Astrometric Mass Ratios of 248 Long-period Binary Stars Resolved in Hipparcos and Gaia EDR3

Valeri V. Makarov\textsuperscript{1} and Claus Fabricius\textsuperscript{2}

\textsuperscript{1} U.S. Naval Observatory, 3450 Massachusetts Ave., Washington, DC 20392-5420, USA; valeri.makarov@gmail.com
\textsuperscript{2} Departament de FQA, Institut de Ciències del Cosmos, Universitat de Barcelona (IEEC-UB), Martí i Franquès 1, E-08028 Barcelona, Spain; claus@fqinstitution

Received 2021 September 6; revised 2021 September 18; accepted 2021 September 22; published 2021 November 24

Abstract

Using the absolute astrometric positions and proper motions for common stars in the Hipparcos and Gaia catalogs separated by 24.75 yr in the mean epoch, we compute mass ratios for long-period, resolved binary systems without any astrophysical assumptions or dependencies, except the presence of inner binary subsystems that may perturb the observed mean proper motions. The mean epoch positions of binary companions from the Hipparcos Double and Multiple System Annex are used as the first epoch. The mean positions and proper motions of carefully cross-matched counterparts in Gaia EDR3 comprise the second epoch data. Selecting only results with sufficiently high signal-to-noise ratio and discarding numerous optical pairs, we construct a catalog of 248 binary systems, which is published online. Several cases with unusual properties or results are also discussed.

Unified Astronomy: Thesaurus concepts: Mass ratio (1012); Astrometric binary stars (79); Optical double stars (1165); Astrometry (80)

Supporting material: machine-readable table

1. Introduction

About 20\% of stars in the ground-breaking Hipparcos catalog (ESA 1997) are components of double or multiple systems. Those that are sufficiently bright and well separated were treated with ad hoc data reduction procedures designed to estimate a larger number of unknowns than the standard 5-parameter model. For example, a resolved double without a measurable orbital motion was typically treated in a 7-, 9-, or 10-parameter adjustment solution, depending on the assumptions about the proper motion and parallax of the secondary component. The resulting astrometric fit is present in the main catalog for the primary (nominally, brighter) components, while the secondaries are, in most cases, missing there. The complete catalog of these special solutions is available in the Double and Multiple System Annex (DMSA). This information about double stars can also be found in a more user-friendly and streamlined form in the Tycho Double Star Catalog (Fabricius et al. 2002), complemented with numerous additional systems resolved in the Tycho mission. The Gaia mission, on the other hand, has not yet released specialized solutions for close double or multiple systems (Gaia Collaboration et al. 2016, 2021). Such objects have been treated in the same way as single stars in the general data reduction pipeline. Many double stars have been resolved in the current Gaia EDR3, however, owing to the high dynamical range and good angular resolution of the instrument. Significant astrometric perturbations of binary stars processed with the general 5- or 6-parameter models have already been reported for Gaia DR1 (Makarov et al. 2017).

Wide binaries with periods longer than 100 yr require decades long ground-based observations to derive their apparent orbits. Most of this work relies on the methods of differential astrometry where only the relative position of the secondary with respect to the primary is involved. Combined with a trigonometric parallax, the estimated orbit provides the total mass of the binary system. The distribution of mass between the components is much harder to estimate. Most of these estimates are based on the photometric data (relative brightness and color) combined with models of stellar evolution. The most accurate empirical masses (and mass ratios) are obtained for the rather rare class of spectroscopic double-lined binaries that are close and bright enough for precision astrometry (Torres et al. 2002). In this paper, we consistently apply the method of absolute two-epoch astrometry (Makarov 2021) to the entire collection of doubles in the DMSA cross matched with Gaia EDR3. The goal is to select likely physical binaries with a measurable orbital motion between the mean epochs (1991.25 for DMSA and 2016 for EDR3) and to estimate their mass ratios along with their formal uncertainties. The main requirements for this method to work are that the orbital period should be significantly longer than the duration of each astrometric mission, which is about 3.5 yr for Hipparcos and 33 months for Gaia EDR3, and the system should be close enough to produce measurable changes in the apparent orbital motion of the components.

Much of the effort on this route was spent on constructing the initial sample of suitable double and triple systems, which is described in Section 2. The resulting collection of 6306 cross matched and verified Hipparcos/EDR3 double systems was processed with a mass-ratio estimation and Monte Carlo simulation algorithms (Section 3). Additional vetting based on objective signal-to-noise ratio (S/N) and model consistency criteria reduced the sample to 248 binaries, for which detailed information from Hipparcos, Gaia, and our own results is collected in a catalog published online (Section 4). Objects of special interest with outstanding or unexpected properties are selectively discussed in Section 5. Discussion of future development and possible applications is presented in the concluding Section 6.
2. Selection of Resolved Binary Systems

