ORBITAL SOLUTION AND DYNAMICAL MASSES FOR THE NEARBY BINARY SYSTEM GJ 67 AB

GUILLERMO TORRES
Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA; gtorres@cfa.harvard.edu

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ABSTRACT

We report spectroscopic observations of the nearby, 19.5 yr binary system GJ 67AB spanning more than 35 yr. We carry out a global orbital solution combining our radial velocity measurements with others from the literature going back more than a century, and with all other available astrometric observations. The latter include measurements of the relative position as well as the Hipparcos intermediate data and photographic observations tracing the motion of the photocentre. We derive masses for the primary and the M dwarf secondary of 0.95±0.11 and 0.25±0.019 M⊙, respectively, as well as a more accurate trigonometric parallax of 79.08±0.63 mas that accounts for the orbital motion. We provide evidence suggesting that the much smaller parallax from Gaia DR3 is biased. The precision in the masses remains limited mainly by the still few measurements of the relative position.

Keywords: binaries: visual; binaries: spectroscopic; stars: low-mass; stars, techniques: radial velocities; Astronomical instrumentation, methods, and techniques, astrometry; Astrometry and celestial mechanics

1. INTRODUCTION

GJ 67 (WDS J01418+4237AB, HD 10307, HIP 7918, HR 483) is a 5th magnitude star only ~13 pc away, with properties very similar to the Sun. The spectral classification has typically been given as G1.5 V or G2 V. Its binary nature was discovered in a proper motion study based on photographic measurements with 61-inch refractor at the Sproul Observatory, and was first announced by Lippincott & Lanning (1976). In a subsequent investigation Lippincott et al. (1983) reported an astrometric orbital solution for the motion of the centre of light, with a period of 19.5 yr and a semimajor axis of 0′.13. The same study also resolved the pair spatially for the first time in the near-infrared by the technique of speckle interferometry. The companion is a mid-to-late M dwarf.

Estimates of the mass of the components have typically relied on various assumptions or external information. Lippincott et al. (1983) reported values of 1.44±0.35 and 0.38±0.07 M⊙ for the primary and secondary, whereas Henry & McCarthy (1993) gave 0.93±0.23 and 0.280±0.071 M⊙, respectively. Martin et al. (1998) found much lower values of 0.80±0.16 and 0.136±0.053 M⊙.

GJ 67 has a long history of radial velocity measurements dating back more than a century. Spectroscopic orbital elements have been reported by Duquennoy & Mayor (1991) and Abt & Willmarth (2006), but relied in part on elements adopted from the astrometry of Lippincott et al. (1983). The first spectroscopic orbit based solely on radial velocities is more recent (Fekel et al. 2018), and used those authors’ own measurements combined with others from the literature to derive much improved elements.

In a separate effort we have been monitoring the radial velocities of GJ 67 at the Center for Astrophysics for more than 35 yr, spanning close to two orbital cycles of the binary. Additionally, a handful of astrometric observations that resolve the companion have appeared since the study of Lippincott et al. (1983), and were used by Miles & Mason (2017) to infer preliminary elements for the relative orbit. The individual Lippincott observations themselves have never been used in any other orbital analysis beyond the original study. GJ 67 was also observed by the Hipparcos mission (ESA 1997), and while the observations did not resolve the binary, the intermediate astrometric measurements for the star are available to strengthen the determination of the photocentre orbit. The existence of all of this observational material, plus a further series of radial-velocity measurements published after the paper by Fekel et al. (2018), motivates us to carry out the first global orbital solution that combines all available observations in a self-consistent manner.

Section 2 reports our spectroscopic observations of GJ 67 using three different instruments. Section 3 summarizes the existing astrometric observations. Our orbital analysis is presented in Section 4 followed by a discussion of results in Section 5 and conclusions.

2. RADIAL VELOCITY MEASUREMENTS

Our spectroscopic observations of GJ 67 at the Center for Astrophysics (CfA) began in September of 1986, and used an echelle spectrograph (Digital Speedometer (DS); Latham 1992) on the 1.5m Wyeth reflector at the (now closed) Oak Ridge Observatory (Massachusetts, USA). This instrument had a resolving power of R~35,000, and was equipped with an intensified photon-counting Reticon detector that limited the recorded output to a single order 45 Å wide centred at 5187 Å, featuring the Mg I b triplet. Typical signal-to-noise ratios were about 45 per resolution element of 8.5 km s⁻¹, and a total of 53 spectra were obtained regularly through September of 2004. Two additional observations were gathered near the end of 2009 with a nearly identical instrument attached to the 1.5m Tillinghast reflector at the Fred L. Whipple Observatory (Arizona, USA).

