Orbit Determination and Astrophysical Study of the Binary System HU 481 (= HD 147442)

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ABSTRACT

I present a revised orbital solution for the binary WDS 16212+2259 = HU 481, composed of stars with *V* magnitudes 8.1 and 9.9, separated by 0.5 arcsec. The methodology employs the "three-dimensional grid search method" for orbital computation as originally outlined by Hartkopf, McAlister, & Franz (1989).

Conducting an astrophysical investigation, fundamental parameters for each stellar components of HU 481 are derived classifying the component as F6V and G9V stars. To achieve this, I utilize a tool constructed by the author. This tool was designed for the deblending of the entire observed multiband photometry, enabling the separation into individual fundamental and photometric parameters. The methodology is rooted in the application of PARSEC isochrones.

Key words: (stars:) binaries: general — binaries: visual - stars: fundamental parameters.

1. INTRODUCTION

This paper continues the investigation line of previous work published in Rica et al. (2017) and Rica and Zirm (2020).

The binary star WDS 16212+2259 = HU 481, also catalogued as HD 147442 and HIP 80117, consist of two stars with *V* magnitudes of 8.1 and 9.9, separated by approximately 0.5 arcsec. While Hartkopf and Mason (2010) previously calculated a grade 3 orbital solution, recent measures have revealed astrometric residuals, necessitating an improved orbital solution for this binary system.

This paper conducts a thorough orbital study, refining the existing orbital solution. The "three-dimensional grid search method," originally outlined by Hartkopf, McAlister, & Franz (1989), is employed for orbital computation.

In addition to the dynamical study, I undertook an astrophysical investigation utilizing combined multiband photometric data and trigonometric parallax information sourced from the literature. This approach enables me to extract individual photometric data and fundamental parameters for each component.

2. METHOD OF ORBITAL CALCULATION

The orbital computation employed in this study utilizes the three-dimensional grid search method as initially detailed by Hartkopf, McAlister, & Franz (1989) and subsequently refined following the modifications described by Mason, Douglass, & Hartkopf (1999). This methodology commences with three known elements (orbital period (P), epoch of periastron (T), and eccentricity (e)) to iteratively determine the geometric elements a (semimajor axis), i (inclination), Ω (ascending node) and ω (argument of periastron) through the method of least squares.

In practical terms, a space of potential values for P, T, and e must be defined. For each set of values, we compute a corresponding orbital solution, selecting the one with the smallest residuals. Additionally in cases where refinement is deemed necessary, a least squares approach is applied using the formula for differential corrections in rectangular coordinates (Heintz 1967a). Notably, this refinement method demonstrates efficacy even when dealing with a relatively short and linear observational arc.

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Formal errors (1σ uncertainty intervals) for the orbital elements are computed using the covariance matrix. The covariance matrix is a square matrix that contains the covariances between all pairs of orbital elements. The formal errors are calculated by taking the square root of the diagonal elements of the covariance matrix.

Prior to commencing any computations, the observed θ values must be corrected by the precession equinox effect, ensuring that all astrometric measurements are expressed for the 2000 equinox. However, not all the θ values require correction. Digital observational techniques (e.g., CCD, speckle, adaptive optics, lucky imaging) that utilized reference binaries to calibrate the orientation of CCD images are exempt from this correction owing to the use of ephemerides based on the 2000 equinox. On the other hand, θ values from digital astrometric points that employ slit masks to calibrate the orientation, must be corrected, because it uses the Earth's rotation. Moreover, θ values obtained from astrometric catalogues (e.g., *Hipparcos*, 2MASS, *Gaia*) do not require θ correction since they are referenced to the 2000 equinox or equivalent astrometric frame (that is ICRS).

