193. More on wide binaries

I REVIEWED some of the contributions being made by Gaia on the subject of wide ($\gtrsim 10^3$ au) binaries in two earlier essays. In essay 14, I looked at evidence that their orbit distributions are inconsistent with Newtonian dynamics and, some claim, more consistent with MOND.

In essay 37, I looked at 'ultra-wide' binaries (separations $\gtrsim 30\,000$ au): how Gaia is able to detect them, and their possible formation and disruption mechanisms.

Both date from 2021, and I will look here at more recent Gaia results regarding their formation and orbit distributions. In cases where recent insights have come from Gaia, but without expanding further, I note this with a superscript indicating the relevant data release.

Gaia's contribution to binary star research more widely is reviewed by El-Badry (2024) and Merle (2024).

ON THE EXISTENCE of wide ($\gtrsim 10^3$ au) binaries in the Galactic field and halo, Kouwenhoven et al. (2010) wrote that *'their origin has long been a mystery'*. Still today, their origin *'remains a mystery'* (Xu et al., 2023), and indeed *'a major puzzle'* (Modak & Hamilton, 2023).

Simulations find that they cannot form by fragmentation of a single molecular cloud core, nor in typical clusters (e.g. Clarke, 2019; Deacon & Kraus, 2020).

Other possible formation processes include the fragmentation of turbulent molecular cores (Goodwin et al., 2007), cluster dissolution (Kouwenhoven et al., 2010; Moeckel & Clarke, 2011; Rozner & Perets, 2023), dynamical 'unfolding' of compact triple systems (Reipurth & Mikkola, 2012), formation in adjacent molecular cloud cores (Tokovinin, 2017), chance trapping in the tidal tails of stellar clusters (Peñarrubia, 2021), or from 3-body encounters (Atallah et al., 2024).

Observations nonetheless suggest that the components are likely to have formed in the same star-forming region. Evidence includes the large fraction of wide pairs of young stars in low-density star-forming regions (Tokovinin, 2017), the chemical homogeneity in the components of wide binaries (Hawkins et al., 2020[DR2]; Andrews et al., 2019[DR2]), the metallicity dependence of the wide-binary fraction (Hwang et al., 2021[DR2]), as well as N-body simulations (Kroupa & Burkert, 2001).

ONE OF THE suggested formation mechanisms is that they arise as a natural consequence of star formation in the turbulent interstellar medium. This has found some interesting support from Gaia.

In this scenario, stars form in molecular clouds and, specifically, within the high-density filaments and cores at the collisional interfaces of converging highly supersonic turbulent flows (Federrath et al., 2009; Mocz & Burkhart, 2018; Inoue et al., 2018; Xu et al., 2019).

Most recently, Xu et al. (2023) found that binaries with separations 1000–100 000 au form as a natural consequence of such a turbulent environment, and that such systems implicitly exhibit a 'superthermal' eccentricity distribution similar to that observed, as expanded on below. These ideas have been further reinforced by the simulations of Hamilton & Modak (2024).

GAIA OBSERVATIONS have provided support for this specific formation channel through two interesting and independent avenues.

The first is by measuring the eccentricity distribution of wide binaries, which has been possible for the first time with Gaia. At fixed separation a, the eccentricity distribution is expected to be 'thermal', $P(e) = 2e$, if binaries are spread out uniformly in phase space.

In contrast, from the DR2-based binary catalogue of El-Badry et al. (2019), Tokovinin (2020) used the direction and speed of relative motions in wide pairs to infer, statistically, their eccentricity distribution. He found that for separations $\gtrsim$1000 au, there is an excess of very eccentric orbits (termed 'superthermal'), with the distribution well-fit by a power law $P(e) = (1+\alpha)e^{\alpha}$, with $\alpha \sim 1.2$. This was further substantiated, using values of the relative separation and velocity vectors of components from Gaia EDR3, by Hwang et al. (2022).

Given that such a distribution does not arise as a result of Galactic tides (Modak & Hamilton, 2023) nor as a result of stellar encounters (Hamilton & Modak, 2024), the latter authors concluded that the eccentricity distributions measured by Gaia favour a turbulent fragmentation origin. A testable prediction is that α should be a monotonically decreasing function of binary age.

THE SECOND PIECE of evidence favouring a turbulent origin of wide binaries is that, in this model, the turbulent velocities of the gas are expected to be imprinted on those of newly formed stars. And indeed, recent Gaia observations find that the velocity differences and spatial separations of young stars statistically follow the power-law velocity scaling of interstellar turbulence.

Ha et al. (2021) used Gaia DR2 and APOGEE–2 data to derive positions and velocities of 1439 young stars in the Orion Molecular Cloud. The velocities exhibit the expected characteristics of turbulence, with their 'velocity structure function', over scales of 1–100 pc, consistent with the Kolmogorov-like predictions of Larson (1981).