Starting in December of 2009 the observations were continued on the Tillinghast reflector with a modern, bench-mounted, fibre-fed instrument (Tillinghast Reflector Echelle Spectrograph (TRES); Szentgyorgyi & Fürtész 2007; Fürtész 2008) providing a resolving power of R~44,000. These spectra cover the wavelength range 3800–
9100 Å in 51 orders. For the order centred at about 5187 Å the typical signal-to-noise ratios of the 48 observations we collected through November of 2021 were about 200 per resolution element of 6.8 km s\(^{-1}\).

Wavelength solutions were based on exposures of a thorium-argon lamp before and after each science exposure. For the DS observations, the velocity zero point was monitored by means of sky exposures at dusk and dawn, and small run-to-run corrections usually smaller than 2 km s\(^{-1}\) were applied to the raw velocities. Observations of minor planets were then used to determine a further correction of +0.14 km s\(^{-1}\) to the IAU system (see Stefánik et al. 1999). For TRES, the much smaller drifts in the velocity zero point (\(\leq 100\) m s\(^{-1}\)) were monitored by observing IAU standards each run, and asteroid observations were again used to transfer the velocities to the IAU system.

The binary companion of GJ 67 is very faint, and all our spectra are therefore single-lined. Radial velocities were measured by cross-correlation using the XCSAO task running under IRAF. The template was taken from a large library of synthetic spectra based on model atmospheres by R. L. Kurucz, and a line list tuned to better match real stars (see Nordström et al. 1994; Latham et al. 2002). To determine the best parameters for the template, we first used our higher-quality TRES spectra to estimate the spectroscopic parameters employing the SPC procedure (Stellar Parameter Classification; Buchhave et al. 2012). This procedure compares the observed spectra against the spectral library, and for each observation it selects the spectroscopic parameters giving the highest cross-correlation coefficient from a multi-dimensional fit. The four parameters are the effective temperature \(T_{\text{eff}}\), the surface gravity \(\log g\), the metallicity \([m/H]\), and the rotational broadening \(v \sin i\). We averaged the spectroscopic properties over all spectra, and obtained \(T_{\text{eff}} = 5854 \pm 50\) K, \(\log g = 4.31 \pm 0.10\), \([m/H] = -0.04 \pm 0.08\), and \(v \sin i = 3.0 \pm 1.0\) km s\(^{-1}\). These properties are fairly consistent with other independent determinations in the literature (see, e.g., Alende Prieto et al. 2004; Ramírez et al. 2007; Böeche & Grebel 2016). For the radial-velocity measurements we chose a template with parameters in our library near these values: \(T_{\text{eff}} = 6000\) K, \(\log g = 4.5\), solar \([m/H]\), and \(v \sin i = 2\) km s\(^{-1}\). For consistency with the DS spectra, we restricted the cross-correlations to the TRES order containing the Mg triplet.

The radial velocities for the DS and TRES may be compared to estimates of the orbital elements from photometric observations of the binary GJ 67. The radial-velocity measurements were compared to the dynamical orbital solutions published by Fekel et al. (2018) for their own spectroscopic study. All of these velocities are shown graphically in Fig. 1 along with our best-fitted model described later. The total time span of the measurements is 115 yr (about 5.9 orbital cycles).

Formal uncertainties for the velocities were taken as published, for the sources that reported them. For the Lick velocities we adopted errors of 0.5 km s\(^{-1}\), and for the Kitt Peak measurements of Abd & Willmarth (2006) we used 0.21 km s\(^{-1}\), following those authors. The observations by Fekel et al. (2018) were reported with weights rather than uncertainties. We converted the weights to uncertainties by adopting 0.1 km s\(^{-1}\) as the error for an observation of unit weight. As formal errors can sometimes be underestimated or overestimated, all radial-velocity uncertainties were adjusted during our analysis as described below.