To generate a sample of cross-matched double and triple systems in Hipparcos and Gaia EDR3, we begin with the Double and Multiple System Annex to the main Hipparcos catalog (ESA 1997), which lists 12,005 double, 182 triple, and 8 quadruple star systems. The components of these systems are not necessarily physically bound—in fact, many of them prove to be optical combinations, i.e., chance projections of unrelated stars on the sky. These sources were treated by a special pipeline separately from the regular 5-parameter solutions. The data reduction algorithm is much more complicated and the results are less reliable because of the greater number of unknowns and the entangled character of the primary observations. Due to the periodical character of the recorded photon counts, multiple solutions to the same set of position of the components (Fabricius & Makarov 2000b). Having one of the components moving by measurable distances with respect to the other (as in optical pairs due to the difference in parallax or proper motion or in nearby binaries due to orbital motion) or significantly varying in brightness exacerbates the problem to the point of being unsolvable. For this reason, most of the solutions in DMSA are flagged as “fixed,” i.e., they were constrained to have the same proper motion and parallax. The effect of fixed solution for optical pairs is especially damaging, because the mean positions are determined at the standard epoch 1991.25, and the unaccounted proper motion differences may compound for fast-moving components whenever the true optimal epoch of observations minimizing the trace of the covariance matrix deviates from this common epoch.

Treating each DMSA component as a separate entity, we found 14,793 counterparts in Gaia EDR3 by a cone search with a radius of 2°5 around positions propagated to the Gaia mean epoch with Hipparcos proper motions. In cases of multiple counterparts within the search cone, the closest entry was selected as the likeliest match. Subsequently, each recovered Gaia entry was matched to the nearest DMSA component. This procedure left 234 DMSA entries without any Gaia counterparts. To identify the reason for these misses, we carefully investigated a smaller selection of 12 pairs from this lot. Only a small fraction (less than 10%) are truly missing in Gaia because they are too bright and saturate the detector pixels even in the special gating mode. The majority of companions are present in Gaia EDR3 but outside of the search radius. Many of them are parts of optical pairs (chance projections) with significantly different proper motions and, possibly, parallax, which obtained “fixed” solutions with a common proper motion in the DMSA processing. The examined 12 cases are predominantly widely separated pairs up to 26″ with much degraded Hipparcos proper motions. Gross errors in position are also present. In three cases out of 12, greatly improved astrometric solutions were obtained with more accurate initial assumptions by Fabricius & Makarov (2000b) using the published Hipparcos transit data. A larger number of difficult cases can be revisited today utilizing additional constraints from Gaia.

The distribution of distances between the matched counterparts is strongly peaked at about 0°03, which corresponds to the expected accumulated proper motion error. A long tail of this distribution stretches all the way to 2°5. A total of 34 components (all B or C in DMSA) are more than 2° from their matched Gaia counterparts. Almost all of them appear to be optical pairs with a few gross errors in DMSA, such as HIP 75741 where the true companion is as faint as 12.3 mag and located on the other side of the primary. Another few systems appear to be genuine binaries where the secondary components moved long distances on the sky in the intervening 24.75 yr, such as HIP 13716, 43225, and 117163.

Further pruning of the sample was aimed at removing Gaia entries with a flag indicating that no parallax or proper motion was available (1125 partial solutions). This elimination broke up additional systems. We identified 773 DMSA primaries that had lost their secondaries and removed them. An additional 75 surviving secondaries without any primaries were then found and removed. Among the remaining 74 tertiary components, one was found to be lacking a secondary, and that system was dropped. The remaining 12,818 components include four original DMSA quadruple systems represented by 15 cross-matched components; namely, HIP 4121 ABCD, 23624 ABCD, 26020 AB + 26026 C, and 26221 A + 26220 BD + 26224 C. These were carefully examined, determined to be optical systems, and rejected.

At this point, 191 components of original DMSA triple systems remained in the sample. This paper concerns only binary stars, so we removed all the triple systems. The emerging working sample includes 12,612 components of 6306 cross-matched binaries. This data set is technically suitable to apply our mass-ratio calculation algorithm, and a heavy filtering and cleaning of the results is still in order.

3. Calculation of Astrometric Mass Ratios

Details on the mass-ratio determination from absolute astrometry of two epochs can be found in Makarov (2021). Here we only provide a brief summary of the algorithm for the sake of presentation consistency. A resolved binary star with two components $i=1, 2$ have position unit vectors $r_{ij}$ at epochs $i=1, 2$, at positions $r_{ij}$, and $\Delta\nu = \nu_2 - \nu_1$. We compute the long-term proper motion $\nu = (r_{ij} - r_{12})/2\Delta t$ for each component, where $\Delta t$ is the epoch difference $t_2 - t_1$. The second epoch catalog (Gaia EDR3) provides short-term proper motions $\mu_{i2}$. Following directly from the inertial motion of the center of mass in space, without any implicit astrophysical assumptions or data, the mass ratio $q = m_2/m_1$ may be computed as

$$q = \frac{||\mu_{12} - \nu||}{||\nu_2 - \mu_{22}||}. \quad (1)$$

The vectors $\nu_1 = \mu_{12} - \nu_1$ and $\nu_2 = \nu_2 - \mu_{22}$ should ideally be aligned in the tangential plane. Random and systematic measurement errors, as well as physical perturbations, which we will discuss later, make these observed vectors nonparallel. The degree of misalignment, defined as

$$\eta = \arccos(\nu_1 \cdot \nu_2/(||\nu_1|| ||\nu_2||)),$$ \quad (2)

is an important indicator of the reliability and quality of a specific estimation.