We applied a data-weighting scheme to astrometric measures, following the guidelines outlined in Rica et al. (2012). This involved considering various criteria, including observational method, telescope aperture, observer experience, and the number of nights observed. Initially, for visual measures, we set θ weights four times larger than ρ weights, a practice proposed by Heintz (1978) and corroborated by Geoffrey & Worley (1992). Any measures with residuals exceeding 3σ within their respective groups, primarily determined by the observational technique, were assigned zero weight. Subsequently, non-zero weight measures underwent re-weighting based on the methodology described by Irwin et al. (1996).

2. PROCEDURE FOR DETERMINE FUNDAMENTAL PARAMETERS AND ASTROPHYSICAL PROPERTIES

We performed an astrophysical analysis, utilizing combined (that is, sum of the light for both stellar components) multiband photometric data, trigonometric parallax, and *V* differential magnitudes between the stellar components retrieved from the literature. My methodology included applying evolutionary isochrones to decompose the combined observed *UBVIJHK* photometry of the binary systems, predominantly sourced from the *Hipparcos*, Tycho-2, and 2MASS catalogs. This procedure led to the extraction of synthetic photometry and fundamental parameters for each individual component.

For our isochronal analysis, I utilize the CMD 3.3 evolutionary isochrones online tool[1], based on PARSEC release v1.2S + COLIBRI S_35 (Bressan et al. 2012, Chen et al. 2014, 2015, Tang et al. 2014, Marigo et al. 2017, Pastorelli et al. 2019). This tool facilitated the acquisition of the necessary isochrones for the investigation.

To do this task in this paper, I use a tool I built called Binary Deblending v5.0 which integrates *UBVIJHK* synthetic photometry from PARSEC isochrones, spanning a diverse range of ages and metallicities [Fe/H].

The "Binary Deblending" tool performs a search algorithm to find two distinct entries within each evolutionary isochrones, minimizing the χ^2 between the combined observational photometry and the PARSEC model's prediction. The output encompasses synthetic photometry in *UBVIJHK* bands, spectral types, and fundamental parameters (masses, effective temperature, surface gravity, luminosity, and radius) for each component.

The tool produces a comparative table that juxtaposes the combined observed photometry with the corresponding combined model photometry. Furthermore, it provides fundamental parameters for each component of the binary system.

I determined the line-of-sight reddening by utilizing the maps provided by Schlafly and Finkbeiner (2011). The derived values are scaled to the *Hipparcos* or *Gaia* distance using the formula presented by Anthony-Twarog and Twarog (1994). In addition, I employ the Stilim web tool (https://stilism.obspm.fr/), which generates 3D maps of the local InterStellar Matter (ISM). These maps are constructed based on measurements of starlight absorption by dust

[1] **CMD** is a service maintained at the Osservatorio Astronomico di Padova, composed by a set of routines that provide interpolated isochrones in a grid, together with derivatives such as luminosity functions, simulated star clusters, etc. The photometry can be produced for many different broad- and intermediate-band systems, including non-standard ones. Online tool: http://stev.oapd.inaf.it/cgi-bin/cmd

[1] https://stilism.obspm.fr/

(resulting in reddening effects) or gaseous species (revealed through absorption lines or bands). The current map originates from the inversion of reddening estimates towards 71,000 target stars.

I also undertook a kinematic study to approximate the stellar ages based on galactocentric velocity (Przybylski 1962) represented as (U, V, W). The Eggen diagrams (1969a, 1969b; see Figure 1 in both papers) were utilized. These diagrams offer valuable insights, applicable to stars of all types, assisting in discriminating between young and old stars.

In addition to the Eggen diagrams, I incorporated the kinematic age parameter introduced by Grenon (1987), designated as fG. Bartkevicius & Gudas (2002) establishing a correlation between fG and age, thus allowing us to distinguish between different age groups. Their statistical analysis suggests that stars with fG < 0.20 belong to the young-middle age group (with an age less than 3-4 Gyr) within the thin disk population. Stars with 0.20 < fG < 0.35 are associated with the old (with an age of 3-10 Gyr) thin disk population. Those with 0.35 < fG < 0.70 are linked to the thick disk population (age greater than 10 Gyr), while stars with fG > 0.70 belong to the halo population.

