Physical and Geometrical Parameters of CVBS. XII. FIN 350 (HIP 64838)*

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Abstract—A complete astrophysical and dynamical study of the close visual binary system (CVBS) Finsen 350 (A7V + F0V), is presented. Beginning with the entire observational spectral energy distribution (SED) and the magnitude difference between the subcomponents, Al-Wardat’s complex method for analyzing CVBS was applied as a reverse method of building the individual and entire synthetic SEDs of the system. This was combined with Docobo’s analytic method to calculate the new orbits. Although possible short (approximately 9 years) and long period (of about 18 years) orbits could be considered taking into account the similar results of the stellar masses obtained for each of them (3.07 and 3.41 M☉, respectively), we confirmed that the short solution is correct. In addition, other physical, geometrical and dynamical parameters of this system such as the effective temperatures, surface gravity accelerations, absolute magnitudes, radii, the dynamical parallax, etc., are reported. The Main Sequence phase of both components with age around 0.79 Gyr is approved.

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1. INTRODUCTION

Most of what look like single stars in the sky are, actually, binary or multiple systems, as revealed by HIPPARCOS mission [1, 2]. In general, stellar binary systems represent the key source of stellar parameters especially masses and distances. As for subgiant stars and the lower part of the Main Sequence, they practically define our understanding of stellar physical properties [3].

Except for eclipsing binary stars, there is no direct way to measure the physical and geometrical parameters of stellar binary systems, even with the aid of modern techniques of observation, such as speckle interferometry and adaptive optics. The situation is a bit complicated in the case of the close visual binary stars (CVBS), especially subgiants, which represent a small stellar category due to their short evolutionary phase [4].

This difficulty was overcome by applying Al-Wardat’s complex method for analyzing CVBS, which combines different observational results and analytical techniques such as speckle interferometry, spectrophotometry, atmospheric modelling, and dynamical analysis. This method yields an accurate determination of the complete set of physical and geometrical parameters which include effective temperatures, gravity accelerations, radii, masses, orbital parameters, absolute magnitudes, densities, spectral types, and luminosity classes of the components of the CVBS. First devised by [5, 6], the method was applied to several Main Sequence CVBS such as ADS 11061, COU 1289, COU 1291, HIP 11352, HIP 11253, HIP 70973, and HIP 72479 [5–9] as well as to the subgiant CVBS, HD 25811 [10], HD 375 [11] and HD 6009 [12]. It was also applied to the spectroscopic CVBS Gliese 762.1 (Paper X in this series).

As a consequence of the previous work, this paper (the XII in its series) presents the analysis of the CVBS FIN 350 ≡ HIP 64838, HD 115488, Tych 4958-1448-1. It was reported as a double star in the Bright Star Catalogue and in the Index Catalogue of Visual Double Stars [13]. Table 1 contains basic data of this system from SIMBAD, NASA/IPAC, HIPPARCOS and Tycho Catalogues (ESA) [14–17]. This star was observed for the first time in 1959.47 by Finsen who established it as a binary and measured a separation, ρ, of 0″.1, with a position angle, θ, of 27°. He also determined that both components were of the same brightness, 7m1, where he
used an eyepiece interferometer developed by himself at that time for his observations.

It is not clear yet whether the components of the system belong to the Main Sequence or to the subgiant phase. Malaroda [18] assigned the system to the F0V MK spectral type, while Cowley [19] assigned it to A7IV (or mild A7m). So, it seems to be an interesting system, and the parameters estimated in this work will enhance our knowledge of binary systems in general, and will consequently help to understand the formation and evolution mechanisms of such systems.

Previous orbits for this system were calculated by  
Baize [20]: \(P = 8.989\) yr, \(a = 86\) mas; Hartkopf et al. [21]: \(P = 9.046\) yr, \(a = 79.7\) mas; and more recently by Horch et al. [22]: \(P = 9.156\) yr, \(a = 80.8\) mas.

