Speckle Interferometry of 21 Gaia Two-Parameter Potential Binaries

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Abstract

Gaia two-parameter (G2P) stars have cumulative errors in parallax and proper motion so great that only their mean positions were reported in DR3. One potential cause of these high errors is another star as indicated by two intensity peaks in the scans. Speckle interferometry astrometric measurements of 21 G2P stars with high multi-peak percentages were obtained with the 1.5m telescope at Mt. Wilson Observatory. Of the 21 G2P stars, five had no reported Gaia companions within 1.0". We found nearby companions for all five. The 16 other G2P stars had known Gaia companions within 1.0". Of these, 13 had separations that agreed closely with the speckle measurements, but their position angles often did not, while the other three did not agree in either separation or position angle. Although some of these issues may be resolved in DR4 or DR5, others may be inherent limitations of Gaia capabilities that speckle interferometry observations may be able to fill.

1. Introduction

Gaia, the European Space Agency's astrometric telescope, was launched in December 2013, began observations at its L2 station in January 2014, and continued these observations until January of 2025. Analysis of the first 34 months of Gaia operation was made available in June 2024 as data release 3 (DR3) (Fabricus et al. 2021, Lidgren et al. 2021, Vallenari et al. 2023). DR4 is expected to be released in mid-2026 and will cover 66 months of observation. DR5, to be released in late 2030, will cover the entire 126 months of observation.

As Kareem El-Badry (2024) pointed out in the Introduction of his paper, *Gaia's binary star renaissance,* that

> Binary stars are a cornerstone of stellar mass and radius measurements that underpin modern stellar evolutionary models. … They are also ubiquitous, accounting for about half of all stars in the Universe. In the era of gravitational waves, wide-field surveys, and open-source stellar models, binaries are coming back stronger than a nineties trend. Much of the progress in the last decade has been enabled by the Gaia mission, which provides high-precision astrometry for more than a billion stars in the Milky Way.

Most stars reported in Gaia DR3 have full astrometric solutions that include position, parallax, and proper motions, making them five parameter solutions (G5P stars). G5P stars have revolutionized binary astronomy over the past decade (El-Badry 2024) because these five parallax values allow surveys of stars within a given distance and, thanks to similar proper motions, to establish likely binarity. It is not surprising that most Gaia binary follow-up analysis has concentrated on G5P stars. Below, we detail three examples of such research.

Gaia photocenter binaries

As described by Halbwachs et al. (2023), by its third data release (DR3), not only had Gaia gathered data on over 1 billion objects, but some 36.5 million stars that were possibly double. These stars were all brighter than G = 19, had a RUWE of greater than 1.4, and were observed over at least 12 visibility periods. RUWE is the renormalized square root of the normalized chi-square of the astrometric fit to the along scan observations (Lindegren et al. 2021); renormalized such that values close to 1.0 are normal. Of these stars, over half a million have been verified as being short-period binary stars with either full photocenter orbital solutions or significant photocenter orbital curvature over the 34 months of observations by DR3. However, these Gaia DR3 photocenter binaries, essentially by definition, have component separations so small (typically under well under 50 mas) that they are well below the resolution limit of Gaia, always imaged as a point source.

Wide binaries

Rather than looking for completed orbits or clear orbital curvature of photocenter binaries in Gaia DR3's 34-month dataset, El-Badry et al. (2021) focused on identifying wider Gaia binaries, compiling an extensive catalog of spatially resolved binary stars within ≈1 kpc of the Sun. They used the Gaia catalogue itself to find 1.1 million Gaia G5P eDR3 pairs with a probability of being binary and not mere chance alignments > 99%. These are likely binaries with separations > 0.4" and, for the most part, > 1.0".

Re-examining known binaries to discover multiple star systems

Andrei Tokovinin (2023) started with a list of 8000 wide binaries within 100 pc with G5P solutions derived from the Gaia Catalog of Nearby Stars. From this he made up a list of multiple star systems where one or both components had large RUWE values, indicators of potential inner subsystems components (Belokurov et al. 2020). Tokovinin observed 1243 of these systems with the 4.1-meter Southern Astrophysical Research (SOAR) telescope and discovered 503 new pairs with separations between 0.03" and 1.0", an astonishing triple-system new discovery rate of 40%.

