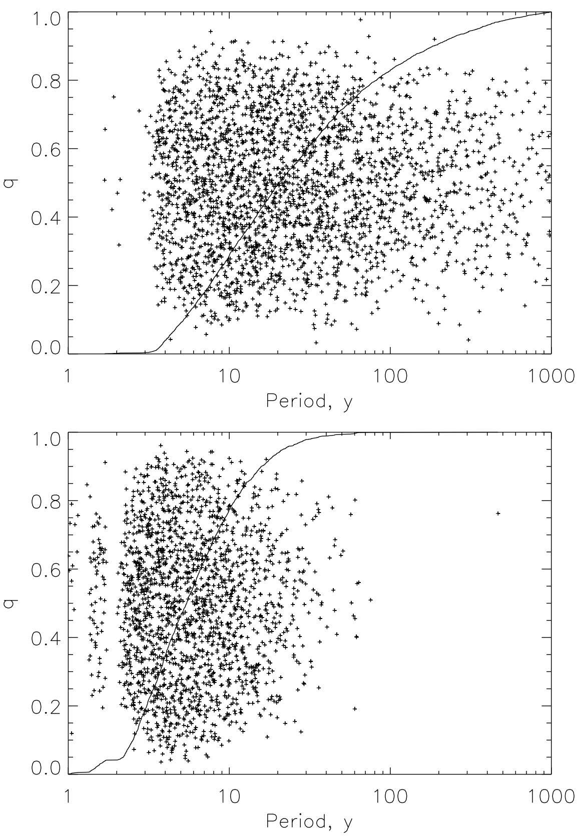

Fig. 4.— Distributions of simulated $\Delta\mu$ (top) and $\dot{\mu}$ (bottom) binaries in the (P, q) parameter space. The curves indicate cumulative period distributions. Binaries with log-uniform period distribution were simulated in this case.

To put our results in the context of binary statistics, we simulated a large number of binaries with dwarf components and $1M_\odot$ primaries which fill uniformly the volume up to 67 pc (parallax p larger than 15 mas). Their orbital periods are between 1 y and 1000 y. In this interval, we use the log-normal period distribution of Raghavan et al. (2010) with median period 293 y and logarithmic dispersion 2.28. The mass ratios of companions $q = M_2/M_1$ are uniformly distributed. The orbital inclinations i are random in space ($\cos i$ is uniformly distributed), and the orbital phases are random. The eccentricities e are distributed as cosine between 0 and 1, $f(e) = (\pi/2)\cos(\pi e)$, average eccentricity 0.5.

Given the orbital period P in years and the mass sum $1 + q$ in solar masses, we determine the semi-major axis a in A.U. by the third Kepler law as $a = [P^2(1 + q)]^{1/3}$. The semi-major axis of the astrometric (photo-center) orbit equals $\alpha = ap\phi$, where the factor ϕ accounts for the mass ratio q and the light ratio r,

$$\phi = \frac{\alpha}{ap} = \frac{q - r}{(r + 1)(q + 1)}. \quad (1)$$

We assume $r = q^{3.75}$ – an approximation of the standard relation for dwarfs below $1M_\odot$ in the V band. This assumption affects only high-q binaries, for the remaining ones the companion's light is negligible and the photo-center motion depends only on q. The maximum astrometric effect $\phi = 0.26$ is produced by binaries with $q \sim 0.5$.

To mimic Hipparcos observations, we simulate 10 measurements uniformly spaced in time t from $-T/2$ to $T/2$, where $T = 3.2$ y is the duration of the Hipparcos mission. The displacement of the photo-center in X, Y caused by a motion due to a binary is calculated for each of these 10 instants in time and fitted by parabolas, for example $X(t) \approx a + bt + ct^2$. Then, the binary-related component of the PM is $\mu_x = b$ and the acceleration is $\dot{\mu}_x = 2c$ provided that t is symmetric around the coordinate origin. We identify $\sqrt{\mu_x^2 + \mu_y^2}$ with the PM difference $\Delta\mu$, assuming that the Tycho-2 PM reflects the true center-of-mass motion of each system. Similarly, the total acceleration is $\dot{\mu} = \sqrt{\dot{\mu}_x^2 + \dot{\mu}_y^2}$. Recall that MK05 used $\Delta\mu$ and $\dot{\mu}$ in each coordinate separately for detecting astrometric binaries, while Frankowski et al. (2007) used total motion and obtained similar results.