3. ASTROMETRIC OBSERVATIONS

3.1. Photocentre Motion from Photographic Plates

The photographic observations of GJ 67AB from the Sprout Observatory that formed the basis of the study by Lippincott et al. (1983) were taken between 1937 and 1982. While the original plate measurements were never published, those authors did report normal point residuals from their solution for parallax, proper motion, and orbital motion at 18 epochs, given to a precision corresponding to about 2 mas. Based on the information provided, it is possible to reconstruct observations that reflect the motion of the centre of light of the binary around the barycentre in the right ascension and declination directions \((\Delta X, \Delta Y)\). Given the faintness of the companion at the wavelength of the photographic observations, for all practical purposes the photocentre coincides with the primary. We used these reconstructed observations as measurements for our analysis. Formal uncertainties \(\sigma_{\Delta X}\) and \(\sigma_{\Delta Y}\) were calculated from the reported standard error of unit weight in each coordinate, and the total weight assigned to each observation by Lippincott et al. (1983). These reconstructed \(\Delta X\) and \(\Delta Y\) observations are given in Table 5.

3.2. Relative Positions

Only a few successful measurements of the relative position of the components in GJ 67AB have been made in the 40 years since the first of them by Lippincott et al. (1983), mostly at near-infrared wavelengths. About as many attempts have failed to resolve the pair, either because of the faintness of the companion at the chosen wavelengths or because the separation was too small. A listing of all of these measurements, contained in the Washington Double Star Catalogue (WDS; Worley & Douglass 1997; Mason et al. 2001), was kindly provided by R. Matson (US Naval Observatory) and is reproduced in Table 4. We include the bandpass and magnitude difference \(\Delta m\) measured for each observation.

A few notes about these measurements are in order. The 1982 speckle observation by Lippincott et al. (1983) was reported split into a north-south separation with an associated uncertainty, and a more uncertain east-west separation without an error. We have accordingly

\(^{1}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
Table 1
Radial Velocities for GJ 67 from the CfA Digital Speedometers

| HJD (2,400,000+) | RV (km s\(^{-1}\)) | \(\sigma_{RV}\) (km s\(^{-1}\)) | Orbital Phase |
|-----------------|-----------------|-----------------|---------------|
| 46685.7187      | 4.72            | 0.36            | 0.4645        |
| 47813.6325      | 4.63            | 0.36            | 0.6225        |
| 48170.7243      | 3.92            | 0.42            | 0.6726        |
| 48558.7617      | 2.80            | 0.65            | 0.7269        |
| 48602.4871      | 2.98            | 0.60            | 0.7330        |

Note. — Orbital phases were computed from the ephemeris given in Section 4. (This table is available in its entirety in machine-readable form.)

Table 2
CfA Radial Velocities for GJ 67 from TRES

| HJD (2,400,000+) | RV (km s\(^{-1}\)) | \(\sigma_{RV}\) (km s\(^{-1}\)) | Orbital Phase |
|-----------------|-----------------|-----------------|---------------|
| 55166.6932      | 3.98            | 0.04            | 0.6527        |
| 55193.5961      | 3.99            | 0.05            | 0.6565        |
| 55549.6456      | 3.57            | 0.03            | 0.7064        |
| 55585.5598      | 3.52            | 0.03            | 0.7114        |
| 55884.7453      | 3.08            | 0.04            | 0.7533        |

Note. — Orbital phases were computed from the ephemeris given in Section 4. (This table is available in its entirety in machine-readable form.)

Figure 1. Radial-velocity measurements for GJ 67 from various sources, as labelled. The solid curve is our best-fitted model described in Section 4, and the dotted line represents the centre-of-mass velocity for the system.

The most recent solution for the astrometric orbit of GJ 67AB was published by Miles & Mason (2017). That study used all six complete observations in Table 4 (with both a position angle and a separation), plus one additional measurement that turns out to be spurious, and unfortunately biased their results. That observation has since been removed from the WDS, and we do not list it in our table.

3.3. Hipparcos Intermediate Data

The Hipparcos mission observed GJ 67AB (HIP 7918) a total of 52 times between December of 1989 and January of 1993, but did not resolve the companion. Therefore the measurements refer to the centre of light of the system. The five-parameter solution to derive the posi-
Table 3
Reconstructed Photocentre Observations for GJ 67AB from Lippincott et al. [1983]