While most Gaia stars have five-parameter solutions (hence G5P), the cumulative error in the measurements of some of a significant fraction of Gaia stars was so great that the Gaia Data Processing and Analysis Consortium withheld parallax and proper motion measurements from DR3, only providing mean RA and Dec positions, making these Gaia two-parameter (G2P) stars (Fabricus et al. 2021). The most common source of this astrometric measurement error is interference from the light of a nearby on-sky star, often a potential new binary companion. Some stars didn't even achieve G2P status because their position error was more than 100 mas1σ.

Fabricius et al. (2021) noticed that, compared to Gaia DR2, eDR3 listed many additional sources at small angular separations (< 0.4"). These close neighbors, which were not present in DR2, exceeded the expected distribution from random field star alignments. However, 74% of these close components at separations < 0.4" were G2P stars with only two-parameter solutions. Medan and Lépine (2023) developed a catalog of likely binaries within 200 pc of the sun that included G2P components by using Gaia and 2MASS photometric observations to estimate the missing astrometric parameters in the G2P stars. Medan et al. (2024) then made speckle interferometry observations of 16 of the potential binaries in their catalog with separations less than 30.0 AU on the 8.1-meter Gemini North and South telescopes. They found, with confidence, that 15 of the 16 were indeed physical binaries.

We have taken yet another approach to studying G2P stars. As described in Section 2, we created a list of G2P stars with a high (80-100%) multi-peak percentage (MP%). Section 3 describes the equipment, reduction, and calibration procedures we used to obtain speckle interferometry observations of 21 of the G2P stars on our target list. Section 4 provides our speckle observation results, while Section 5 discusses these results, comparing our ground-based astrometry with Gaia's space-based astrometry. Section 7 provides our conclusions.

2. Target Selection

Stars were selected from DR3 which only had G2P solutions. Furthermore, these stars were selected to have 80 to 100 percent MP% scans and a magnitude range between 9.5 and 12.9. Stars listed in the Washington Double Star Catalog (Hartkopf et al. 2001) were excluded as we were interested in exploring new territory. The slow-moving dome of the 1.5-meter telescope at Mt. Wilson Observatory was left parked due south to increase observing efficiency, so stars were selected that would transit the dome's slit during our evening observing sessions in June. Of the many potential targets, we observed the 21 G2P stars reported in this paper, as well as 50 known binaries in another research program.

To avoid repeating the long Gaia DR3 designations, each G2P target was given a number T1, T2, …, and any nearby Gaia companion (< 1.0" separation) was given a matching "C" companion number. Before assigning these numbers for this paper (but after the observations and analysis), the targets were divided into three logical categories: (I) no matching companion in Gaia, (II) a good match with Gaia in separation, but an increasingly poor match in position angle, and (III) a poor match with Gaia in both separation and position angle.

Table 1 provides information on the 21 Gaia G2P targets, and the 16 Gaia companions that we extracted from DR3. There were no known close (<1.0") Gaia companions brighter than 14^{th} magnitude for T1-T5. VPU is the number of visibility periods used where full astrometric solutions are only provided when VPU>8 (Lindegren et al. 2021), 5Σ is the longest semi-major axis of the 5-d error ellipsoid (mas), APS is the number of Gaia parameters (2, 5, or 6), MP% is the percentage of passes reporting multiple peaks, and c*/σc* is the corrected value of the Bp and Rp excess over G normalized by dividing by the 1 σ variance (Riello et al. 2021). Values of c*/σc* > 1.65 are indicators of a background object. As second star in the scan that is unresolved by the Bp and Rp photometry sensors yield very large values of c*/σc*.

Table 1 Gaia DR3 extracts 21 Gaia G2P targets and 16 Gaia close companions.