Typical separations of 100-y binaries are around 0.″3, comparable to the grating period in Hipparcos, 1.″2074. Therefore our implicit assumption that astrometric motion measured by Hipparcos refers to the true photo-center of the combined light is no longer true and the situation is more complex. Moreover, Hipparcos measured stellar positions in one dimension with a scanning law that is specific to each star. For these reasons the simulations are not an exact match to reality.

In our simulations, the binary is considered detected by Hipparcos if $\Delta\mu > 5\,\mathrm{mas\,y}^{-1}$ and/or $\dot{\mu} > 4\,\mathrm{mas\ y}^{-2}$. These limits are chosen to match the MK05 data, as shown below. Among 10 000 simulated binaries, we find $N_\mu = 2905$, $N_a = 1767$, and the total $N_{\mu,a} = 3614$. The ratio $N_a/N_\mu = 0.74$ is slightly larger than 0.61 for real astrometric binaries from FG-67pc, but the periods of some real $\Delta\mu$ binaries may be longer than 1000 y, driving this ratio down a bit.

Figure 4 shows the distribution of simulated astrometric binaries in the (P, q) plane. The detection space of the two astrometric techniques is clearly defined by these plots. The median period of $\Delta\mu$ binaries is 20.4 y, 80% of the periods are between 5.2 y and 184 y. The periods of $\dot{\mu}$ binaries are shorter: the median is 5.4 y, 80% of the periods between 2.5 y and 15.8 y. The gap at $P = 1.6$ y corresponds to two orbits during the 3.2 y mission baseline; in this case accelerations cancel out.

We compare the distributions of $\Delta\mu$ and $\dot{\mu}$ of simulated and real astrometric binaries in Fig. 5. The thresholds adopted in our simulations for the detection of astrometric binaries by Hipparcos are confirmed by these plots. We see that the real astrometric binaries from FG-67pc have, on average, the larger PM and acceleration compared to the simulation. The discrepancy in acceleration is stronger. The discrepancy can be reduced if we assume that 10% of binaries have white dwarf companions with $q = 0.5$ and additional 20% have dark companions with $q = 1$, similar to the companion of HIP 11072 (dotted lines in Fig. 5). In this case the simulated fraction of acceleration binaries $N_a/N_\mu = 0.56$ also becomes closer to the 0.61 fraction in MK05. We should bear in mind that our simulations involve a number of simplifying assumptions and that the observed parameters $\Delta\mu$ and $\dot{\mu}$ can be affected by errors. Therefore the degree of agreement with our simulations is quite satisfactory.

For evaluating the fraction of objects resolved with NICI and speckle, we simulated 1000 binaries with the same statistics as above (without dark companions), of which 337 turned out to be detectable astrometric binaries. Their separations at a random moment of time and magnitude differences in the V (Hipparcos), I (speckle) and K (NICI) bands are compared to the detection limits of respective techniques, and objects above those limits are declared "resolved". Table 3 lists the adopted detection limits $(\rho, \Delta m)$, interpolated linearly between these points. We find 195 binaries "resolved" with NICI and 151 with speckle (147 of those also with NICI). The fraction of simulated resolutions with AO and speckle is 0.55 and 0.43 respectively, higher than the actual fractions of 0.41 and 0.37. The separation distributions of actually resolved binaries and simulated resolved binaries match well both for NICI and for speckle,

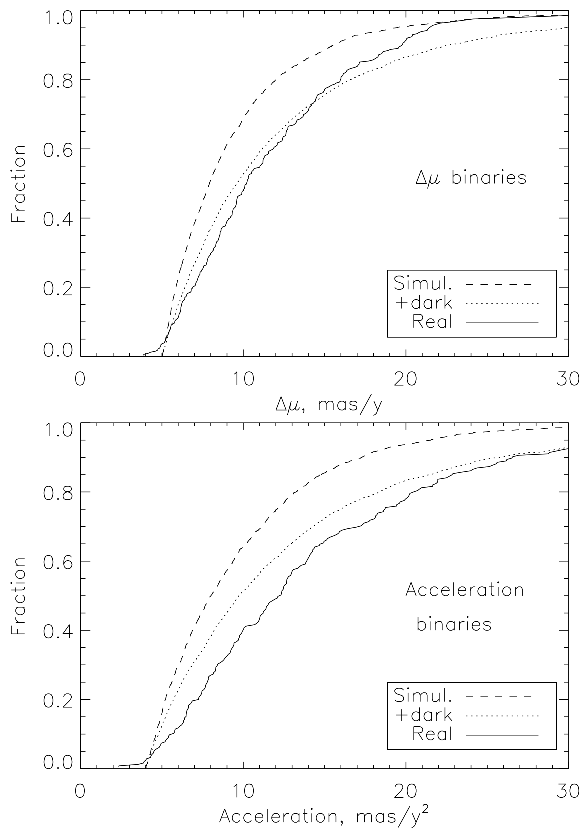

Fig. 5.— Cumulative distributions of simulated and real astrometric binaries. The simulations are performed assuming either only red-dwarf companions (dashed lines) or a certain fraction of dark and massive companions (dotted lines). Top: distribution of $\Delta\mu$, bottom: distribution of $\dot{\mu}$.