| Date (year) | ΔX (″) | σ_ΔX (″) | ΔY (″) | σ_ΔY (″) | Orbital Phase |
|-------------|--------|-----------|--------|-----------|--------------|
| 1938.48     | −0.042 | 0.015     | −0.064 | 0.014     | 0.9972       |
| 1940.35     | 0.023  | 0.012     | −0.014 | 0.011     | 0.0929       |
| 1941.66     | 0.077  | 0.015     | 0.037  | 0.014     | 0.1599       |
| 1963.52     | 0.072  | 0.010     | 0.135  | 0.009     | 0.2785       |
| 1964.83     | 0.094  | 0.013     | 0.149  | 0.013     | 0.3456       |
| 1965.82     | 0.106  | 0.015     | 0.150  | 0.014     | 0.3962       |
| 1968.80     | 0.080  | 0.007     | 0.142  | 0.007     | 0.5487       |
| 1969.88     | 0.049  | 0.006     | 0.131  | 0.005     | 0.6040       |
| 1970.80     | 0.038  | 0.007     | 0.131  | 0.007     | 0.6511       |
| 1973.81     | −0.007 | 0.007     | 0.031  | 0.007     | 0.8051       |
| 1974.83     | −0.031 | 0.008     | −0.019 | 0.008     | 0.8573       |
| 1975.75     | −0.048 | 0.008     | −0.021 | 0.008     | 0.9044       |
| 1976.76     | −0.058 | 0.006     | −0.059 | 0.005     | 0.9561       |
| 1977.94     | −0.016 | 0.008     | −0.056 | 0.007     | 0.9164       |
| 1978.80     | 0.012  | 0.006     | −0.031 | 0.005     | 0.0604       |
| 1979.77     | 0.033  | 0.007     | 0.002  | 0.006     | 0.1101       |
| 1980.74     | 0.052  | 0.006     | 0.051  | 0.006     | 0.1597       |
| 1982.09     | 0.088  | 0.007     | 0.092  | 0.006     | 0.2288       |

Note. — Orbital phases were computed from the ephemeris given in Section 4.

Table 4
Relative Positions of GJ 67AB from the WDS

| Date (year) | P.A. (deg) | Separation (″) | λ (μm) | Δm (mag) | Orbital Phase | Reference          |
|-------------|------------|----------------|--------|----------|--------------|--------------------|
| 1982.755    | N–S        | 0.550 ± 0.028  | K      | 3.6 ± 0.2 | 0.2628       | Lippincott et al. [1983] |
| 1982.755    | E–W        | 0.38 ± 0.04    | K      | 3.6 ± 0.2 | 0.2628       | Lippincott et al. [1983] |
| 1989.773    | 203 ± 2    | 0.623 ± 0.027  | K      | 4.30 ± 0.07 | 0.6220       | Henry & McCarthy [1993] |
| 1990.906    | 199 ± 2    | 0.442 ± 0.018  | K      | 4.50 ± 0.12 | 0.6799       | Henry & McCarthy [1993] |
| 1990.915    | 194 ± 2    | 0.448 ± 0.030  | J      | 4.37 ± 0.25 | 0.6084       | Henry & McCarthy [1993] |
| 1990.931    | 196 ± 2    | 0.485 ± 0.025  | K      | 4.50 ± 0.05 | 0.6812       | Henry & McCarthy [1993] |
| 1995.7587   | (190.3°)   | 0.306 ± 0.020  | V      | ...      | 0.9283       | Hartkopf et al. [1997] |
| 2002.7760   | 212.0 ± 1.0 | 0.75 ± 0.02   | I      | 5.5 ± 0.4 | 0.2874       | Roberts [2007]       |
| 2006.687    | ...        | 0.78 ± 0.04    | K_S    | 3.9      | 0.4875       | Serabyn et al. [2007] |

Note. — Orbital phases were computed from the ephemeris given in Section 4. The 1995 P.A. in parentheses was not used. The HD identifier given in the original paper for the 2002 observation (HD 10105) is incorrect.

4. ORBITAL ANALYSIS

Unlike all previous studies of GJ 67AB, here we made use of all observations simultaneously to solve for the orbital elements. This is particularly helpful in this case because the astrometric information is rather sparse, whereas the radial-velocity measurements are much more numerous, they cover a larger number of orbital cycles, and they therefore constrain the shape of the orbit and the ephemeris very well. The astrometry’s job is mostly to set the angular scale and orientation of the orbit on the plane of the sky.