GAIA TARGET								GAIA COMPANION						
Tgt	VPU	Σ5	APS	MP%	c*/σc*	Designation		Cmp	VPU	Σ5	APS	MP%	c*/σc*	Designation
T1	16	6.85	2	95	101.2	Gaia DR3 4376527797238120320								
T2	22	2.42	2	94	77.8	Gaia DR3 4446145815493081472								
T3	22	2.13	2	85	45.1	Gaia DR3 4446826486207252864								
T4	29	5.04	2	85	80.9	Gaia DR3 1224087708250606720								
T5	15	2.68	2	80	103.8	Gaia DR3 4426488235514632960								
T6	9	1.98	2	97	189.5	Gaia DR3 4433728966255193856		C6	16	2.03	2	100	133.2	Gaia DR3 4433728966257750528
T7	16	2.03	2	100	133.2	Gaia DR3 4433728966257750528		C7	9	1.98	2	97	189.5	Gaia DR3 4433728966255193856
T8	11	1.38	2	98	162.7	Gaia DR3 1164340418192713216		C8	11	1.44	2	93	174.7	Gaia DR3 1164340418193799808
T9	16	1.51	2	90	148.1	Gaia DR3 1273129324165219968		C9	27	3.58	2	78	104.8	Gaia DR3 1273129328460262912
T10	14	2.33	2	93	153.9	Gaia DR3 1213718111006872576		C10	10	0.48	5	97	152.3	Gaia DR3 1213718111007475584
T11	21	1.91	2	93	114.5	Gaia DR3 1203937783282839168		C11	6	1.90	2	70	202.4	Gaia DR3 1203937783283326080
T12	9	2.69	2	100	136.1	Gaia DR3 6319097322890540928		C12	16	3.24	2	96	140.3	Gaia DR3 6319097322891691008
T13	18	4.95	2	92	118.1	Gaia DR3 4437793379707330944		C13	10	4.20	2	85	220.6	Gaia DR3 4437793379710339840
T14	22	11.06	2	94	158.9	Gaia DR3 4571182075942887040		C14	9	0.25	5	92	174.1	Gaia DR3 4571182075939811712
T15	21	2.33	2	80	124.7	Gaia DR3 1308686155817944320		C15	19	7.87	2	65	83.3	Gaia DR3 1308686160115591040
T16	22	1.67	2	96	99.1	Gaia DR3 4443360688115386624		C16	8	7.19	2	59	237.0	Gaia DR3 4443360683820667008
T17	25	1.38	2	97	84.2	Gaia DR3 1218395880150034816		C17	14	1.10	6	95	207.9	Gaia DR3 1218395880147771904
T18	6	1.81	2	96	-----	Gaia DR3 4420251668118135808		C18	15	0.52	5	94	114.8	Gaia DR3 4420251663823717248
T19	14	4.67	2	98	123.3	Gaia DR3 1169005199352782848		C19	7	230.95	2	46	-----	Gaia DR3 1169005195058227584
T20	29	2.25	2	91	87.0	Gaia DR3 1320858269230075520		C20	4	4376.82	2	54	217.4	Gaia DR3 1320858269228497408
T21	5	20.68	2	99	-----	Gaia DR3 1153076196443974656		C21	14	0.04	5	10	0.5	Gaia DR3 1153076196444774144

3. Equipment, Reduction, and Calibration

Speckle interferometry observations were conducted on June 23, 25, and 26, 2024 at the bent Cassegrain focus of the 1.5-meter telescope at Mt. Wilson Observatory. A ZWO ASI 6200MM Pro CMOS camera (Sony IMX455 sensor), was used with a single Astronomik ProPlanet 642 BP 2850002585 filter with a midpoint transmission of 750 nm.

Each target was imaged 1000 times with 512x512 region-of-interest with exposures typically between 50 and 100ms, along with 300 single-star reference images. Reductions to obtain position angles and separations were made with the Speckle Toolbox (Rowe & Genet 2015, Harshaw et al. 2017).