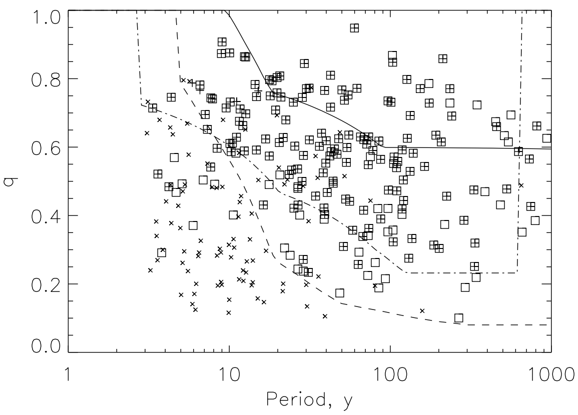

Fig. 6.— Simulated direct resolution of 353 astrometric binaries by NICI (squares, $N = 195$) and speckle (pluses, $N = 151$). Unresolved objects are plotted as small crosses. The curves indicate approximate limits of direct resolution with Hipparcos (full line), NICI (dashed line) and speckle (dash-dot line) for binaries at 50 pc.

in all cases the median separations are in the interval between 0.″27 and 0.″30.

The fraction of binaries resolved with NICI can be reconciled with our simulations if we assume that there are ~ 5 dark companions in the observed sample of 51 stars (subtract from the total number) and take into account the removal of ∼10% previously resolved systems from the NICI program (add 5 to the total and resolved count). The corrected resolution rate is then $(21+5)/(51+5-5) = 0.51$. If we consider only $\Delta\mu$ systems, the resolved fraction 16/34=0.47 is still less than the 0.68 predicted by simulation. The agreement can be restored to within statistical uncertainty by assuming ∼10% of dark companions.

5. Spurious accelerations in Hipparcos

A subset of Hipparcos stars marked with the acceleration flag "G" in the catalog has drawn special attention because of their apparently enigmatic nature. These stars have small parallaxes, sometimes even unphysical negative values, indicating large distances, and yet, their large accelerations suggest orbits of considerable size. Using the simple formulae from (Kaplan & Makarov 2003) or the Q-factor from MK05, we obtain incongruously large lower bounds for the masses of the invisible companions. Although multiple systems with dim companions which comprise a tight binary with a total mass exceeding the mass of the primary do exist, the lower limit masses of the most distant accelerating stars suggest the presence of more exotic or hypothetical objects, such as stellar-mass black holes or failed supernova (Gould & Salim 2002).

Table 4 includes a sample of some of the most interesting distant accelerating stars from the original Hipparcos catalog (ESA 1997) with parallaxes < 2 mas (none of them belong to our FG-67pc sample). The large distances for these stars inferred from Hipparcos parallaxes are confirmed by secondary criteria. The star HIP 111759 has been observed after the publication of the Hipparcos catalog spectroscopically (J. Sperauskas, private communication) and by ground-based interferometry, providing no clue of binarity. The negative result for this star casts doubt on the validity of accelerations for the entire sample. However, the formal significance of the accelerations, given in the last column of the table, is always greater than 3.5σ, implying a very small probability of error. Even more confusingly, binarity of these stars appears to be confirmed by significant $\Delta\mu$ (columns 3–4).

We performed further computations for the stars in Table 4 using the HIAD. For each star, we solved the entire set of observational equations by a weighted least-squares method, for the standard set of five astrometric unknowns. In each case, the results for proper motion components *without* solving for acceleration components turned out to be statistically consistent with the Tycho-2 proper motions. Thus, the astrometric solutions in the original Hipparcos catalog were strongly perturbed by the inclusion of additional acceleration unknowns in the observational equations. This gives a clear clue that the accelerations for the 11 stars in Table 4 are spurious. Comparison between 5- and 7-parameter solutions for HIP 2777 shows that the acceleration is not statistically significant, resulting from the poorly-conditioned system of least-squares equations. The new Hipparcos reduction (van Leeuwen 2007) gives 5-parameter solutions for all stars in Table 4 (except for one stochastic solution i.e. HIP 107466); the HIP2 PMs, also listed in Table 4, are close to those of Tycho-2.

