A New Analysis of the Double Star M40*

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Abstract: The double star M40 has been a continuing puzzle because of its inclusion in Charles Messier's Catalogue. With the latest release from Gaia DR3, Part 1, new high accuracy parallaxes verify the components to be an optical double with a physical separation of 166.4 ± 0.56pc. The optical nature of the components confirms earlier investigations by Nugent (2002), who used spectroscopic parallaxes and Merrifield (2016), who used preliminary parallaxes from Gaia Data Release 1 (DR1). Gaia DR3 Part 1 provides, for the first time, radial velocities of each component. The radial velocities, along with the most accurate parallaxes and proper motions to date, have allowed a 3-dimensional analysis of the system.

Introduction and Background

The presence of the double star M40* in Messier's Catalogue has always been a mystery. With the exception of the 4-star asterism M73, it is the only non-nebulous, non-cluster and non-galaxy object in the catalogue. The original assertion of a nebula at the position of M40, according to historians, seems to have been made by the German-Polish astronomer Johannes Hevelius in 1660. Researchers have surmised that Hevelius may have seen the galaxy NGC 4290 12' to the west (see Figure 1). In 1764, Messier searched for a nebula and found the two stars of equal brightness very close together at the reported position by Hevelius. Burnham (1978) suggests that Hevelius misjudged these two stars as a nebula. Chaple (2010) suggested Messier thought it was nebulous either by using low power or an inferior instrument. It is unlikely that Messier saw the galaxy NGC 4290, m = +12.7 as it was too faint for his 4-inch telescope. Despite Messier's failure to find the nebula reported by Hevelius, he cataloged the two stars anyway. The comet hunter Friedrich August Theodor Winnecke, who re-discovered the pair in 1863, reported a position angle of 88.0° and separation of 49.2" and cataloged the pair as Winnecke 4.

In an earlier investigation, this author (Nugent 2002) used data from the Hipparcos/Tycho-2 astrometry mission to estimate the component distances to determine if the stars comprised a physical binary. Unfortunately, the Tycho-2 parallaxes for these two stars were of such poor quality (primary parallax error was 3x the parallax, secondary had a negative parallax) that no reliable distance could

*Also known as WDS 12222+5805, Winnecke 4, SAO 28353, SAO 28355, HD 238107, HD 238108 be established. Nugent then used the method of spectroscopic parallax to estimate the component distances. Skiff (2001) provided spectral types which led to Nugent deriving absolute magnitudes (corrected for absorption) and distances (using the distance modulus $m - M = 5\log r - 5$) for the primary: 590 ± 230pc and secondary 170 ± 70pc. Errors in using spectroscopic parallaxes to derive distances are typically large (25–30%) due to observational errors in measuring *B–V* magnitudes and the scatter of absolute magnitudes (±1 mag) in the H–R diagram. With the unreliable distances from this method, Nugent used the estimated component masses, angular separation and applied a series of "best guess" distances to derive a physical separation and orbital period. Using a 100 pc distance to the pair, the separation was estimated to be 5,000 AU and period of 232,000 years. For a 150 pc distance, the separation was 7,500 AU and period 427,000 years. All of these results clearly showed the improbability of M40 being a binary star system.

Gaia Mission Data

From the first release of the Gaia mission (DR1), Merrifield (2016) used preliminary parallaxes and found the distance to M40's primary star to be 350 ± 30pc and the secondary star to be 140 ± 5pc. This result provided more verification that M40 is an optical pair as two unrelated stars. The Gaia DR1 parallax errors for M40 were 0.24mas. Gaia's DR3 Part 1 parallax errors used in this study are 0.011mas and 0.015mas for the primary and secondary, 20x times more accurate than the DR1 via the 5-parameter and 6-parameter solutions. (Vallenari, et. al. 2022).

To illustrate the higher precision from Gaia DR1 vs. Gaia DR3 Part 1, the DR1 parallax gave the distance to M40's components as primary: 350 ± 30pc and secondary: 140 ± 5pc. Gaia DR3 Part 1 distances are primary: 310.6 ± 0.7pc and secondary: 144.2 ± 0.53pc. The Gaia DR3 Part 1 data for M40 is given in Table 1.