The elements of the relative orbit of GJ 67AB are represented by the standard elements \( P \) (orbital period), \( a'' \) (angular semimajor axis), \( e \) (eccentricity), \( i \) (inclination angle), \( \omega_B \) (argument of periastron for the secondary),...
Ω (position angle of the ascending node), and $T$ (reference time of periastron passage). The orbit of the photocentre is a scaled version of the relative orbit, with angular semimajor axis $a''_{\text{phot}}$. As mentioned earlier, the secondary star is so faint ($\Delta V \approx 7.5$ mag) that in practice the photocentre coincides with the primary for observations at optical wavelengths. Our orbital analysis in this section does not require this assumption; we assume only that the location and motion of the photocentre is the same for both the photographic measurements of Lippincott et al. (1983) and the Hipparcos measurements (but see below). Two more elements were used to describe the spectroscopic orbit: $K$ (velocity semiamplitude of the primary), and $\gamma$ (the centre-of-mass velocity).

We have chosen to consider five additional adjustable parameters in our analysis to account for possible differences in the velocity zero points of the various spectroscopic data sets, relative to one of them taken as the reference. The potential for these shifts has often been overlooked in previous analyses of the spectroscopic orbit of GJ 67AB. Given our efforts to carefully place the CfA velocities (DS + TRES) on the IAU system (Section 2), we chose those as the reference data set. The five offsets ($\Delta RV_{\text{C}}$, $\Delta RV_{\text{B}}$, $\Delta RV_{\text{H}}$, $\Delta RV_{\text{A}}$, and $\Delta RV_{\text{F}}$) correspond to the data sets of Campbell (1928), Beavers & Eitter (1986), Halbwachs et al. (2018), Abt & Willmarth (2006), and Fekel et al. (2018), respectively, and are to be added to those velocities to place them on the same system as the CfA measurements.

Our use of the Hipparcos observations introduces another five adjustable parameters that represent corrections to the position of the barycentre ($\Delta \alpha^*, \Delta \delta$), the proper motion components ($\Delta \mu^*_\alpha$, $\Delta \mu^*_\delta$), and the parallax ($\Delta \pi_t$) reported in the catalogue. The formalism for incorporating the Hipparcos intermediate data in an orbital fit follows the description of Pourbaix & Jorissen (2000), including the correlations between measurements from the two independent data reduction consortia (see ESA 1997).

We solved simultaneously for all orbital elements and auxiliary parameters using standard non-linear least-squares techniques (e.g., Press et al. 1992). The use of different types of observations requires careful relative weighting for a balanced solution. We handled this by applying multiplicative scaling factors to the uncertainties, determined by iterations so as to achieve reduced $\chi^2$ values near unity for each data set. For the WDS and photographic observations this was done separately in each coordinate. The results of our analysis may be found in Table 5 and the final multiplicative error scaling factors are given in Table 6. The bottom section of Table 5 lists various derived properties that we discuss in the next section.

A graphical representation of the photographic observations by Lippincott et al. (1983) that trace the photocentre motion is presented in Fig. 2, with our best-fitted model. On the same plot we indicate the orbit in which Hipparcos observations were made, as well as the section covered by the measurements included in the Third Data Release (DR3) of the Gaia mission (Gaia Collaboration et al. 2022), in which the star has the identifier 348515297330713120.
confirmed that the values are entirely consistent within the uncertainties (0±0.030 and 0′′1328±0′′0041, respectively), the Hipparcos result is much poorer, and the p.m. determinations are weakened as well. This motivated us to assume a common value for $\alpha_{\text{phot}}$, which has no impact on any of the other orbital properties.

The relative orbit of GJ67AB is presented in Fig. 3 along with all complete WDS measurements, as well as the N-S and E-W measurements for the 1982 epoch. The 1995 and 2006 observations lacking a position angle cannot be represented, but their predicted locations are indicated with triangles. The photocentre orbit is shown to scale along with the photographic measurements from Fig. 2.

A comparison of our orbital elements with all other determinations in the literature is presented in Table 7.

5. DISCUSSION

Our mass determinations for the primary and secondary of GJ67AB are consistent with those of Henry & McCarthy (1993), and improve on the uncertainties by at least a factor of two. As a check, we derived another value for the mass by using stellar evolution models in conjunction with our SPC determination of the spectroscopic properties in Section 2, which serves to also estimate the radius of the star and other properties.

For this exercise we used the EXOFASTv2 code of Eastman et al. (2019) coupled with a fit to the spectral energy distribution (SED) constrained by our parallax determination and brightness measurements in the Johnson, Tycho-2, Sloan, 2MASS, and WISE systems (Mermilliod 1994, Høg et al. 2000, Mallama 2014, Cutri et al. 2003, 2012). The light contribution of the secondary was assumed to be insignificant for our purposes. For the model isochrones the EXOFASTv2 code relies on the MIST series of Choi et al. (2016), and the spectroscopic quantities were used as priors in the fit. Fluxes were based on the NextGen model atmospheres of Allard et al. (2012).