3. THE BINARY STAR WDS 16212+2259 = HU 481 = ADS 10017

The binary star HU 481 (= HD 147442 = HIP 80117) was discovered by Hussey at Lick Observatory (1902), utilizing a 0.9 telescope. It consists of two stars with *V* magnitudes of 8.1 and 9.9 separated approximately by 0.5 arcsec. Since its discovery, this binary system has been observed on 86 occasions covering about one revolution although less than half of a revolution it is covered by speckle astrometric measures. Hartkopf & Mason (2010) calculated the last orbital parameters, but the more recent astrometric measures start to show astrometric residuals. Therefore, this binary star needs an improved orbital solution.

3.1 Astronomical literature

HD 147442 is a star located at 66 pc (*Hipparcos*) poor in metallicity with a combined spectral type of F8 (Cannon & Pickering 1928-1924) and with an age similar to the Sun or younger. The *Hipparcos* catalogue lists a parallax of 15.11 ± 0.84 mas while *Gaia* DR3 lists an object with a higher parallax (18.84 ± 0.36 mas) and with a RUWE parameter of 8.75, indicating an issue with the single-star astrometric model. This high RUWE value is likely caused by the presence of the close secondary as pointed out by Belokurov et al. (2020).

The RUWE parameter in Gaia Catalog
The RUWE (Renormalized Unit Weight Error) is a measure of the quality of astrometric data for a source in the Gaia catalog. It is calculated as the ratio between the observed astrometric error and the expected astrometric error for a source of that magnitude and position. A RUWE value close to 1 indicates that the data fit well to a simple model of a star, while a value greater than 1 indicates that the data may be from a more complex object, such as a binary system, a variable star, or an extragalactic object.

To determine if one of these parallaxes are not realistic, I calculated the dynamical total mass utilizing the orbital period (*P*) and the semimajor axis (*a*) published by Hartkopf & Mason (2010). If we use the *Gaia* DR3 parallax, a dynamical total mass of 1.1 solar masses is obtained, which is not a realistic total mass. While using the *Hipparcos* parallax, the dynamical total mass is 2.0 solar masses, much in agreement with the expected mass. Therefore, in this work I will utilize the *Hipparcos* parallax.

Related with metallicity, Table 1 lists the values found in the literature:

Table 1. Metallicity data for HD 147442

[Fe/H]	Reference
-0.32	Marsakov & Shevelev (1995)
$-0.14^{+0.21}_{-0.14}$	Ammons et al. (2006)
-0.32	Holmberg et al. (2009)
-0.28	Casagrande et al. (2011)
-0.10	Gontcharov (2012)

Holmberg et al. (2009) determined a galactocentric velocity (*U*, *V*, *W*) of (-5, -20, -17) km s^{-1} which corresponds to a star within the young-medium (3-4 Gyr) stellar population in the thin Galactic disk, in agreement with other references.

Tokovinin et al. (2010) estimated a differential magnitude for the stellar components of 2.0 (for wavelengths of about 550 nm, that is,

Table 2.
Comparison of observed and synthetic phptometries for HU 481

Photometric band	Observed photometry	Source	Synthetic photometry	Difference
B	8.41 ± 0.05	*Hipparcos*	8.41	0.00
V	7.87 ± 0.04	*Hipparcos*	7.88	-0.01
I	7.27 ± 0.05	*Hipparcos*	7.26	0.01
J	6.84 ± 0.03	2MASS	6.84	0.00
H	6.58 ± 0.03	2MASS	6.60	-0.02
K	6.54 ± 0.02	2MASS	6.53	0.01
B - V	0.54 ± 0.03	*Hipparcos*	0.52	0.02
V - I	0.60 ± 0.02	*Hipparcos*	0.62	-0.02
V - K	1.33 ± 0.04		1.35	-0.02
J - H	0.26 ± 0.04	2MASS	0.24	0.02
H - K	0.04 ± 0.04	2MASS	0.07	-0.03
J - K	0.26 ± 0.04	2MASS	0.24	0.02

near the visible wavelength). Using all the visual measures from the WDS catalogue, I estimate a Δmag = 1.76 ± 0.31 mag. The *Hipparcos* Δmag converted to Δ*V* is used for the analysis (1.81 ± 0.16 mag.).