Table 1. Gaia DR3 Part 1 parallax (π), proper motion and radial velocity (V_r) data for M40.

	π-mas	σ–mas	PM RA-mas	σ–mas	PM DEC-mas	σ–mas	Radial velocity	Mag
Primary	3.219132	0.01184	-47.1487	0.01071	-6.48290	0.01154	-37.5 km/sec	9.47
Secondary	6.932792	0.01554	-28.1604	0.01674	66.88822	0.01515	30.74 km/sec	10.02

No radial velocity (V_r) data was available for M40 until the release of Gaia DR3 Part 1. To measure radial velocities, Gaia used an on board instrument known as the *Radial Velocity Spectrometer* (RVS). The RVS uses only a small part of the full wavelength range to determine radial velocity: 845nm to 872nm (ESA-Gaia 2022). Previous releases of Gaia (DR1, DR2, DR3) only included astrometric data which gave just two components of the target's motion in space. The addition of V_r now allows investigators to evaluate double and binary stars in three dimensions.

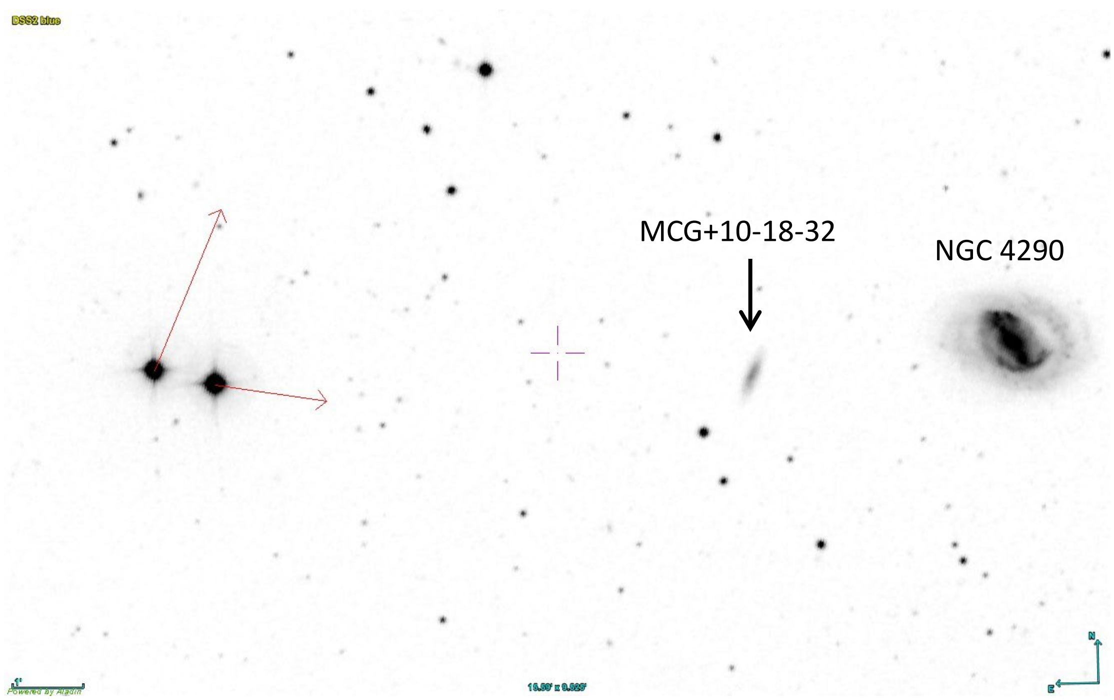

Figure 1. M40's components with Gaia DR3 Part 1 proper motions. To the right are galaxies MCG +10-18-32 and NGC 4290. Proper motions generated using Aladin Sky Atlas v11. DSS2 Blue image Jan 1, 1994.

Distance and Space Motion

The revised distances provide new absolute magnitudes and hence new estimates for the stellar masses using the mass-luminosity function: Primary: 1.9 $M_\odot$, Secondary: 1.1 $M_\odot$. Distance, physical separation and radial velocities for M40's components from Gaia DR3 Part 1 are given below. To derive the physical separation, Gaia's RA and DEC coordinates were first used to determine the angular separation. Then the Gaia distances and angular separation were applied using the law of cosines to determine the physical separation.