The resulting SED fit is shown in Fig. 4 and the primary mass we obtained is $M_A = 0.986 \pm 0.060 \, M_\odot$. This is consistent with our formally less precise dynamical estimate from the previous section. The radius of the primary is estimated to be $R_A = 1.129 \pm 0.023 \, R_\odot$, its luminosity is $L_A = 1.353 \pm 0.034 \, L_\odot$, and the age according to the MIST models is 7.3±3.1 Gyr. The main factor entering into the uncertainty in our dynamical mass determination through Kepler’s Third Law is the error in angular semimajor axis of the orbit, which contributes about twice as much as the error in the parallax. The period uncertainty has a negligible contribution.

As a further consistency check, we used our mass determinations from Table 5 along with stellar evolution models to compute the brightness contrast between the primary and secondary in several standard photometric filters, and compared those values with the measured magnitude differences from Table 4. For this we used model isochrones from the PARSEC series by Chen et al. (2014), which have been shown by those authors to perform better than others for low-mass stars such as the secondary of GJ67AB. The results are presented in Fig-

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3 https://github.com/jdeast/EXOFASTv2

4 This may not be quite true at the longer wavelengths. For example, Henry & McCarthy (1993) estimated a brightness difference in the K-band of about 1.3 mag (see Table 4). However, we verified that small corrections for this effect do not significantly change our results below.
McCarthy (1993), while the magnitude difference at each panel.

Uncertainties in the predictions stemming from the mass panel are seen to be in good agreement with predictions.

between 1 and 9 Gyr. The measured $\Delta m$ of the primary changes by up to about 0.75 mag because the age of the system is not well constrained by the observations, and the brightness of the primary by up to about 0.75 mag between 1 and 9 Gyr. The measured $\Delta m$ values in the top panel are seen to be in good agreement with predictions. Uncertainties in the predictions stemming from the mass errors are indicated schematically along the bottom of each panel.

The contrast at $V$ is roughly as estimated by Henry & McCarthy (1993), while the magnitude difference at $B$

![Figure 4](image-url) Fit to the spectral energy distribution of GJ 67 with EXOFASTv2 Eastman et al. (2019). The curve is based on a model atmosphere from the NextGen series of Allard et al. (2012) constrained by our SPC parameters from Section 4. Red error bars represent the brightness measurements, and the blue dots correspond to the computed flux from the model.

Figure 4. Fit to the spectral energy distribution of GJ 67 with EXOFASTv2 Eastman et al. (2019). The curve is based on a model atmosphere from the NextGen series of Allard et al. (2012) constrained by our SPC parameters from Section 4. Red error bars represent the brightness measurements, and the blue dots correspond to the computed flux from the model.

Table 7
Comparison of Published Orbital Solutions for GJ 67AB

| Source               | $P$ (yr) | $a''$ (") | $e$ | $i$ (deg) | $\omega A$ (deg) | $\Omega$ (deg) | $T_b$ (yr) | $K$ (km s$^{-1}$) | $\gamma$ (km s$^{-1}$) |
|----------------------|---------|-----------|-----|----------|-----------------|--------------|-----------|-----------------|------------------|
| Lippincott et al. (1983) | 19.50   | 0.616c   | 0.42 | 104.0   | 100.0           | 32.6         | 2016.60   | ...            | ...              |
| Duquennoy & Mayor (1991) | 19.50   | ...      | 0.42 | ...     | 210.8           | ...          | 2016.60   | 2.68            | 3.12             |
| Henry & McCarthy (1993)  | fixed   | fixed     | 3.5 | fixed    | fixed           | fixed        | 2016.60   | ...            | ...              |
| Martin et al. (1998)    | fixed   | fixed     | fixed | fixed  | fixed           | fixed        | ...       | ...            | ...              |
| Söderhjelm (1999)      | 19.5    | 0.59     | 0.43 | 105     | 202             | 32           | 2016.6    | ...            | ...              |
| Abt & Willmarth (2006)  | 18.46   | ...      | 0.34 | ...     | 193             | ...          | 2013.86   | 2.52            | 3.25             |
| Miles & Mason (2017)    | 18.12   | 0.631    | 0.434 | 98.8    | 144.3           | 205.0        | 2011.75   | ...            | ...              |
| Fekel et al. (2018)     | 19.550  | ...      | 0.4474 | ...    | 209.6           | ...          | 2016.789  | 2.710           | 3.300            |
| This work              | 19.542  | 0.6104   | ...  | 100.36  | 207.15          | 32.25        | 2016.702  | 2.7160          | 3.3672           |