Using the *Hipparcos BVI* photometry, the 2MASS *JHK* photometry as well as magnitude difference (Δ*V*), I employ *Binary Deblending v5.0* which minimum χ^2 solution gives individual spectral types of F6V and G9V. The difference between the synthetic photometry and the unreddening and combined observed photometry are listed in **Table 2** while the fundamental parameters and others astrophysical data for each components are listed in **Table 3** for the first time.

Table 3.
Astrophysical data for the binary HU 481.

Data	A	B
***V*o**	8.08	9.86
(*B* - *V*)o	0.48	0.77
Mv	3.97	5.76
Mass [M_{sun}]	1.11	0.84
T_{eff} [ºK]	6380	5411
log *g*	4.33	4.59
log L/L_{sun}	0.28	-0.39
R/R_{sun}	1.13	0.73
SpT	F6V	G9V
Distance [pc]	66.2	
Age [Gyr]	2.8	

Literature reports only combined astrophysical data and no paper determined the astrophysical data for the stellar components. The effective temperature (T_{eff}) and spectral types obtained in this paper, are consistent with the literature, that reports a T_{eff} of 6100 K from Ammons et al. (2006), 6067 K from Holmberg et al. (2009), and 6131 K from Casagrande et al. (2011).

My study gives a minimum χ^2 solution for [Fe/H] = -0.16 and an age of 2.8 Gyr. Although the 68% confidence interval is from -0.29 to +0.05 for metallicity (in moderated agreement with the values listed in Table 1) and ≤ 4.8 Gyr for the age.

3.2 New Orbital solution

Hartkopf and Mason (2010) calculated a grade 3 orbital solution, but the more recent measures start to show astrometric residuals. Therefore, this binary star needs an improved orbital solution. Utilizing the three-dimensional grid search method orbital methodology, I compute a new orbital solution that was refined with a differential correction method using rectangular coordinates. The new orbital solution is very similar to the previous one, but the RMS residuals are reduced significantly. The orbital parameters, with the formal errors, for the new orbital solution is listed in **Table 4**. For comparison, the previous orbit is also listed.

Figures 1-3 show the orbit plot in addition to the θ and ρ evolution against time. The black solid thick ellipse is the new orbit, and the dashed and dotted ellipse is the previously calculated orbit in the literature. North is down and East is right. The filled black circle is the main stellar component at (0 , 0) coordinate. Astrometric measures are

Table 4. New orbital solution for HU 481

	This work			Hrt2010
P [yr]	122.49	±	0.89	119.500
To [yr]	1997.83	±	0.07	1997.950
e	0.569	±	0.003	0.567
a [arcsec]	0.466	±	0.004	0.464
i [deg]	154.4	±	1.2	146.8
ω [deg]	165.0	±	2.8	160.5
Ω_{2000} [deg]	178.0	±	2.8	172.6
RMS(ϑ) [deg]	0.99			2.34
RMS(ρ)[arcsec]	0.009			0.026
χ2 red [arcsec]	1.2			7.3
Σmass [M_{sun}]	1.96			2.03

represented by green "+" (micrometric measures), red square (the *Hipparcos* and Tycho-2 measures), large blue circle (speckle measures), small blue circle (photographic and CCD measures). Rejected measures are plotted with red "X".

I can see those micrometric distances (ρ) measured before the year 1940, seem to show a systematic residual of -0.08 arcsec.