6. Discussion

Our direct imaging resolved about 40% of Hipparcos astrometric companions. Although at least half of those were also detected by RV variability, their estimated periods exceed 10 y and only a few have known SB orbits. In contrast, imaging is a fast and efficient way to estimate periods and mass ratios of resolved binaries.

Our simulations show that our results are in reasonable agreement with statistics of solar-type binaries within 25 pc (log-normal period distribution and uniform mass-ratio distribution, see Raghavan et al. 2010). The separations of resolved pairs are distributed in agreement with these simulations, with a median around $0''.3$. The fraction of directly resolved companions is slightly less than expected. This can be explained by the presence of $\sim$10% of "dark" companions – white dwarfs (WD) and close pairs of M-dwarfs. The expected fraction of WDs (former primaries) depends on such unknowns as multiplicity of massive stars and star formation history. Duquennoy & Mayor (1991) quote a rough estimate of WD companions 1.2% per decade of period in their Sect. 6.2. The fraction of secondary companions that are themselves binary is not constrained observationally, given the difficulty of detecting such sub-systems. In the simulations we adopted 10% of WDs and 20% of binary secondaries to illustrate the effect of massive companions on the distribution of acceleration and $\Delta\mu$. However these distributions are influenced by several other factors and assumptions, therefore the improved fit in Fig. 5 cannot be considered as a safe estimate of dark-companion frequency.

We believe that the majority of unresolved astrometric binaries are real, but their companions are just too faint and/or too close to be resolved. In few cases this is confirmed by SB orbits. Yet, our work reveals some problems and unsolved questions.

First, we find that 9 acceleration-only binaries have in fact wide companions, too wide to cause the acceleration. Considering that Hipparcos measured stellar positions by 1-dimensional scanning with grating, it is plausible that faint companions with separations comparable to the grating period $1''.2074$ caused systematic errors that mimic acceleration. The issue could be further studied by modeling, although a companion with $\Delta m = 5$ produces only a small effect of few mas.

Second, we show that the original Hipparcos catalog contains some spurious accelerations accompanied by erroneous PMs. This is proven for distant stars whose accelerations imply improbably massive invisible companions, should they be real. Nearby stars may also suffer from such errors caused by fitting too many parameters in an ill-conditioned least-squares problem. The new reduction HIP2 contains less stars with acceleration, eliminating some spurious acceleration solutions but also missing some real astrometric binaries. The situation is not clear and has to be addressed by careful examination of each individual case. For now, acceleration binaries in HIP and HIP2 should be considered with caution and confirmed by other techniques whenever possible.

Simulations demonstrate that Hipparcos astrometry combined with Tycho-2 readily detects stellar-mass companions to dwarfs within 67 pc with periods from few to few hundred years. Substellar companions (brown dwarfs) can be discovered only in exceptional cases for the nearby stars; in addition, such companions are intrinsically rare (brown dwarf dessert).

The situation will change dramatically when high-precision GAIA astrometry becomes available. Owing to the short 5-y mission duration and the lack of an accurate long-term reference analogous to Tycho-2, only the $\dot{\mu}$ method of binary detection will be valid; it will be able to reveal companions of planetary mass. However, some lessons learned from Hipparcos astrometric binaries will be still relevant at this new level of precision.