The results have been further substantiated by Ha et al. (2022) based on similar studies using Gaia EDR3 in the star-forming regions of Ophiuchus (at 140 pc using 107 stars), Taurus (140 pc, 139 stars), Perseus (320 pc, 138 stars) and Orion (410 pc, 2468 stars).

Zhou et al. (2022) extended the study, using DR2, to 15 149 YSOs in 150 associations younger than 3 Myr within 3 kpc. They found that their associated clouds are elongated, and oriented parallel to the disk mid-plane. As probed by the YSOs, the turbulence is isotropic, and the 2D velocity dispersion is related to size by $\sigma_v \propto r^{0.67}$. The turbulent energy dissipation rate decreases with Galactocentric radius which, they suggest, is explained if the turbulence is driven by cloud collisions.

RETURNING to the topic of essay 14 (April 2021), on the orbit distributions of wide binaries. At that time, based on Gaia DR2, there was a consensus that there is a non-Newtonian tail of their component velocity ratios beyond $\gtrsim$ 7000 au. But it was unclear whether this is evidence for some form of Modified Newtonian Dynamics, MOND (Hernandez et al., 2019), or explicable as stars born in the same cluster and currently undergoing a chance close 'flyby' (Pittordis & Sutherland, 2019), or as a population of hidden triple systems (Clarke, 2020).

In the past year, two papers (Chae, 2023; 2024), both using wide binary stars from DR3, have argued for a gravitational anomaly showing up at low accelerations, $\lesssim 10^{-10}\,\mathrm{m\,s^{-2}}$.

In the first, Chae (2023) selected 26 615 wide binaries within 200 pc with accurate distances, proper motions, and reliably inferred stellar masses, then de-projected the observed velocities and separations to 3D relative velocities and separations by Monte Carlo modelling.

The difference between the observed (kinematic) acceleration, v^2/r, and the Newtonian expectation, GM/r^2 (where M is the total system mass), shows a significant deviation of 0.109 ± 0.013 at accelerations below $10^{-10.15}\,\mathrm{m\,s^{-2}}$. *'What is even more surprising'*, Chae concludes, *'is that the trend and magnitude of the gravitational anomaly agree with what the AQUAL (Bekenstein & Milgrom, 1984) theory predicts'.*

In the second paper, Chae (2024) confirmed the conclusions for separations 2000–5000 au, with a more stringently selected sample from Gaia DR3. From 2463 binaries with a precision on parallaxes and proper motions better than 0.005, and radial velocities better than 0.2, the ratio of observed to predicted acceleration is $1.49^{+0.21}_{-0.19}$ for accelerations $\lesssim 10^{-10}\,\mathrm{m\,s^{-2}}$.

At about the same time, Hernandez (2023) repeated his earlier analysis using Gaia DR3, now using the Gaia-determined stellar masses and estimates of binary probabilities for each star using spectroscopic information, along with a larger sample of radial velocities. He confirmed his previous findings that the resulting relative velocity scalings accurately trace Newtonian expectations for the high-acceleration regime, but remain markedly inconsistent at low accelerations. As he states, *'A non-Newtonian low-acceleration phenomenology is thus confirmed'.*

Meanwhile, Pittordis & Sutherland (2023) provided an update of *their* 2019 study using Gaia EDR3 for 73 159 wide binaries within 300 pc and with $G < 17$ mag. Component masses were estimated from a main-sequence mass–luminosity relation. The frequency distribution of pairwise relative projected velocities as a function of projected separation was compared to simulations.

As in their earlier study, their distributions show a peak at a value close to Newtonian expectations, along with a long 'tail' which extends to much larger velocity ratios. Hypothesising that this is caused by hierarchical triple systems with an unresolved or unseen third star, they fit the observed distributions with a simulated mixture of binary, triple and flyby populations, for GR or MOND orbits, finding that standard gravity is somewhat preferred over one specific implementation of MOND.

Extending these tests, Banik et al. (2024) used DR3 data for 8611 wide binaries within 250 pc, with separations 2000–30 000 au. They integrated the binary orbits in a gravitational field that includes MOND's 'external field effect' but, crucially, admit line-of-sight contamination and undetected close binary companions to the component stars. They found that their best Newtonian model is preferred over MOND at 19σ confidence.

WHERE DOES this leave us with Gaia's present insights into wide binaries? Still with an incomplete understanding of their formation, although with the remarkable findings that, compared to models of a turbulent origin, the expected turbulent gas velocities appear to be matched by those of the newly formed stars.

Whatever the formation mechanism, Gaia DR3 confirms that the orbits of very wide binaries deviate from the Newtonian prediction. Proponents of a MOND-like explanation have confirmed their earlier conclusions, while undetected close binary companions perhaps still offer a more conventional explanation.