		Distance	Radial Velocity V_r
Primary	=	310.6 ± 0.7pc	–37.50 ± 0.16 km/sec
Secondary	=	144.2 ± 0.5pc	30.74 ± 0.24 km/sec
Separation	=	166.4 ± 0.56pc	

Figure 2 shows M40's components in a 3-dimensional view. The radial velocity vectors V_r in Figure 3 show the components moving in opposite directions from the Sun. Gaia's radial velocities show the Primary (furthest from Sun) is moving toward us at 7.9 AU/yr, and the Secondary (closest to Sun) is moving away from us at 6.48 AU/yr. The net result shows they are approaching each other. Using Gaia DR3 Part 1 proper motions and radial velocities, Figure 3 shows their space velocity with respect to the Sun.

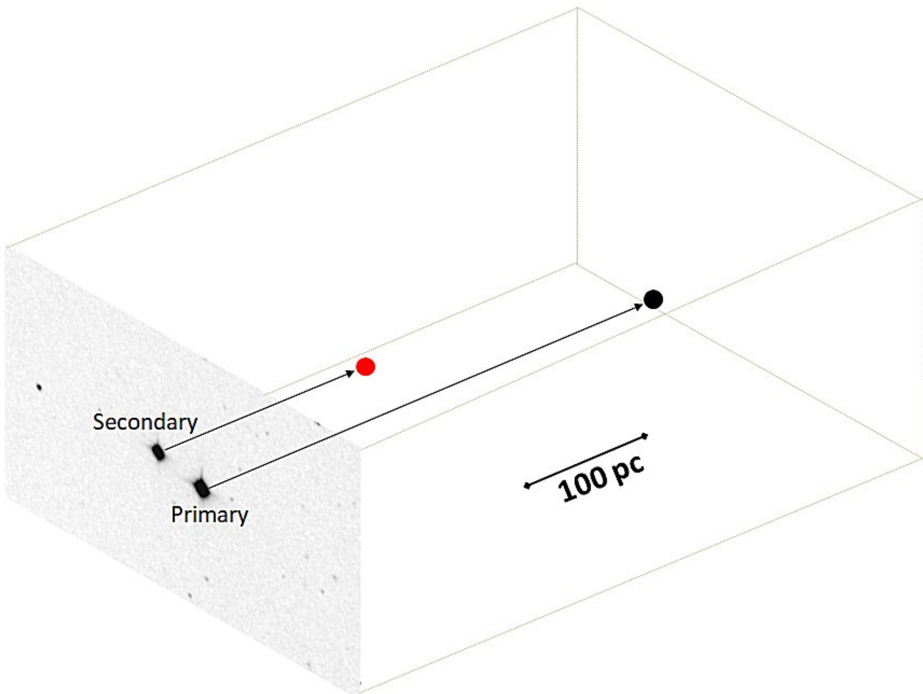

Figure 2. Distance diagram for M40. Primary (black) distance = 310.6 pc, Secondary (red) distance = 144.2 pc. Primary-Secondary physical separation = 166.4 pc.

Given the radial velocities are showing the components approaching one another, will they ever be a true physical binary? If so, one might ask when will their closest physical separation occur? At the current space velocity and direction of motion, M40's components will be at their minimum separation of 126.004pc 963,225 years from now, hence no chance of a gravitational capture resulting in a real binary.