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Table 1

Measures of companions resolved with NICI

HIP	Date	Red 2.272 μm			Blue 1.587 μm			Rem
		P.A.	Sep.	Δm	P.A.	Sep.	Δm	
5144	2011.8433	38.6	0.254	3.96	41.0	0.251	4.46	
6273	2011.8434	117.0	0.269	2.29	117.5	0.270	2.79	
6712	2011.8434	9.2	0.104	0.64	6.4	0.094	0.72	
8498	2011.8490	283.0	0.272	2.46	282.9	0.272	2.67	
11537	2011.8490	347.6	4.113	3.48	347.7	4.119	3.92	
12425	2011.8383	77.9	0.344	3.77	80.9	0.334	4.51	?
14527	2011.7753	194.8	0.295	3.65	193.8	0.289	3.50	
16853	2011.7753	90.0	2.696	3.26	90.0	2.683	3.69	
21079	2011.7752	23.4	1.622	1.91	23.4	1.619	2.14	
21778	2011.8027	176.2	0.165	3.03	177.2	0.151	3.19	?
22387	2011.7752	64.5	0.165	3.76	68.1	0.158	3.96	?
24336	2011.7972	351.3	1.250	1.46	351.4	1.246	1.64	
25148	2011.8027	195.2	0.054	1.29	188.5	0.065	1.11	?
28241	2011.6960	356.4	0.539	2.50	355.5	0.542	2.79	
97676	2011.6978	33.6	0.156	1.91	34.2	0.156	2.15	
103260	2011.6979	359.0	3.975	1.83	359.0	3.968	2.08	
108041	2011.8512	114.1	0.812	2.29	113.8	0.814	2.49	
108649	2011.8513	39.6	0.202	2.94	40.2	0.199	3.33	
109443	2011.8513	346.3	1.420	2.92	346.2	1.433	3.18	
114880	2011.8512	146.8	0.100	2.52	146.7	0.090	3.27	?
115505	2011.8512	262.6	0.462	3.65	262.5	0.461	4.20	AB
115505	2011.8512	319.4	13.735	4.61	319.7	13.778	5.47	AC
116125	2011.8512	143.1	0.239	3.45	143.5	0.239	3.73	
117258	2011.8513	18.6	0.228	1.76	18.9	0.227	2.13	

Table 2

Summary data on observed astrometric binaries

HIP	p_{HIP} mas	$\Delta\mu$ mas y^{-1}	$\dot{\mu}$ mas y^{-2}	ΔRV km s^{-1}	M_1 $M_\odot$	q	ρ arcsec	P^* y	Flags N S W	Remark
493	26	0	4	C	0.97				- s -	
1573	22	13	0	1.3	1.12				- s -	
2066	16	12	0	-	1.05	0.65	0.386	28.8	- S W	YR 4
5144	23	8	0	C	1.04	0.28	0.254	31.2	N - -	
5697	19	18	14	SB	0.86			39.7	n - -	SB1, $q>0.2$
6273	30	19	0	2.2	0.92	0.58	0.269	8.9	N - -	AB
6712	18	16	25	0.8	0.93	0.86	0.102	9.5	N - -	
7142	15	6	0	-	0.84				n - -	
7580	24	19	8	SB	1.34	0.72	0.079	28.8	- S W	SB2, KUI 7
7869	15	0	12	6.9	1.09				n s -	sb2
8498	19	9	0	1.2	1.06	0.55	0.273	41.6	N S -	
8653	21	0	2	-	0.85				n - -	
10611	16	10	7	-	0.96	0.92	0.044	3.2	- S -	
11072	45	0	19	5.1	1.28	0.43	0.465	26.5	- S W	LAF 27, VB
11537	16	0	26	-	0.92				N - -	Comp. at 4.1”
12425	15	0	17	C	0.98	0.23	0.359	97.3	N - -	
12716	24	9	0	SB	1.03	0.56	0.378	48.8	- S -	SB2 1d, triple
12843	70	0	26	C	1.15				- s -	
12889	20	10	10	1.8	1.09				n s -	
13350	17	10	6	C	0.88				n - -	
14527	19	8	0	1.5	0.95	0.29	0.297	55.2	N s -	
16370	20	0	18	1.4	1.27	0.70	0.070	4.1	- S -	sb2
16851	19	6	11	2.0	1.26				n - -	
16853	23	0	5	4.0	1.02	0.41	2.696	1056.2	N s -	triple?
17108	16	0	6	1.6	1.36				n - -	
17478	19	0	13	2.5	0.99				n - -	
17820	20	0	30	4.7	0.94				n s -	
17895	19	14	0	9.5	1.23	0.81	0.329	46.0	- S W	YR 23, sb2, triple
19147	15	10	9	C	1.14				n - -	
20375	18	13	0	1.7	1.13				n s -	
20524	20	5	0	C	0.94				n - -	
21008	21	5	0	-	1.15	0.50	0.170	16.1	- S W	PAT 10
21053	24	6	0	C	1.21		0.300	37.7	- s W	PAT 11
21079	20	5	0	3.8	0.94	0.63	1.622	569.0	N - -	triple?
21543	20	0	17	SB	1.15	0.60	0.513	93.5	- S W	SB1 1.8y, CHR 153
21778	23	15	11	1.6	0.98	0.50	0.159	14.4	N s -	
22221	25	20	18	3.0	1.06		0.100	7.3	- s -	PAT 16
22387	18	9	8	2.3	1.05	0.32	0.165	21.9	N s -	
23818	26	0	19	C	1.30	0.83	0.046	1.6	- S W	FIN 376, sb2
24336	24	0	17	C	0.95	0.70	1.250	295.3	N - -	
24419	34	0	16	SB	0.93			2.2	- s -	SB1 $q>0.14$
25148	15	5	0	3.7	1.00	0.66	0.066	7.1	N - -	
25180	20	3	0	31.7	1.40				- s -	
25905	25	14	12	0.6	0.86				n - -	
27260	16	8	0	-	0.97				n - -	
27371	22	22	15	0.8	0.86				n - -	
28083	16	0	7	-	1.02				n - -	
28241	16	10	0	C	1.03	0.55	0.539	154.3	N - -	
28333	16	7	20	4.1	1.00				n - -	
29860	51	8	0	SB	1.07	0.48	0.884	26.8	- S W	SB1, CAT 1
30480	31	6	0	1.4	1.17				- s -	
31480	15	7	0	4.9	1.28				- s -	
32329	20	5	0	6.8	1.19				- s -	
35642	27	11	12	1.0	1.18				- s -	
36836	22	14	0	3.0	1.21				- s -	
37853	65	64	6	1.8	1.06	0.62	0.326	8.5	- S -	
38134	19	11	6	5.6	1.05				- s -	
42408	24	14	17	1.2	0.92				- s -	