For astrometric calibration, four plate solutions were obtained from four long-exposure images of the periphery of globular cluster M13 or M56 to obtain the plate scale of 0.0306"/pixel +- 0.0020, and camera angle of 175.411° +- 0.073.

4. Results

Table 2 shows both our speckle interferometry results for the target/companion binary pairs, as well as the Gaia values for these same pairs. As mentioned previously, the targets were, after observations and analysis, divided into three logical categories: (I) no matching companion in Gaia, (II) a good match with Gaia in separation, but an increasingly poor match in position angle, and (III) a poor match with Gaia in both separation and position angle. Note that there are no Gaia values for the five Category I pairs because there were no known companions brighter than 14^{th} magnitude within 1.0°, and thus our observed companions were new discoveries.

Table 2: Mt. Wilson and Gaia observations of the 22 targets/companion pairs.

SPECKLE BINARY PAIR OBSERVATIONS					GAIA BINARY PAIR OBSERVATIONS			
Target	Date	Rho "	Theta °		Cmp	Date	Rho "	Theta °
Category I								
T1	2024.475	0.31	21.0					
T2	2024.484	0.41	61.4					
T3	2024.484	0.22	3.6					
T4	2024.484	0.23	291.0					
T5	2024.484	0.36	56.4					
Category II								
T6	2024.484	0.50	52.7		C5	2016.0	0.51	231.91
T7	2024.484	0.51	52.6		C6	2016.0	0.51	231.91
T8	2024.484	0.52	163.0		C7	2016.0	0.49	162.20
T9	2024.484	0.37	40.1		C8	2016.0	0.34	221.87
T10	2024.484	0.54	318.0		C9	2016.0	0.52	138.30
T11	2024.484	0.46	52.2		C10	2016.0	0.44	49.05
T12	2024.484	0.47	332.0		C11	2016.0	0.50	329.64
T13	2024.475	0.40	59.0		C12	2016.0	0.36	67.30
T14	2024.484	0.42	267.0		C13	2016.0	0.39	90.50
T15	2024.484	0.25	149.0		C14	2016.0	0.25	164.55
T16	2024.475	0.54	17.0		C15	2016.0	0.50	246.63
T17	2024.475	0.43	262.0		C16	2016.0	0.44	20.37
T18	2024.482	0.50	52.7		C17	2016.0	0.55	311.73
Category III								
T19	2024.484	0.40	349.0		C18	2016.0	0.20	175.42
T20	2024.484	0.44	358.0		C19	2016.0	0.79	212.57
T21	2024.484	0.47	330.0		C20	2016.0	1.16	166.59

5. Discussion

Of the 21 G2P stars we observed, five (Category I) did not have any known companions within 1.0° brighter than 14^{th} magnitude. Our speckle interferometry observations established that all five had a close relative bright companion within 1.0°, a new companion discovery rate of 100%. Gaia did list some other nearby stars, but they were not within 1.0").

This high rate of discovery was not entirely unexpected, as we had selected G2P stars with a high multi-peak values (>80%). It seems likely, given their relative brightness, that these newly discovered companions are gravitationally bound. We plan, in future observations, to obtain Sloan multicolor fluxes and, from these, photometric parallaxes which could help establish likely binarity.

It might be noted that Gaia DR4 will feature SEAPipe, the source environment analysis pipeline. SEAPipe will provide image reconstruction from transit data. Analysis of these images will find additional sources, and will determine their mean positions, proper motions, parallaxes, and brightnesses (Harrison et al. 2023). SEAPipe could confirm our discoveries, and more fully characterize many of the current G2P stars, perhaps upgrading them to G5P stars. SEAPipe does not run on all sources however, as a minimal coverage in orientation angle is demanded, so there will still be cases that would still benefit from speckle interferometry investigation after the DR4 release.

Table 3 compares our speckle measurements of the pairs of stars with the GAIA DR3 observations of these same pairs. The differences in the pair's separations, Δ Theta, disregard any disagreements between the speckle and Gaia observations as to which stars are primary or secondary by making 180° corrections as required (Δ Theta in *Italics*).

Table 3: Difference between speckle and Gaia binary pair observations.

