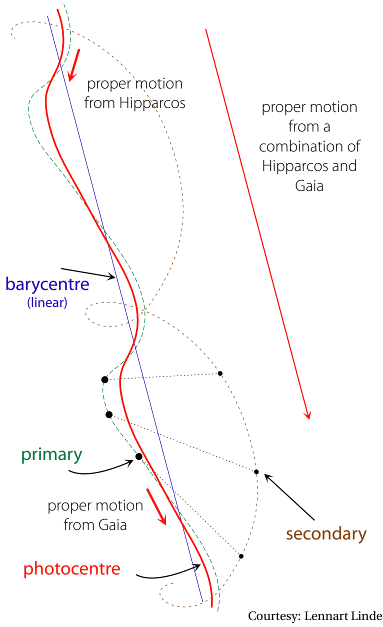
174. Proper motion anomalies

Binary stars are loosely classified as *visual* (where both components are resolved), *astrometric* (where the companion's presence is revealed by the photocentric motion), *spectroscopic* (showing orbit variations of spectral lines), or *eclipsing* (where light from one component is eclipsed by the orbital motion of the other).

I have discussed binary systems in essays 79 and 134 (I use the term 'binary' although higher multiplicities are usually also implied), where I explained how Gaia is contributing, profoundly, to their discovery and classification over this broad range of phenomenological type.

A subset of astrometric binaries effectively evaded identification as such over the observation period of the Hipparcos mission, but they can become recognisable from the difference in the proper motion determined by Hipparcos and that measured by Gaia.

These are frequently referred to as systems showing 'proper motion anomalies'. I will explain the phenomenon, the recent work which has underlined their ubiquity, and give some examples of their importance.



Courtesy: Lennart Lindegren

The diagram illustrates the principles. It shows the sky-projected orbital motion of the primary and secondary components of a representative binary, the linear motion of the system's barycentre (blue), and the non-linear motion of the photocentre (red). It is evident that the proper motion (of the photocentre) measured by any series of observations is a function of the orbital period compared with the measurement duration.

If, for example, the observation interval covers only a small fraction of the orbital period, then the orbital motion may not be distinguishable from the underlying space motion. The measured proper motion vector can then deviate substantially from that measured by Gaia, or from the long-term barycentric motion over the time interval between the Hipparcos and Gaia missions.

For orbital periods of, say, 20–30 years or more, space astrometry can then exploit the near 30-year time interval between the Hipparcos and Gaia proper motions, because each samples the star's reflex motion at very different epochs in a long-period orbit.

The Hipparcos catalogue included a main part giving the single star (5-parameter) solutions, and a 'Double and Multiple Systems Annex' with five categories of astrometric solution (Lindegren et al., 1997):

- component solutions (C): with component separations in the range $\rho = 0.1-30$ arcsec, for which the 5 astrometric parameters are given for each component;
- acceleration solutions (G): apparently single stars with significantly non-linear motion, fitted by a quadratic or cubic polynomial of time (7- or 9-parameter solution);
- orbital solutions (O): with full orbital solution for the photocentre in addition to the 5-parameter astrometric solution for the barycentre;
- variability-induced movers, or VIMs (V): these are unresolved binaries in which one component is variable (I have touched on these already in essay 163);
- stochastic solutions (X): for those cases where no reasonable single or double star solution could be found.

The numbers of each are given in the following table, where it is clear that the single-star solutions dominated.

Hipparcos: solution type	Annex	No. of entries
Single-star solutions	–	100 038
Component solutions	C	13 211
Acceleration solutions	G	2 622
Orbital solutions	O	235
Variability-induced movers	V	288
Stochastic solutions	X	1 561
No valid astrometric solution	–	263
Total number of entries		118 218
Entries with valid astrometry		117 955

AVAILABLE to probe such proper motion anomalies are the Hipparcos observations, which extended over 3.3 years (1989.8–1993.2) with catalogue mean epoch J1991.25. Gaia DR2 spans an observation duration of 22 months with reference epoch J2015.5, and Gaia DR3 covers a 34 month interval with reference epoch J2016.0.

Estimates of the general fraction of stars that are binaries vary widely, from around 30–35%, with a lower fraction amongst low-mass stars, and perhaps up to 80% for the most massive O–B stars (e.g. Lada, 2006).

Naively, therefore, we might not be too surprised to find that some 30 000 of the Hipparcos single-star solutions display such a proper motion anomaly, albeit with different fractions amongst the various categories.