TABLE 2—*Continued*

HIP	p_{HIP} mas	$\Delta\mu$ mas y^{-1}	$\dot{\mu}$ mas y^{-2}	ΔRV km s^{-1}	M_1 $M_\odot$	q	ρ arcsec	P^* y	Flags N S W	Remark
43299	24	20	0	2.5	1.04				- s -	
44874	21	18	0	2.9	1.31		1.700	503.3	- s W	RST 2610
44896	23	8	0	0.5	1.16				- s -	
45705	20	20	20	1.6	1.03	0.75	0.123	10.8	- S W	CHR 239
45995	26	0	4	7.5	1.02				- s -	
48072	26	7	0	5.0	1.03				- s -	
48095	21	16	4	2.6	1.21				- s -	
49767	23	6	4	0.8	1.03				- s -	
50870	18	10	8	1.6	1.41	0.33	1.076	310.2	- S -	
53217	19	6	33	SB	1.32			3.3	- s -	SB 6.8d+3.3y
53424	19	0	9	8.5	1.00				- s -	
55714	21	8	0	1.8	1.01		0.100	7.2	- s W	CHR 242
59926	25	11	12	0.7	1.16				- s -	
60024	22	11	6	1.3	0.90				- s -	
64219	36	20	10	SB	0.92		0.310	23.5	- s W	SB1 20.4d, TOK 28
67620	51	46	0	SB	0.96	0.67	0.143	10.3	- S W	SB1, WSI 77
73241	41	9	6	SB	1.09	0.59	0.363	14.9	- S W	SB1, WSI 80
82621	37	14	9	-	1.22	0.43	0.359	21.7	- S W	WSI 86
85141	17	16	9	1.8	1.16	0.93	0.144	15.0	- S W	RST 3972, VB, sb2
88648	17	19	0	-	0.69				n - -	
92103	15	6	0	C	1.45				n - -	
97676	18	23	31	2.2	0.95	0.66	0.145	16.9	N - -	
103260	22	0	7	C	1.11	0.64	3.975	1694.7	N - W	I 18
103735	21	10	0	3.4	1.09				n - -	
103987	19	0	21	SB	1.23	0.67	0.084	1.0	- S W	SB1, WSI 6
108041	20	15	0	C	0.88	0.57	0.812	209.8	N - -	
108095	18	8	0	C	0.91				n - -	
108649	15	5	0	C	1.14	0.48	0.199	35.0	N - -	
109067	19	7	0	SB	0.76			4.6	n - -	SB1 q >0.23
109443	16	0	11	2.5	1.16	0.49	1.420	617.7	N - -	
109470	16	0	21	2.2	1.26				n - -	
110649	48	33	0	1.5	1.21				- s -	
112052	18	0	16	-	0.85				n - -	
112506	25	26	0	-	0.96	0.68	0.304	31.5	- S W	WSI 93
114313	15	0	37	SB	0.88			3.1	n - -	SB1
114880	16	8	0	2.5	1.05	0.51	0.095	10.5	N - -	
115505	17	9	0	2.6	1.09	0.36	0.462	107.0	N - -	triple?
116125	15	0	21	C	1.25	0.43	0.239	43.3	N - -	
117258	25	11	0	1.4	1.01	0.65	0.228	20.2	N - -	
117493	15	15	4	4.1	1.37				n - -	
117513	15	0	13	-	1.01				n - -	

Notes to Table 2

HIP 493: The visual binary HIP 495AB at 573″ is co-moving, same parallax. HIP 493 is $\sim 1.3^m$ below the Main Sequence in the $(K, V-K)$ color-magnitude diagram.