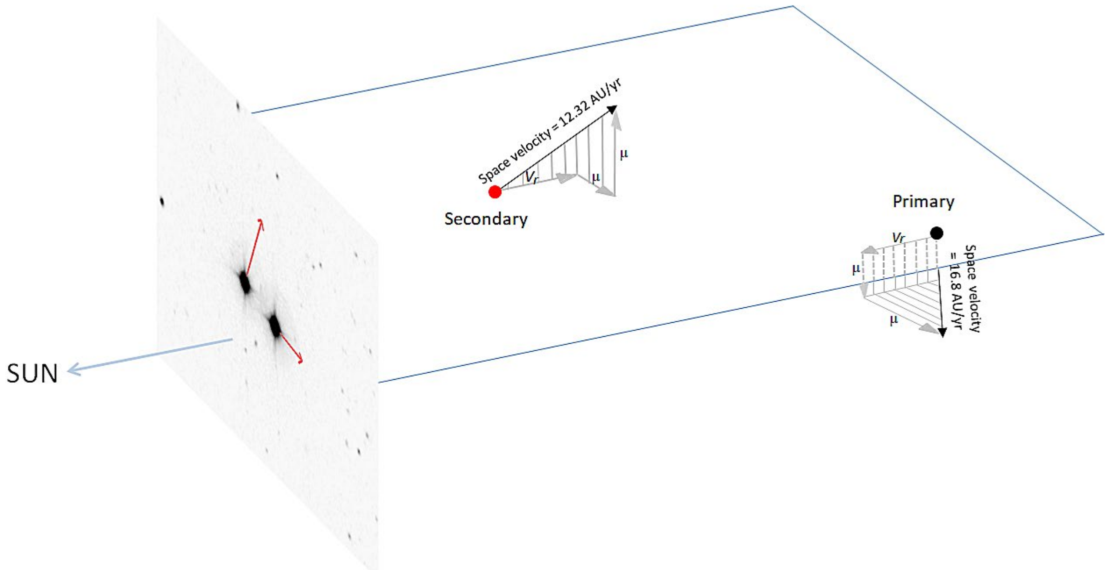

Figure 3. Space velocity vectors. Radial velocity denoted by V_r and proper motion by μ.

At this minimum 126pc separation, celestial mechanics tells us, if there was an orbit, the period would exceed 27 billion years!

M40's historical angular separation was decreasing until 1748 when it reached a minimum of 49.4". After 1748 it began increasing and is now 53.4" (from Gaia RA & DEC). If we go back in time to 7800 BC, the components of M40 had the same angular separation (11.8') as present day Mizar and Alcor, the Big Dipper handle stars. This same separation occurs in 11,286 AD. Table 2 shows Primary-Secondary separations and distances for M40 at various future dates. At their closest separation in the year 965,248AD, the Primary star will brighten to m = +9.26 and the Secondary will be fainter at m = +10.42 as seen from Earth.

Table 2. Angular and physical separations of M40 over time

YEAR	Separation " or °	Pri-Sec separation pc	Sun-Primary distance pc	Sun-Secondary distance pc
2023 AD	53.4"	166.3	310.6	144.3
200,000 AD	4.08°	153.3	303.0	153.5
400,000 AD	8.23°	141.9	295.3	156.8
600,000 AD	12.5°	133.1	287.6	163.1
800,000 AD	16.8°	127.6	280.0	169.4
965,248 AD	20.5°	126.0*	273.6	174.6
1,200,000 AD	26.1°	129.2	264.7	181.9
1,400,000 AD	31.2°	136.8	257.0	188.2
1,600,000 AD	36.6°	148.9	249.3	194.5
1,800,000 AD	42.6°	165.2	241.7	200.8
2,000,000 AD	49.2°	185.2	234.0	207.1

*Closest approach between Primary and Secondary components

Discussion

The components of M40 are two gravitationaly unrelated stars. As with any optical double, they appear to be close and are portrayed as a double star. Nugent (2022) pointed out the majority of WDS entries are likely unrelated stars and chance optical alignments, yet they continue to be measured. M40, as with many other optical doubles, on first glance appear to be physically connected. This perception is the result of a few coincidences. The components are close on the celestial sphere, and have similar apparent magnitudes. Similar apparent magnitudes of optical doubles are the result of stars with vastly different luminosities yet they are at substantially different distances away from Earth. Therefore, by chance they appear to have the same or similar magnitude. Very little interest has been given to M40 in the amatuer and professional astronomical community as it remains an oddity in the Messier catalogue.

M40's proximity to the Big Dipper makes it easy to find. It is 1.4° northwest of Megrez in the Big Dipper's bowl. Figure 4 shows the apparent place on the celestial sphere of M40 and the Big Dipper stars over time from their Gaia proper motions.