Note. — The second line for each entry contains the uncertainties. The correct value for the argument of periastron of Lippincott et al. (1983) is $\omega_A = 200.0^\circ$ (see also Henry et al. 1992), which reproduces the Thiele-Innes constants from her paper. Unfortunately, Martin et al. (1998) adopted the erroneous value of 100.0; and this biased their reanalysis of the Hipparcos data giving unrealistically low masses for the components (Section 1), as they were also surprised to find.

This is the argument of periastron for the primary. The secondary values from Söderhjelm (1999) and our own have been shifted by 180°, to facilitate the comparison.

Original epochs have been shifted by an integer number of periods to more closely match the reference time of periastron in this paper.

Value obtained by conversion of the linear semimajor axis given in the paper to angular measure, using the published parallax.

See comment at the end of Section 3.2 about a bias in this orbit. A 180° shift in $\omega$ and $\Omega$ would bring the latter closer to other results, but $\omega$ would still be discrepant.

(approximately the bandpass of the photographic observations of Lippincott et al. (1983) is larger, between 8 and 9 mag. The light contribution of the secondary at these wavelengths is therefore very small, so that for most practical purposes the measured semimajor axis of the photocentre motion from the photographic observations can be considered to be equal to the semimajor axis of the primary. A separate measure of the mass ratio $M_B/M_A$ may then be derived as $q_{\text{phot}} = a''_{\text{phot}}/(a''_{\text{phot}} - a''_{\text{phot}}) \approx 0.278 \pm 0.012$. This estimate is independent of the parallax, but is consistent with the value $q = 0.268 \pm 0.013$ listed in Table 5 that relies on $\pi_i$ through Kepler’s Third Law and other properties. The predicted magnitude differences for the space missions Hipparcos and Gaia are given in the lower panel of Figure 5. For Hipparcos the secondary is 7–8 mag fainter than the primary; for Gaia it is about a magnitude brighter than that.

Concerning the parallax, we note that our result from the reanalysis of the Hipparcos intermediate data is not very different from the values reported in both the original catalogue (ESA 1997) and the revision by van Leeuwen (2007). On the other hand, the parallax entry in the Gaia DR3 catalogue (Gaia Collaboration et al. 2022) is very different. We compare these values, along with others, in Table 8, which also lists proper motion determinations.

The Gaia DR3 parallax is more than 10 mas lower than ours, and lower also than all other sources shown in the table. It is very different as well from the value in the previous edition of the catalogue (Gaia DR2; Gaia Col-
The uncertainties for the proper motions from \( \text{Gaia} \) DR2 and DR3 have been increased following Brandt (2018, 2021). Early Third Data Release (EDR3) are identical to those in the \( \text{Gaia} \) DR2 catalogue. Tycho-2 catalogue, USNO-B1.0 catalogue, EOC-3 catalogue, PPMX catalogue.

Note. — The uncertainties for the proper motions from \( \text{Gaia} \) DR2 and DR3 have been increased following Brandt (2018, 2021). Note that the position, proper motions, and parallax from the \( \text{Gaia} \) Early Third Data Release (EDR3) are identical to those in the final DR3.

As a final note, we draw attention to the proper motion solution, which is a measure of the quality of the DR3 astrometric solution, is 2.892, much larger than typical values for well-behaved astrometric solutions (\( \text{RUWE} \leq 1.4 \); see Lindegren (2018)). The DR3 results are therefore suspect. Such a small value for the parallax (68.02±0.37 mas), together with our semimajor axis and period, would imply a primary mass of about 1.48 M\( \odot \), which is inconsistent with the spectral type of the star.