HIP 5697: The SB1 orbit suggests mass ratio $q > 0.2$ and axis 0.″21. The companion is probably just a bit too faint or too close to be resolved with NICI.

HIP 6273: Two astrometric orbits are derived by Goldin & Makarov (2006), the longest one has $P = 8.93$y, axis 55 mas, $e = 0.84$.

HIP 6712: Possible physical companion at 24.″4, 227° in 2MASS.

HIP 8653: Small acceleration of 2 mas/y^2, possibly single.

HIP 11072: The astrometric binary with 26.5-y orbit has a massive secondary with $q \sim 1$ (see text).

HIP 11537: The 4″ companion is partially resolved in 2MASS images, for that reason the star is not found in the 2MASS point-source catalog. The companion is physical, because it keeps the same position for 10 y despite PM of 0.″2 y^{-1}. This is a pre-Main-Sequence star according to SIMBAD.

HIP 12425: A faint companion near the detection limit is found, our measures are uncertain. The estimated long period $P \sim 100$y suggests that Hipparcos aceleration of 17 mas y^{-2} is spurious.

HIP 12716: Triple. The A-component is 0.955d SB2, the tertiary is resolved with speckle. As A is located some 1.7^m above the Main Sequence, the object can be closer than indicated by the Hipparcos parallax of 24.6 mas.

HIP 12843: Despite large acceleration of 26 mas/y^2, no RV variability was found in the GCS from 2 measures.

HIP 14527: The companion with $q = 0.29$ is resolved with NICI but unresolved with speckle, being too faint in the optical.

HIP 16370: The double-lined SB detected in GCS is resolved by speckle. Its estimated orbital period 4 y explains the acceleration.

HIP 16853: Likely triple: the inner pair produces RV variability and acceleration, the outer companion at 2.″7 is discovered with NICI.

HIP 17895: Triple, the RV amplitude of 9.5 km/s and double lines seen in GCS cannot be caused by the visual system YR 23 with estimated period of ∼50 y which could however be responsible for $\Delta\mu$.

HIP 21008: Member of the Hyades (vB 81) and "probable SB" according to Griffin et al. (1988). This WDS pair PAT 10 was resolved by speckle.

HIP 21053: Hyades. The 0.″3 binary PAT 11 was not resolved by speckle. The GCS did not detect RV variability despite large scatter of 4.8 km/s in their 3 measures.

HIP 21079: Possibly triple: the new companion at 1.″6 should not produce RV variability by 3.8 km/s.

HIP 21543: Hyades. The visual companion CHR 153 at 0.″54 shows only linear motion (Hartkopf, Tokovinin, Mason 2012), it can be another member of Hyades or a wide pair in projection. The acceleration could be produced by the 1.8 y SB companion.

HIP 21778: Resolved with NICI, uncertain measure. Not resolved with speckle.

HIP 22221: Hyades. The 0.″1 pair PAT 16 was not resolved with speckle; its estimated period is 7 y.

HIP 22387: The companion is close to the detection limit, but it is considered to be real. The measurement is uncertain.

HIP 24336: The 1.″25 companion discovered with NICI is hardly the one that produced the acceleration of 17 mas/y^2.

HIP 24419: The acceleration is due to the 2.2 y SB with estimated axis of 55mas and $q > 0.14$. The companion is too faint and close to be resolved with NICI or speckle. The system is triple with a faint common-proper-motion (CPM) companion at 14.″6.

HIP 25148: The companion at 66 mas is at the diffraction limit, the NICI measurement is not accurate. The pair can be resolved by speckle.

HIP 25180: Large RV amplitude (31.7 km/s) hints at short orbital period, but only small $\Delta\mu = 3$ mas/y is detected by Hipparcos. Triple?

HIP 28241: A triple system consisting of the 0.″54 inner pair resolved with NICI and the physical companion B at 11″.

HIP 29860: The 27-y pair CAT 1 with computed visual (Hartkopf, Tokovinin, Mason 2012) and SB orbits is responsible for $\Delta\mu$. Triple with the CPM companion LEP 24 AE at 103″.

HIP 37853: Triple system at 15 pc. The inner astrometric pair with large $\Delta\mu$ is resolved with speckle. It is accompanied by the white dwarf NLTT 18141 = GJ 288B at 914″.

HIP 44874: Possibly triple: the known companion RST 2610 at 1.″7 with estimated period 500 y is unlikely to cause the RV variability and $\Delta\mu$.