AS A SMALL aside, the Hipparcos ‘stochastic solutions’ replaced deterministic solutions with a quadratic increase in the standard error (typically 3–30 mas) such that the rms normalised residual was equal to unity.

The similar *re-normalised unit weight error*, RUWE, itself related to the reduced χ^2 of the single-star solution, is included in the Gaia catalogues to capture photocentric perturbations due to unmodelled orbital motion or calibration errors (Lindegren et al., 2018, §5.1).

Tested on a sample of known spectroscopic binaries, Belokurov et al. (2020) showed that the implied amplitude of the centroid perturbation scales, as expected, with the binary period and the mass ratio, and illustrated how the binary fraction evolves across the HR diagram.

FIRST STEPS in deriving long-term proper motions using the Hipparcos observations as one epoch of a much longer time span was the 2.5-million star Tycho 2 Catalogue (Høg et al., 2000). This combined the Tycho 1 Catalogue ($\sigma_\mu \sim 10-25$ mas/yr) with the much earlier Astrographic Catalogue ($\Delta t \sim 100$ yr), and 143 other ground-based astrometric catalogues, to create Tycho 2 with long-term proper motions with $\sigma_\mu \sim 2.5$ mas/yr.

The first proper motions resulting from a combination of the Hipparcos and Gaia observations was the Tycho–Gaia astrometric solution (TGAS, Michalik et al., 2015), for which 2 million sources with a proper motion accuracy of ~1 milli-arcsec/yr (around 0.06 mas/yr for the subset of 94 000 Hipparcos stars) were included as part of the Gaia DR1 data release (Brown et al., 2016).

I HAVE OUTLINED the motives underlying the determination of long-term proper motions, and the implications of ‘proper motion anomalies’ when comparing the difference between their long-term Hipparcos–Gaia and short-term Gaia proper motion vectors. Let me now briefly survey the results of various investigations of the Hipparcos–Gaia 25-yr baseline proper motions.

A number of early studies used Gaia DR2 (Brandt, 2018; Kervella et al., 2019a; Makarov, 2020). Amongst these, Kervella et al. (2019b) determined a binary fraction of 80% for their sample of classical Cepheids.

Studies with EDR3 started with the Hipparcos–Gaia Catalogue of Accelerations by Brandt (2021). Kervella et al. (2022) derived tangential velocity anomalies with $\sigma(\Delta v_{\rm T}) = 0.26\,{\rm m\,s^{-1}\,pc^{-1}}$, a factor 2.5 improvement compared to Gaia DR2. They identified 37 515 Hipparcos stars (32%) with a 3σ anomaly, and with detection limits extending into the exoplanet mass regime. Including the Gaia EDR3 re-normalised unit weight error (RUWE > 1.4) as an additional measure, 50 720 Hipparcos stars (43%) exhibit at least one indicator of binarity. Of the Gaia EDR3 stars within 100 pc, they found common proper motion companions for 39 490 (7.3%).

Penoyre (2022a; 2022b) applied a similar approach to the Gaia Catalogue of Nearby Stars (Smart et al., 2021). They found 22 699 binaries within 100 pc (~10%), with the binary fraction ranging from 20% for giants, 10% on the main sequence, and ≲1% for white dwarfs.

ONE SPECIFIC APPLICATION for systems showing long-term proper motion anomalies has already been particularly well exploited. In essay 88, I explained how the implied accelerations can be used to determine companion masses, and specifically for previously imaged exoplanets, or as ‘dynamical beacons’ to pinpoint where on the sky a new planet must lie.

I will not go further into this topic here, other than to simply list some of the associated studies that have been made using the Hipparcos–DR2 temporal baseline (Brandt et al., 2019; Dupuy et al., 2019; Currie et al., 2020; Damasso et al., 2020; Kiefer et al., 2021), and subsequently based on Hipparcos–EDR3 (Brandt et al., 2021; Kammerer et al., 2021; Franson et al., 2022; Kuzuhara et al., 2022; Bonavita et al., 2022; Herz et al., 2023).

IN ANOTHER interesting application, Dodd et al. (2024) examined the nature of Be stars, the rapid rotating emission-line subset of B stars, for which the origin of rotation remains unclear. From the proper motion anomaly, and the Gaia-provided RUWE, they could identify unresolved binaries down to separations of 0.02 arcsec using the Hipparcos–DR3 temporal baseline.

They concluded that it is binary interactions that cause the Be phenomenon, with migration causing the dearth of Be binaries between 0.02–0.04 arcsec, and with triplicity playing a key role in the migration.