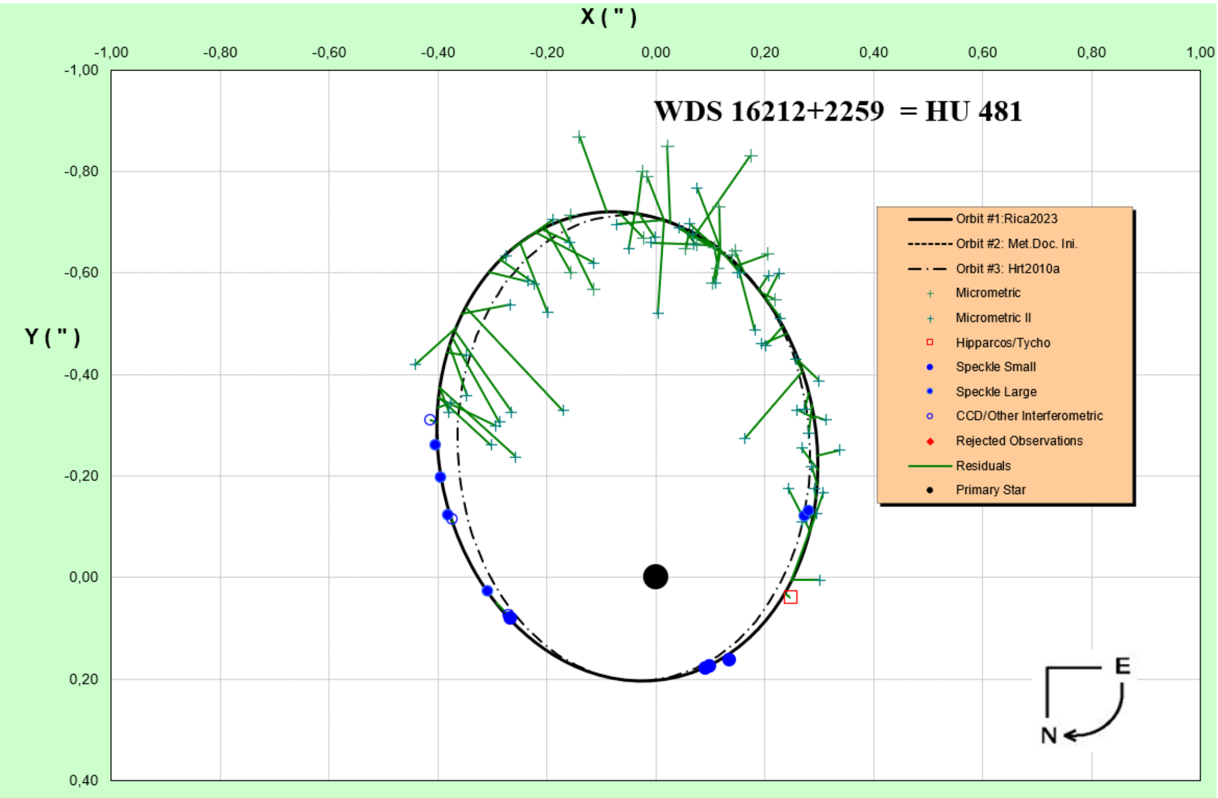

Figure 1, Orbit plot for HU 481.