Target	**ΔRho "**	**ΔTheta °**
Category II		
T6	-0.007	*0.8*
T7	0.003	*0.7*
T8	0.007	0.8
T9	0.029	*1.8*
T10	0.016	0.3
T11	0.021	3.2
T12	-0.031	2.4
T13	0.039	*8.3*
T14	0.030	3.5
T15	0.001	*15.6*
T16	0.039	*49.6*
T17	-0.009	61.6
T18	-0.052	*79.0*
Category III		
T19	0.203	6.4
T20	-0.348	34.6
T21	-0.693	16.6

Of the 16 G2P stars we observed that had known close companions, 13 (Category II) agreed closely in separation (within 52 arcsec), while 9 had position angles within 3.5° of each other, while the other four disagreed by 15.6° or more. Gaia's reported values differed significantly in both separation and position angle from our measurements of the 3 Category III stars

Our measured position angles of many known binaries observed on the same nights (different research program) agreed closely with their orbital predictions, so we concluded that Gaia position angles of close companions may often be inaccurate, as previously noted by Holl et al. (2023). Tokovinin also (2024) noted this same problem with Gaia DR3 observations. Although the mean date for the Gaia position angles was 2016 and our observations were in 2024, these wide binaries all had long periods so there could only have been slight changes in position angles over the intervening eight years.

Tokovinin cites two potential causes for such position angle discrepancies. The first is that Gaia may mix the two stars measurements, possibly due to small magnitude differences between the two stars. He quotes Holl et al. (2023) for further explanation. A second contribution to discrepant Gaia position angle estimates advanced by Tokovinin is simply that the Gaia data needs to be interpreted carefully. Many of the stars we observed had low numbers of visibility periods used (VPU), large Σ5 values in many of the G2P stars, and high RUWE values in the G5P/G6P stars. This suggests that the influence of these unusual values may be a good explanation for the remaining poor matches. While some of these issues, such as too few passes, may be resolved in DR4 or DR5, others may be permanent limitations of Gaia capabilities that speckle interferometry observations may be able to fill.

Since our June 2024 observations reported in this paper, we have observed additional G2P stars on the 1.5- and 2.5-meter telescopes at Mt. Wilson Observatory. Instead of observing many high multi-peak percentage G2P stars with close Gaia companions and only a few without known companions, we concentrated entirely on the G2P stars without any known close companions. Also, instead of just observing G2P targets with high multi-peak percentages, we observed some with lower percentages to get a better feel for the relationship between this parameter and the actual multiplicity of G2P stars as well as looking for any relationship between multi-peak percentages and separations detectable by speckle interferometry.

The 2024 speckle interferometry results reported in this paper were based on observations made with a single non-standard filter, precluding meaningful photometric analysis. Our own analysis and that of Riello et al. (2921) has established that starting around 2.0" apparent separation, Gaia Bp and Rp photometric values become increasingly blended, and below 1.0" are often completely blended (i.e. equal values for each component). Thus, most of our G2P observations after this paper have been made with Sloan gri filters, allowing a g-i color index and r flux values from our bispectrum analysis that should allow us to estimate photometric parallax and other parameters (Bailer Jones et al. 2018).

Given the likely errors in position angles and occasional errors in separation for G5P (and G6P) stars with separations < 1.0", as well as the almost totally blended Bp and Rp photometry, it seems likely that even somewhat modes-aperture telescopes equipped for multi-color speckle interferometry can contribute to our understanding of binaries."

6. Conclusions

Five of the G2P stars we observed had no Gaia companion within 1.0". We discovered, via speckle interferometry, close companions to all five stars.

Sixteen of the G2P stars we observed had Gaia companions within 1.0". Most of these had separations close to our speckle interferometry measurements but often differed in position angle. Although some of these issues may be resolved in DR4 or DR5, others may be inherent limitations of Gaia capabilities that speckle interferometry observations may be able to fill.

Our current research is focusing on G2P stars with no known nearby companions. We hope to characterize these newly discovered potential binaries via speckle photometry.

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