These formulae were used for the sample of 6306 cross-matched and verified Hipparcos/EDR3 double systems described in the previous Section. Computations of $q$ and $\eta$ are straightforward and fast, but the resulting values should be accompanied by formal errors to evaluate their uncertainties. To this end, we perform 4000 Monte Carlo simulations perturbing the observed positions and proper motions for each component in their distribution stretches all the way to 2°5. A total of 34...
accordance with the full covariance matrices of the involved astrometric parameters, as detailed in Makarov (2021). The 0.1573 and 0.8427 quantiles of the emerging sampled distributions of \( q \) are the estimated boundaries of the 0.6854 confidence interval, which corresponds to the \( \pm 1\sigma \) confidence interval for a Gaussian distribution of probabilities. The differences between these quantiles and the median \( q \) are called the lower bound error \( (e_q^-) \) and upper bound error \( (e_q^+) \) in this paper.

Apart from the angle \( \eta \) and the interval of uncertainties, we found a quantity called SNR (signal-to-noise ratio) \( S/N \) quite useful for separating the wheat from the chaff. Even though most of the working sample are genuine widely separated binaries of considerable astronomical interest, they are too distant from us and moving too slowly on the sky to generate a measurable proper motion signal over \( \Delta t = 24.74 \) yr. This value is computed for each pair as

\[
S/N = \text{Min} \left[ (v' \cdot C_i^{-1} \cdot v)^{1/2}, \quad i = 1, 2 \right],
\]

where \( C_i \) is the full \( 2 \times 2 \) covariance matrix of component \( i \). This is a multivariate analog of the commonly used estimate of a derived quantity as a multiple of its estimated standard deviation.

To identify likely optical pairs, we compute a quantity called normalized parallax difference, which is

\[
d_{\varpi} = \left[ (\varpi_2 - \varpi_1)^2 / (\sigma_{\varpi_1}^2 + \sigma_{\varpi_2}^2) \right]^{1/2},
\]

using EDR3 parallaxes and their formal errors \( \sigma \). The histogram of the decimal logarithm of \( d_{\varpi} \) for the entire working sample is shown in Figure 1. There is a dip separating the main peak that contains mostly genuine physically bound components from the secondary bump representing optical pairs. The dip is shallow, so no matter where we select the threshold \( d_{\varpi} \), a small fraction of optical pairs will contaminate the sample. We choose a rather relaxed limiting value \( d_{\varpi} = 10 \) taking into account that the quality of Gaia parallaxes may be degraded for double stars. The adverse effects of duplicity on Gaia astrometry starting from the first release are evident (Makarov et al. 2017; Arenou et al. 2018; Fabricius et al. 2021) but cannot be corrected or calibrated, and the best strategy is to give accommodation for the increased dispersion if possible.

A more radical cut to the starting sample is provided by the \( S/N \) estimates (Equation (3)). The orbital motion of distant binaries is too slow to generate a measurable difference between the long-term and short-term proper motions. Preliminary results reveal a strong pileup of estimated \( q \) at zero, which is caused by such distant systems dominating the sample. The likely reason for this bias is the stronger perturbation of astrometric solutions for the secondaries in Gaia. This perturbation is also confirmed by a large fraction of estimates with misalignment angles \( \eta \) dispersed across the range \( [0, \pi] \). For the initial cleaning step, we choose a limit of \( S/N > \sqrt{5} \). Together with the \( d_{\varpi} < 10 \) filter, this eliminated most of the sample with only 884 binaries remaining.

This sample still includes a substantial population of binaries with unreliable results, as witnessed by a widely dispersed angles \( \eta \). Both Hipparcos and especially Gaia EDR3 have limited resolution power on double stars. The observational sample is dominated by wide binaries with a small amount of orbital motion corresponding to our timeline of 24.75 yr. As a filter for our next reduction, we use a rough proxy of the orbital period:

\[
P_{\text{proxy}} = \left( \frac{\rho}{|\varpi|} \right)^{3/2},
\]

with \( \rho \) being the angular separation of the components in Gaia EDR3 in mas, \( \varpi \) the parallax from Gaia EDR3 in mas (the

Figure 1. Histogram of the decimal logarithm of normalized parallax differences for 6306 resolved and cross-matched doubles in Gaia EDR3 and Hipparcos. The vertical bar shows the initial selection threshold to remove likely optical pairs.
absolute value is required because there are negative parallaxes at this point. \( P_{\text{proxy}} \) is equal to the orbital period for a total mass of \( 1M_\odot \) of the binary when the the projected separation equals the semimajor axis. The actual orbital period can be longer because \( \rho \) is smaller than the instantaneous separation in 3D, or it can be shorter because the total mass is likely to be greater than \( 1 M_\odot \). In the statistical sense, the median ratio \( \rho/a \) is close to unity for a thermal distribution of eccentricity (Tokovinin et al. 2020), but the sample distribution of estimated periods is skewed toward longer values. The calculated distribution of \( \log_{10}(P_{\text{proxy}}) \) appears to include two overlapping bumps, the sharper one being centered at 2.7 (several hundred years) and the wider one at \(~4\). Our epoch difference is too short to be hoping to catch binary systems with long orbital periods in motion. We apply an additional filter on \( \log_{10}(P_{\text{proxy}}) \) leaving \( 422 \) binaries.