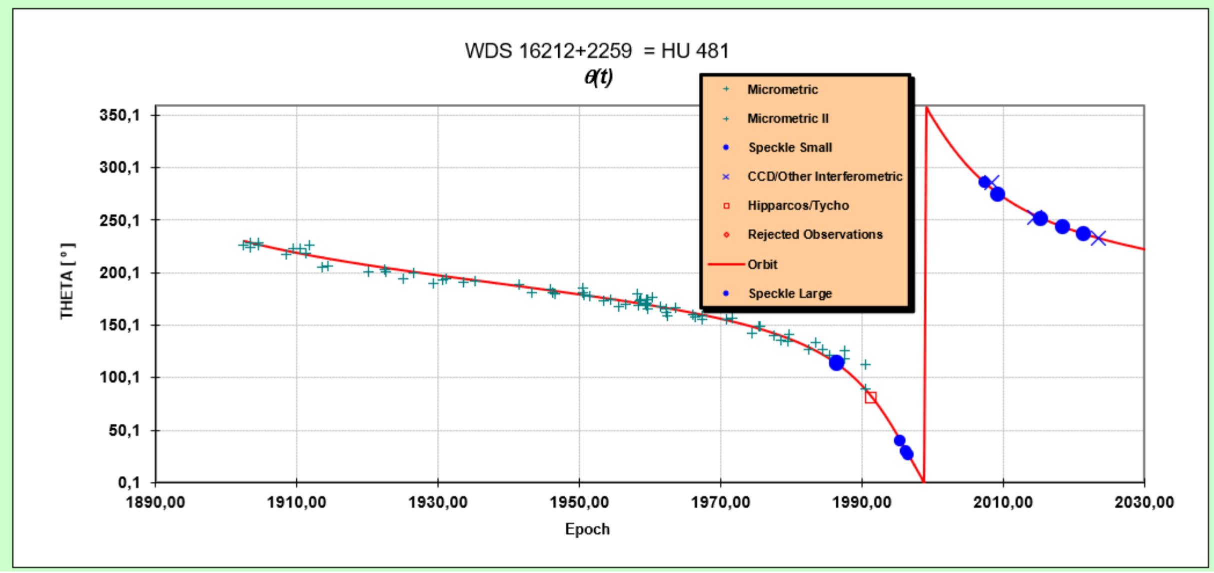

Figure 2. Position angles as a function of epoch for HU 481.

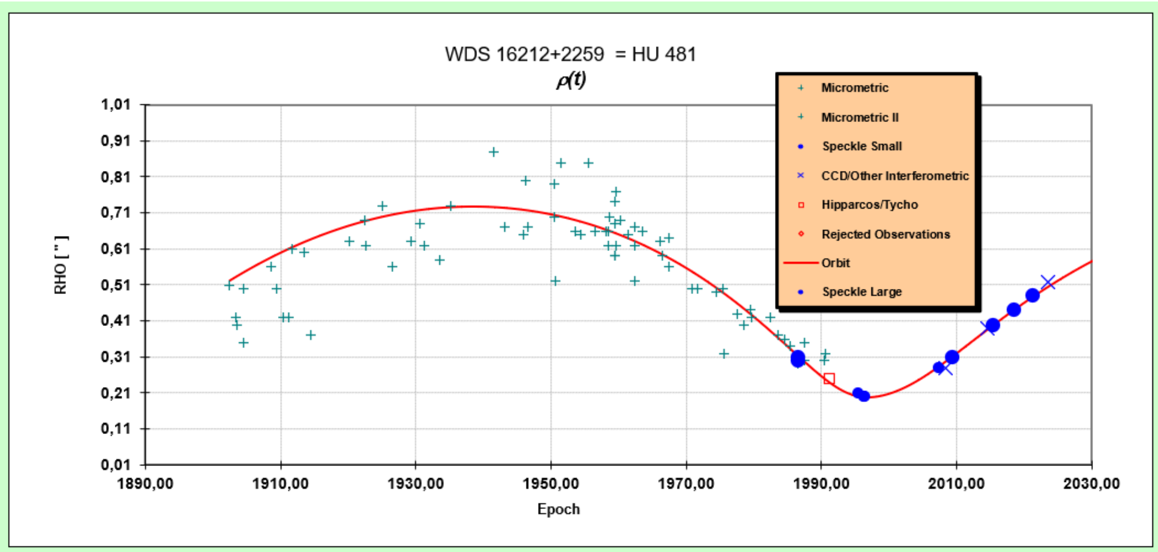

Figure 3. Angular distance as a function of epoch for HU 481.

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