Fig. 2 is also helpful to understand the differences among the p.m. measurements in Table 8. Both editions of the \textit{Hipparcos} catalogue show a larger p.m. in declination compared to ours, because the primary was moving southward at the time, relative to the barycentre. The right ascension component is smaller than ours, because the primary was moving toward the west. During the \( \text{Gaia} \) observations, the net motion of the primary was toward the east, and indeed the DR3 value of \( \mu_\delta \) is larger than ours. On the other hand, the net motion in declination was probably very small (southward for the first half, then northward), explaining why the \( \text{Gaia} \) \( \mu_\delta \) value is similar to ours. Most other p.m. determinations in the table (Tycho-2, USNO-B1.0, EOC-3, PPMX), which we have set aside from the others, happen to rely on positional measurements that span decades, or up to a century in some cases, which tends to average out the orbital motion. This is likely why they more closely resemble our own estimates from the reanalysis of the \textit{Hipparcos} data, which properly removed the effect.

We believe the explanation has to do with where in the orbit those observations were obtained. This is shown by the shaded area in Fig. 2. As opposed to the situation with the \textit{Hipparcos} observations, which were gathered on a part of the orbit with little curvature, the DR3 measurements occurred precisely at the time when the photocentric path presents the most curvature — arguably the worst possible place for determining the five standard astrometric parameters if the orbital motion is not taken into account.\(^5\) Not surprisingly, the renormalised unit weight error (\( \text{RUWE} \)) for the \( \text{Gaia} \) entry, which is a measure of the quality of the DR3 astrometric solution, is 2.892, much larger than typical values for well-behaved astrometric solutions (\( \text{RUWE} \leq 1.4 \); see Lindegren (2018)). The DR3 results are therefore suspect. Such a small value for the parallax (68.02±0.37 mas), together with our semimajor axis and period, would imply a primary mass of about 1.48 M\( \odot \), which is inconsistent with the spectral type of the star.

As a final note, we draw attention to the proper motion determination by Brandt (2021) in Table 8, which is at least an order of magnitude more precise than any of the others. This value was derived from the positional difference between \textit{Hipparcos} and the \( \text{Gaia} \) Early Third

\(^5\) This bias could possibly be alleviated by the addition of acceleration terms (proper motion derivatives) in the \( \text{Gaia} \) solution, but GJ67 is not one of the objects in the DR3 catalog for which this was attempted.

Figure 5. Top: Predicted contrast between the primary and secondary of GJ 67AB compared with measurements from Table 4 (represented with triangles), in magnitude units. Predictions in standard photometric bands as labelled are based on solar-metallicity model isochrones from Chen et al. (2014), for ages of 1 Gyr (bottom) to 9 Gyr (top). Uncertainties in the predictions are indicated along the bottom. Bottom: Same as above, for the bandpasses of the space missions \textit{Hipparcos} (Hp) and \text{Gaia} (G).
measurements in Table 8 (bottom line) by just Hipparcos differ from the motion derived from our reanalysis of the agreement at the 0.7
0
Hipparcos Subtracting these values from the nominal in all orbital elements involved, and their correlations.

51
80 and 1
83, where the uncertainties account for the errors in all orbital elements involved, and their correlations. Subtracting these values from the nominal Hipparcos measurements in Table 8 (bottom line) by just 0.53 ± 0.80 and 1.37 ± 1.08 mas yr
−1
, indicating good agreement at the 0.7σ and 1.3σ significance levels.

6. CONCLUDING REMARKS

GJ 67 is among the closest three dozen or so G dwarfs in the sky, and as pointed out by [Henry et al. (1992), half of them are binaries. While the binary nature of GJ 67 has been known for nearly 50 yr, only partial orbital solutions have been reported since then that have not made use of all available measurements. In this paper we present our own spectroscopic monitoring of the object spanning more than 35 yr, and combine it with other velocities from the literature, and with all astrometric observations of which we are aware. The latter include the reconstructed photographic measurements by Lippincott et al. (1983) that led to its discovery as a binary, the few existing measures of the relative position, and the more recent Hipparos intermediate data. Our global fit to the observations leads to improved mass estimates for both components, particularly for the M dwarf secondary, and to what we expect to be a more accurate determination of the parallax for the system, accounting for orbital motion.

This work has provided evidence supporting the conclusion that the parallax from the Gaia DR3 catalogue may be seriously biased. While the individual Gaia measurements will not be available for reanalysis until future data releases or until the end of the mission, by then the coverage of the 19.5 yr orbit will be substantial, allowing for a much improved determination not only of the parallax, but of other orbital elements of the photocentric orbit as well. To complement those observations, it is hoped that observers will also continue monitoring the system with spatially resolved observations – challenging as they are – to better constrain the scale of the relative orbit, which is the most poorly determined of its properties.

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7. DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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