The final round of trimming directly uses the calculated \( \eta \), as well as a stricter limit on the \( S/N \). A combination of \( \eta < 50^\circ \) and \( S/N > 3.3 \) yields the final sample of \( 248 \) binary systems with estimated mass ratios, which is published with this paper.

### 4. Description of the Results

The table of results includes \( 248 \) rows. Each row corresponds to one unique binary and includes information from Hipparcos, Gaia EDR3, and our computed parameters for both components. The first four columns contain the Hipparcos identification numbers and component names (capital letters) for the primary and secondary components. The identification numbers are not always identical for binary system components from Hipparcos. The letters can be A, B, C, D, and S. Columns 5 through 20 contain Gaia EDR3 information about the primary component, including its source id, R.A. and decl. coordinates, parallax, proper motion, formal errors of the five astrometric parameters, astrometric \( \chi^2 \), RUWE, and \( G \), \( G_{\text{BP}} \), \( G_{\text{RP}} \) magnitudes (when available). The third block of columns (21–36) includes the same information about the secondary component. The remaining columns provide data derived in this paper: \( q = m_2/m_1 \), alignment angle \( \eta \) in degrees, lower bound error \( e_{\eta-} \), upper bound error \( e_{\eta+} \), median \( q \) from Monte Carlo simulations, \( S/N \) separation in Gaia in mas, position angle from Gaia in degrees, and quality flag \( \{1, 2, 3\} \). The highest quality solutions (flag 1) are those with \( S/N > 50 \) and \( \eta < 72.45 \), the lowest quality solution (flag 3) is assigned to entries with \( S/N < 50 \) and \( \eta > 72.45 \), and quality 2 comprises the remaining solutions. The median errors of \( q \) on both sides, \( (e_{q-}, e_{q+}) \), are for quality 1: \((-0.052, +0.057)\), for quality 2: \((-0.124, +0.135)\), for quality 3: \((-0.183, +0.217)\). Quality 1 through 3 subsets comprise 80, 91, and 77 binaries, respectively. The median parallaxes are 27.9 mas for quality 1 systems, 18.8 mas for quality 2, and 14.6 mas for quality 3. The catalog columns are listed and numbered in Table 1 with a short description and units.

As a sanity check, we compute the absolute \( G \) magnitudes for all 496 components using EDR3 parallaxes and observed \( G \) magnitudes. The result is depicted in Figure 2. The great majority of the sample are found within a steep upper envelope as expected. The envelope extends to \( q > 1 \), however, where even some quality 1 pairs reside. We will see that not all of these cases of fainter and apparently more massive secondaries are caused by errors in the data. Many, if not all, cases of high-quality solutions in this category are caused by unresolved triple and higher-multiplicity systems. The effect of close companions is twofold. They can significantly perturb the short-term proper motions in both astrometric catalogs. Hidden companions to the resolved secondaries also boost their dynamical masses to a much greater degree than their brightness. These options are impossible to disentangle with the data at hand. We conclude that pairs with \( q > 1 \) and fainter secondaries are prime candidates for hierarchical multiplicity. A few pairs with \( q > 1 \) and slightly brighter secondaries are