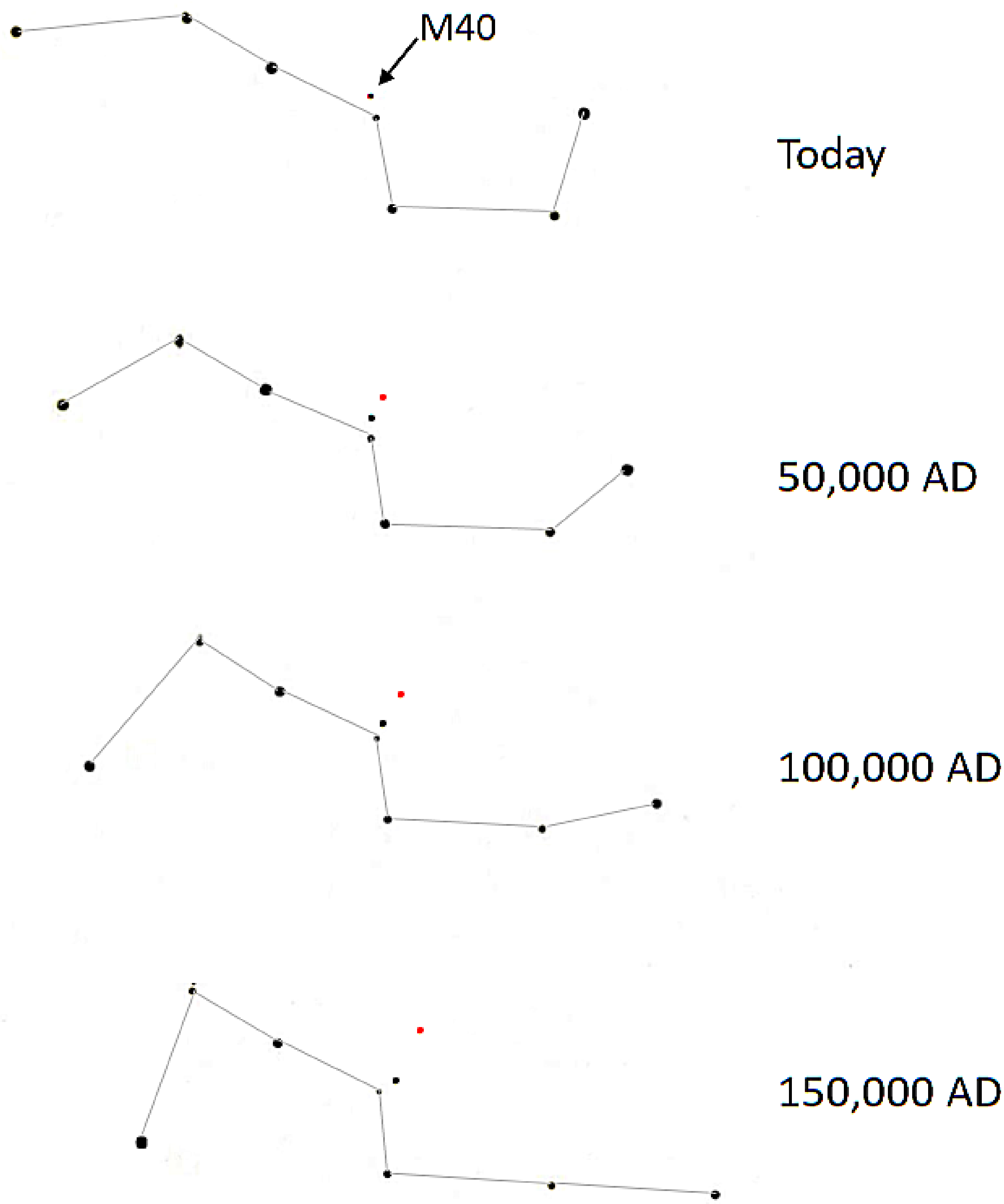

Figure 4. Proper motion of M40 components and Big Dipper stars for the next 150,000 years. M40's Primary star = black, Secondary star = red.

Acknowledgements

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