HIP 50870: The 1.″1 speckle companion can explain $\Delta\mu$, but not the acceleration.

HIP 53217: Triple with inner SB1 of 6.8d and outer SB system of estimated 3.3 y period which produces large acceleration. The estimated axis is 40 mas, unresolved with speckle.

HIP 55714: The 0.″1 pair CHR 242 has only 1 observation in the WDS, unresolved with speckle. Double lines were noted by the GCS. This star remains a mystery.

HIP 64219: Triple: the inner SB1 of 20.4 d period has tertiary companion TOK 28 at 0.″31 with mass ratio of 0.2 which produces the acceleration and $\Delta\mu$. This tertiary is too faint to be resolved in the optical.

HIP 67620: The 10.3-y SB1 orbit by Abt & Willmarth (2006) matches the speckle pair WSI 77 and explains the large $\Delta\mu$

HIP 73241: The 14.9-y SB1 orbit is mentioned by Raghavan et al. (2010).

HIP 92103: The NICI images are of poor quality resulting in a shallow detection limit (at 0.″2, $\Delta K < 3$ and $\Delta H < 2$)

HIP 97676: NICI resolved the astrometric binary with variable RV. Triple system with a CPM companion at 83″.

HIP 103260: The known 3.″9 pair I 18 with estimated period ∼ 1700 y cannot explain the acceleration.

HIP 103987: The 1-y SB with large acceleration has been resolved with speckle. However, we can't exclude that it is a triple system.

HIP 108095: NICI images contain a hint of faint companion at ∼ 280°, 0.″12, not accepted as real.

HIP 109067: The 4.6 y SB1 with estimated $q > 0.23$ and axis 53 mas is below the NICI detection limit. This is a subdwarf with large PM, below the Main Sequence.

HIP 109443: Possibly triple. The 1.″4 companion found with NICI can't explain the RV variability and acceleration.

HIP 114313: SB1 with P=3.1 y, estimated $q > 0.15$. The orbital axis is 31 mas, too close for NICI. Large acceleration.

HIP 115505: $\Delta\mu$ is explained by the newly resolved 0.″5 pair. Triple with companion at 13.″8 in 2MASS. This companion is measured with NICI as well at the same position, its colors matching a low-mass dwarf. Considering the low density of background stars, the companion is physical, although we cannot confirm it as CPM owing to the small PM of the main target.

Table 3

Detection limits $\Delta m(\rho)$

Hipparcos		Speckle		NICI	
ρ	ΔV	ρ	ΔI	ρ	ΔK
0.09	0	0.04	2	0.058	1
0.14	2.2	0.15	4.0	0.144	4
0.4	4.0	0.5	5.7	0.27	7.4
10	4.3	1.5	5.7	9.0	7.4

Table 4

Selected distant Hipparcos stars with large accelerations and significant differences between Tycho-2 and Hipparcos proper motions.

HIP	Parallax mas	HIP PM mas yr^{-1}	Tycho-2 PM mas yr^{-1}	HIP2 PM mas yr^{-1}	$\dot{\mu}$ mas yr^{-2}	$\dot{\mu}/\sigma(\dot{\mu})$
2777	1.7	(46.9, -8.9)	(30.2, -4.8)	(34.1,-6.2)	17.2	4.8
14133	1.4	(24.2, -17.8)	(3.0, -3.2)	(1.1,-0.7)	25.8	4.0
55442	0.5	(-25.0, -37.6)	(-34.7, -23.9)	(-31.0,-25.5)	16.8	3.6
58036	-0.1	(-107.1, -9.3)	(-50.8, 13.0)	(-46.6,12.3)	60.6	6.2
76245	1.3	(-4.9, -2.4)	(-15.6, 1.0)	(-11.6,-1.6)	11.3	4.7
101344	1.2	(18.5, -63.2)	(11.0, -72.9)	(12.8,-74.3)	12.3	4.0
101941	1.3	(-14.5, -23.3)	(-18.7, -24.5)	(-15.6,-24.2)	4.3	3.5
107466	0.2	(12.3, 21.8)	(12.0, 14.3)	(16.5,17.7)	7.5	4.8
110978	0.9	(-11.8, -17.2)	(-0.7, -18.4)	(-4.4,-18.8)	11.1	3.6
111759	1.7	(-0.9, 0.8)	(-10.8, 3.1)	(-10.3,3.8)	10.2	4.3
111835	-1.4	(-16.0, -24.0)	(-11.0, 4.1)	(-10.2,1.3)	28.5	6.7