### Table 1

| Number | Units | Explanation |
|--------|-------|-------------|
| 1      |       | Primary Hipparcos identifier |
| 2      |       | Primary Hipparcos component identifier |
| 3      |       | Secondary Hipparcos identifier |
| 4      |       | Secondary Hipparcos component identifier |
| 5      |       | Primary Gaia EDR3 identifier |
| 6      | deg   | Primary Gaia EDR3 R.A. (J2016) |
| 7      | deg   | Primary Gaia EDR3 decl. (J2016) |
| 8      | mas   | Primary Gaia EDR3 parallax |
| 9      | mas yr\(^{-1}\) | Primary Gaia EDR3 proper motion along RA |
| 10     | mas yr\(^{-1}\) | Primary Gaia EDR3 proper motion along DE |
| 11     | mas   | Uncertainty in Primary RA |
| 12     | mas   | Uncertainty in Primary Decl |
| 13     | mas   | Uncertainty in Primary parallax |
| 14     | mas yr\(^{-1}\) | Uncertainty in Primary proper motion along R.A. |
| 15     | mas yr\(^{-1}\) | Uncertainty in Primary proper motion along decl. |
| 16     |       | Primary astrometric \( \chi^2 \) |
| 17     |       | Primary RUWE parameter |
| 18     | mag   | Primary Gaia EDR3 G-band apparent magnitude |
| 19     | mag   | Primary Gaia EDR3 Blue passband apparent magnitude |
| 20     | mag   | Primary Gaia EDR3 Red passband apparent magnitude |
| 21     |       | Secondary Gaia EDR3 identifier |
| 22     | deg   | Secondary Gaia EDR3 R.A. (J2016) |
| 23     | deg   | Secondary Gaia EDR3 decl. (J2016) |
| 24     | mas   | Secondary Gaia EDR3 parallax |
| 25     | mas yr\(^{-1}\) | Secondary Gaia EDR3 proper motion along RA |
| 26     | mas yr\(^{-1}\) | Secondary Gaia EDR3 proper motion along DE |
| 27     | mas   | Uncertainty in Secondary R.A. |
| 28     | mas   | Uncertainty in Secondary decl. |
| 29     | mas   | Uncertainty in Secondary parallax |
| 30     | mas yr\(^{-1}\) | Uncertainty in Secondary proper motion along R.A. |
| 31     | mas yr\(^{-1}\) | Uncertainty in Secondary proper motion along decl. |
| 32     |       | Secondary astrometric \( \chi^2 \) |
| 33     |       | Secondary RUWE parameter |
| 34     | mag   | Secondary Gaia EDR3 G-band apparent magnitude |
| 35     | mag   | Secondary Gaia EDR3 Blue passband apparent magnitude |
| 36     | mag   | Secondary Gaia EDR3 Red passband apparent magnitude |
| 37     |       | Mass ratio; secondary/primary masses |
| 38     | deg   | Alignment angle |
| 39     |       | Lower bound error in mass ratio |
| 40     |       | Upper bound error in mass ratio |
| 41     |       | Median \( q \) from MC simulations |
| 42     |       | Signal-to-Noise ratio |
| 43     | mas   | Gaia EDR3 separation (J2016) |
| 44     | deg   | Gaia EDR3 position angle (J2016) |
| 45     |       | Quality flag |

(This table is available in its entirety in machine-readable form.)
very likely swapped designations in the DMSA for near twins, which are rather inevitable when one or both of the components are variable. Theoretically, near-twin components can change their relative brightness in $G$ and $Hp$ magnitudes because of the differences in the spectral transmissivity curves and some peculiar colors. Using the photometric polynomial transformation for $G - Hp$ as a function of $G_{BP} - G_{RP}$ color, we made sure that there is only one pair in our catalog with the expected magnitude differences $G_1 - G_2$ and $Hp_1 - Hp_2$ of opposite signs, namely, the near-twin system HIP 99689 AB.

Figure 3 shows the color–magnitude diagrams for the primary (left plot) and secondary (right plot) components, computed with the $M_G$ absolute magnitudes and $G_{BP} - G_{RP}$ colors (whenever available) from Gaia EDR3. Most of these components are main-sequence dwarfs. A few stars may be slightly evolved, possibly subgiants, and one secondary is remarkably blue and fairly luminous. This star is discussed among other interesting cases in the following section. However, photometric data from Gaia for resolved double stars should be treated with caution. In particular, colors of the secondaries with small separation may be strongly perturbed beyond the formal errors. The colors in Gaia are derived from a simple sum of the fluxes in the BP and RP spectra in windows of 2$''$ across scan and 3$''$5 along scan. For separations below 1$''$–2$''$, the photometry for the secondary is therefore compromised. The $G$ magnitude is expected to be more robust. As a result, at small separations, the two components get the same color, which can be seen in the HR diagram of the secondaries if we color code the data points according to the separation. These close secondaries are effectively dispersed mainly below the main sequence inheriting the blue colors of the primaries. The black circles in Figure 3 indicate the loci of components in pairs with separations greater than 2$''$5, whose magnitudes are considered to be reliable. The main sequence is well defined for

---

4 https://gea.esac.esa.int/archive/documentation/GEDR3/Data_processing/chap_cu5pho/cu5pho_sec_photSystem/cu5pho_ssec_photRelations.html
this smaller subset, with a mostly upward diffusion for some of the early dwarfs probably caused by post-MS evolution or hidden tighter companions.

5. Objects of Note

Some binaries stand out of the sample because of various kinds of oddities. We investigate a few of them and perform literature search for those that caught our attention.

5.1. HIP 89234 AB

This well-known double star shows up in our catalog with the highest mass ratio \( q = 5.33^{+0.74}_{-0.71} \). Although the wide error brackets and the quality flag 3 indicate a strongly perturbed solution, we would like to understand what kind of perturbation can produce such a result. Theoretically, a stellar mass black hole companion to the B component can generate a mass ratio of this magnitude. Such objects seem to be quite rare and hard to find in the solar neighborhood even in much larger samples (Makarov & Tokovinin 2019). We have to carefully inspect other, less exotic possibilities.

The system is listed as triple in WDS (Mason et al. 2021). The fainter companion resolved in Hipparcos at a separation of 2.7'103, position angle (PA) 270.7 deg is a more distant tertiary. It is also present in Gaia EDR3, albeit without \( G_{BP}, G_{RP} \) magnitudes, with a separation of 2.7'103, PA = 270.7 deg. This suggests the pair moves slowly counterclockwise on the sky with a long period. The inner pair (Aa and Ab) was first resolved in 2008 at SOAR and named TOK 58. Only short segments of position measurements are available for both pairs. Preliminary orbital fits suggest a period of 42 yr for the inner pair and \( \sim400 \) yr for the outer pair (A. Tokovinin 2021, private communication). Our bizarre solution for \( q \) comes from the fact that the observed vectors \( v_1 \) and \( v_2 \) in Equation (1) are \((-18.30, 5.67) \) and \((-3.59, -0.54) \) mas yr\(^{-1}\), respectively, i.e., the observed orbital signal is much greater for the primary. It is tempting to swap the cross-matched Gaia counterparts (which we had to do for two other systems as explained below), but the large magnitude difference precludes such an error in identification. The more likely explanation is obtained from the character of the inner pair. This binary has moved almost linearly between 2008 and now because of its inclination, which is close to 90\(^\circ\). The Ab component has moved mostly eastward on the sky at a proper motion of \( \sim60 \) mas yr\(^{-1}\) relative to Aa. The observed reflex motion of Aa is roughly \(-20 \) mas yr\(^{-1}\) in R.A. due to the estimated mass ratio. Correcting for this inner pair motion takes out almost all of the derived \( v_1 \). We conclude that in this case, our solution for \( q \) suffers from the hierarchical trinary nature of the system and physically perturbed Gaia proper motion measurements.

A similar case is found for HIP 62322 = \( \beta \) Mus, an O-type supergiant and a member of the Sco-Cen OB association. Our estimated \( q = 1.8 \) of quality 3 likely originates from the orbital motion of the tight inner pair that was discovered by Rizzuto et al. (2013) separated by 45.6 mas with a magnitude difference of 3.5. It may also be responsible for the large difference of 12.5 mas yr\(^{-1}\) between the proper motion in decl. of the resolved A and B components. Being a very bright star, \( \beta \) Mus may also be astrometrically perturbed in Gaia because of the required special gating mode of measurements.

5.2. HIP 2552 AB

HIP 2552 = Gl 22 is an archetypical and well-studied multiple system of late-type main-sequence dwarfs, for which our much perturbed solution \( q = 4.3 \) betrays the fast orbital motion of the inner, unresolved components. A brief summary of the impressive observational history can be found in Docobo et al. (2008). The preliminary orbit of the outer pair (AB in our catalog) obtained by Hershey (1973) from photographic measurements has been much improved over the decades and complemented with a tighter inner orbit of the Aa and Ab components, as per WDS designation (Söderhjelm 1999; Lampens & Strigachev 2001). The orbital periods of the inner Aa–Ab and the outer AB pairs are 15.6 and 223 yr,
respectively. The inner pair has an estimated semimajor axis of 0°51 and it passed its periastron in 2016. The estimated masses are 0.377\(M_\odot\) for Aa, 0.138\(M_\odot\) for Ab, and 0.177\(M_\odot\) for B. The presence of a small-amplitude wobble in the motion of the B component suggests that it is a binary too (Andrade & Docobo 2011) harboring a companion with an estimated mass of 0.015\(M_\odot\), which can be a brown dwarf or a giant planet. The astrometric picture is further complicated by the photometric variability and flare activity of the primary, which is a UV Cet type active dwarf (Tamazian & Malkov 2014). The A component is clearly disturbed in Gaia in both astrometry and G-band photometry. It has an \textit{ipd\_frac\_multi\_peak} of 44\%, so the Ab component is in fact clearly visible to Gaia. Future Gaia releases will resolve this pair. Since the primary is unresolved in either Hipparcos or EDR3, the observed position is subject to a strong Variability Induced Motion (VIM) effect (e.g., Makarov & Goldin 2016) if it is observed during a flaring event. According to the WDS (Mason et al. 2021), the Ab component is fainter by 3.1 mag than the Aa component, and the latest observation puts them at a separation of 0\°4 in 2014. The photocenter of this pair observed by Gaia may be shifted by ~22 mas from the true position of the primary. Flare amplitudes for M dwarfs of UV Cet type vary in a wide range with the most energetic (but rare) events reaching several magnitudes. If an observed flare with a peak amplitude of 0.1 mag takes place on the brighter primary component, the magnitude of VIM is only about 2 mas. If the Ab component is responsible for the observed extra flux, the VIM excursion is as high as 37 mas. This example shows that astrometric analysis of unresolved binaries with a variable component may be complicated and hidden by ambiguity. Furthermore, the Hipparcos-epoch position is likely perturbed too in the “component” solution by the photocenter effects and by the considerable clock motion of the inner pair.

5.3. HIP 4493

This relatively less studied stellar system is listed in the WDS catalog with components A and B spanning PA = 120\°, \(\rho = 0\°4\) in 1931 and PA = 53\°, \(\rho = 0\°8\) in 2008. A speckle interferometry measurement in 2008.5461 places it at PA = 52.5\°, \(\rho = 0\°822\) (Tokovinin et al. 2010). The pair has moved appreciably since then because Gaia EDR3 finds them at PA = 47.8\°, \(\rho = 0\°836\). The secondary is fainter by 0.8 mag in \(V_T\) (Fabricius & Makarov 2000a); however, the components have nearly equal \(G_RP\) and \(G_GP\) magnitudes in EDR3 while the \(G\) magnitude of B is fainter by approximately 2 mag. This is the same effect of merged fluxes for close components we noticed in Section 4. The excess factor (\(G_{\text{Flux}}/(B_{\text{Flux}} + R_{\text{flux}})\)) is 8.2, where something slightly higher than 1 is expected. Photometric data from Fabricius & Makarov (2000a) must clearly be preferred for this pair. Another indicator that the Gaia solution is strongly perturbed comes from the RUWE parameter, which is as high as 16.1 for A. It is not clear how much the Gaia data can be trusted for this object. Our estimated \(q = 9.1\) comes from the fact that the long-term motion \(v_2\) is close to the EDR3 proper motion of B (within 1 mas yr\(^{-1}\)) while the corresponding values for A are quite different, so that \(v_1 = (6.3, 4.9)\) mas yr\(^{-1}\). We also note that the EDR3 proper motion of A differs from that of B by \((9.6, −3.4)\) mas yr\(^{-1}\). Could this be a sign of fast orbital motion within the A component like in the previous examples? A few circumstances cast doubt on this interpretation. The EDR3 parallax difference is significant at 2.4\(\sigma\) level, thus the pair just barely escaped our parallax consistency culling. Furthermore, Gaia EDR3 lists a third, fainter and redder companion of \(G = 14.89, G_{BP} − G_{RP} = −2.14\) mag, which is separated by 12\°769 from A. With a parallax and a proper motion quite close to the parameters of the B component, this star makes a legitimate member of a physical multiple system. The data about this puzzling case suggest two routes of interpretation. The original A component may be a rather improbable interloper leaving only much a wider binary pair BC. A more credible explanation is that this is an outstanding borderline hierarchical triple system with an A component being strongly perturbed in Gaia observations by an agent yet to be revealed.

5.4. HIP 80017

This is a known double star, which is undoubtedly a wide physical binary. The primary is an early and blue dwarf of B9–9.5V type. McDonald et al. (2017) estimate a \(T_{\text{eff}} = 8414\) K and \(L_{\text{bol}} = 24.85 L_\odot\) from astrometric and photometric data and spectral energy distribution models. The pair appears to have barely moved between the Hipparcos and Gaia epochs changing the position angle from 314°1 to 314°02. Given a separation of 1°224 and a parallax of 7.3 mas in Gaia, a slow orbital motion is in line with our expectation, which also accounts for the low quality of our mas ratio estimate \(q = 0.35^{+0.13} _{-0.09}\), \(S/N = 3.38, \eta = 30\°\). However, this unreliable result draws much interest in view of the outstanding position of the secondary in the Hertzsprung–Russell diagram in Figure 3 owing to its peculiar color \(G_{BP} − G_{RP} = −0.5 ± 0.4\) mag. The star appears to occupy the area of hot subdwarfs (sdO–sdB), which are dying stars in the post-AGB stage. These stars are too blue to be regular dwarfs but still too luminous to be white dwarfs. To have an independent mass estimate for a hot subdwarf would be interesting; however, this result should be taken with much caution. The separation is small enough for the color-equalizing error (Section 4) to take hold. Indeed, the photometry excess factor is 5.4 and all its (rather few) transits are flagged as blended. The formal error of 0.4 mag for the \(G_{RP}\) magnitude is unusual for stars of similar brightness. The more reliable Tycho-2 color from Fabricius & Makarov (2000a) is much redder with \(B_T = 9.58 ± 0.02\) and \(V_T = 9.02 ± 0.1\) mag, although it still seems too blue for a K-dwarf companion suggested by the magnitude difference and our estimated mass ratio.

6. Discussion and Future Work

Using commonly accessible information from the ESA’s Hipparcos and Gaia space missions, we were able to process the entire cross-matched sample of resolved double stars and selected 248 high-probability binary systems with statistically significant estimates of mass ratio. The purely astrometric method proposed in Makarov (2021) is free of any astrophysical models and assumptions about the nature of the observed stars. However, this method is founded on the assumption that the system under investigation is truly binary, i.e., there are no tighter subsystems perturbing the mean proper motions of the wide components. Law et al. (2010) estimate a rate of 45% of tighter subsystems for a sample of wide early M-dwarf binaries. The rate of long-period binaries with components luminous in X-rays is 2.4 times higher than among fainter X-ray stars (Makarov 2002), which indicates a significant rate of active short-period binaries among widely
proper motions are not expected to be strongly perturbed by the inner pair’s dynamics when the orbital period is much shorter than the mission time span (33 months for Gaia EDR3). The output is presented as an online catalog with relevant information copied from the Hipparcos DMSA and Gaia EDR3, as well as mass ratio estimates and their uncertainties derived from a dedicated Monte Carlo simulation. The output is a small fraction of the initial 6306 doubles in the cross-matched sample with the required data. The attrition is mostly due to a high rate of distant and wide physical pairs whose orbital motion is too slow to generate a significant astrometric signal (i.e., a measurable change in components’ proper motions), and the presence of unrelated optical pairs. A closer look at a few peculiar outcomes reveals that the next significant difficulty comes from hierarchical triple or higher-multiplicity systems that are not resolved in either DMSA or Gaia EDR3. Unless the orbital period of the inner subsystems is much shorter than the mission length, the fast motion of the unresolved photocenter perturbs the mean-epoch proper motion of the corresponding component. The effect on the estimated mass ratio depends on which component harbors a tight binary. If it is the primary component, as in the triple system HIP 89234, the additional apparent acceleration perturbs mostly the short-term Gaia proper motion signal in the numerator of Equation (1), leading to a blown-up estimate of \( q \). If a binary is hidden in the secondary DMSA component, the extra astrometric signal affects mostly the denominator resulting in a lower estimate for \( q \). The former scenario is easier to catch because due to the frequent occurrence of binaries with near-twin components, and the resulting \( q \) may come up way above 1. Additional candidate triple systems can be identified upon a careful comparison of the astrometric mass ratios with photometric estimates based on stellar evolution models.

The preponderance of wide, long-period systems in the DMSA sample is the greatest limitation to the application of the astrometric method with the currently available data. The epoch difference of 24.75 yr is too short to generate a measurable proper motion signal of binaries with period of the order of 1000 yr and longer. A next-generation space mission of absolute astrometry some 25–30 yr after the Gaia mission will give a boost to the signal-to-noise ratio on the known systems and will add thousands new targets beyond the Hipparcos limiting magnitude. A Gaia follow up in the near infrared (Gaia-NIR; Hobbs et al. 2021; McArthur et al. 2019), for example, is expected to widen the horizon of applicability including many objects of special astrophysical interest, such as degenerate stars and hot subdwarfs. Having two epochs of absolute astrometry at the Gaia’s level of accuracy separated by 25–30 yr will lead to characterization of millions of fainter and more distant binaries. In the shorter-term perspective, the future Gaia data releases (DR4 and DR5) will more than double the processed observational cadence, and a modified version of this method for Gaia-only astrometric measurements will take it to a new level of accuracy of the empirical binary star masses.

The authors are grateful to the referee A. Tokovinin for valuable and constructive remarks. This work made use of data from the European Space Agency (ESA) Hipparcos astrometry satellite. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This work was (partially) supported by the Spanish Ministry of Science, Innovation and University (MICIU/FEDER, UE) through grant RTI2018-095076-B-C21, and the Institute of Cosmos Sciences University of Barcelona (ICCUB, Unidad de Excelencia “María de Maeztu”) through grant CEX2019-000918-M.

**ORCID iDs**

Valeri V. Makarov @ https://orcid.org/0000-0003-2336-7887

**References**

Andrade, M., & Docobo, J. A. 2011, Icar, 215, 712
Arenou, F., Luri, X., Babusiaux, C., et al. 2018, A&A, 616, A17
Docobo, J. A., Tamazian, V. S., Balega, E. Y., et al. 2008, A&A, 478, 187
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200 (Noordwijk: ESA)
Fabricius, C., Høg, E., Makarov, V. V., et al. 2002, A&A, 384, 180
Fabricius, C., Luri, X., Arenou, F., et al. 2021, A&A, 649, A5
Fabricius, C., & Makarov, V. V. 2000a, A&A, 356, 141
Fabricius, C., & Makarov, V. V. 2000b, A&A, 144, 45
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Hershey, J. L. 1973, AJ, 78, 935
Hobbs, D., Brown, A., Høg, E., et al. 2021, ESA, 51, 783
Lampens, P., & Strigachev, A. 2001, A&A, 368, 572
Law, N. M., Dhital, S., Kraus, A., et al. 2010, ApJ, 720, 1727
Makarov, V. V. 2002, ApJL, 576, L61
Makarov, V. V. 2021, RMxAA, 57, 399
Makarov, V. V., Fabricius, C., & Fouroud, J. 2017, ApJL, 840, L1
Makarov, V. V., & Goldin, A. 2016, ApJS, 224, 19
Makarov, V. V., & Tokovinin, A. 2019, AJ, 157, 136
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2021, yCat, B/wds
McArthur, B., Hobbs, D., Høg, E., et al. 2019, BAAS, 51, 118
McDonald, I., Zijlstra, A. A., & Watson, R. A. 2017, MNRAS, 471, 770
Rizzuto, A. C., Ireland, M. J., Robertson, J. G., et al. 2013, MNRAS, 436, 1694
Söderhjelm, S. 1999, A&A, 341, 121
Tamazian, V. S., & Malkov, O. Y. 2014, AcA, 64, 359
Tokovinin, A., Mason, B. D., & Hartkopf, W. I. 2010, AJ, 139, 743
Tokovinin, A., Petr-Gotzens, M. G., & Briceno, C. 2020, AJ, 160, 268
Torres, G., Boden, A. F., Latham, D. W., et al. 2002, AJ, 124, 1716