The latest speckle observations suggested a revision of the earlier solutions and, taking into account the small difference of magnitude between the components, we decided to calculate not only the short-period orbit (approximately 9 yr) but also the long-period orbit (of about 18 yr) twisting several measurements by 180° (see Fig. 1 and 2). Concretely, the orbit of Horch et al. [22] provides the following residuals in θ for the measurements of 2007.329, 2009.260, and 2009.446 (three observations in this last epoch), which are near the periastron passage: +5°7, +3°0, +3°0, +3°0, +5°8, and +5°4. Moreover, Horch himself provided us with the unpublished observations performed in 2013.4026. Docobo’s analytic method [23, 24] was used to calculate the new orbits.

The first column in Table 2 indicates the date of observation. Columns 2, 3, 4, and 5 give the values of the position angle and the separation with their corresponding standard errors. Columns 6 and 7 show the observed difference of magnitude between the components, while columns 8 and 9 include the wavelength and the standard error used in the observations. The size of the telescope utilized to perform the measurements is indicated in column 10. Finally, columns 11, 12, and 13 contain the reference of the publication where the measurements were announced, the technique used, and the weight assigned to the observation, respectively.

### Table 2. Observational data of Finsen 350

| Date   | θ, deg | σθ, deg | ρ, arcsec | σρ, arcsec | δm, mag | σδm, mag | Filter λ, nm | Δλ | Telescope size, m | Ref.*  | Method* | Weight* |
|-------|-------|---------|----------|------------|---------|----------|-------------|----|-----------------|--------|---------|---------|
| (1)   | (2)   | (3)     | (4)      | (5)        | (6)     | (7)      | (8)         | (9) | (10)            | (11)   | (12)    | (13)    |
| 1959.47 | 27.1  | 0.131   | 0.0      | -          | -       | -        | 0.7         | Fin1959b | J    | 5                |
| 1960.55 | 29.2  | 0.126   | 0.1      | -          | -       | -        | 0.7         | Fin1961  | J    | 5                |
| 1964.530 | 162.5 | 0.104   | 0.0      | -          | -       | -        | 0.7         | Fin1965a | J    | 5                |
| 1965.545 | 186.3 | 0.126   | 0.0      | -          | -       | -        | 0.7         | Fin1966a | J    | 5                |
| 1966.520 | 201.5 | -       | -        | -          | -       | -        | 0.7         | Fin1967a | J    | 0                |
| 1966.527 | 203.2 | 0.134   | 0.0      | -          | -       | -        | 0.7         | Fin1967a | J    | 5                |
Table 2. (Cont.)

| Date       | $\theta$, deg | $\sigma_{\theta}$, deg | $\rho$, arcsec | $\sigma_{\rho}$, arcsec | $\delta_{m}$, mag | $\sigma_{\delta_{m}}$ | Filter $\lambda$, nm | $\delta_{\lambda}$, nm | Telescope size, m | Ref.* | Method* | Weight* |
|------------|----------------|-------------------------|----------------|--------------------------|------------------|---------------------|---------------------|---------------------|------------------|---------|---------|---------|
| 1967.5447  | 208.4          | -0.140                  | -               | 0.0                      | -                | -                   | 0.7                  | Fin1969a           | J                | 5       |
| 1968.545   | 200.8          | -0.137                  | -               | 0.0                      | -                | -                   | 0.7                  | Fin1969a           | J                | 5       |
| 1976.2959  | 12.5           | 0.131                   | 0.001          | -                        | -                | -                   | 552                 | 20                  | 3.8              | McA1978b | Sc      | 15      |
| 1976.3697  | 13.9           | -0.114                  | -               | -                        | -                | -                   | 552                 | 20                  | 2.1              | McA1982b | Sc      | 10      |
| 1976.4570  | 15.0           | 0.129                   | 0.001          | -                        | -                | -                   | 552                 | 20                  | 3.8              | McA1978b | Sc      | 15      |
| 1977.0877  | 18.6           | 0.131                   | 0.001          | -                        | -                | -                   | 552                 | 20                  | 3.8              | McA1979a | Sc      | 15      |
| 1977.1751  | 15.9           | -0.120                  | -               | -                        | -                | -                   | 552                 | 20                  | 2.1              | McA1982b | Sc      | 10      |
| 1977.3280  | 19.9           | -0.119                  | -               | -                        | -                | -                   | 552                 | 20                  | 2.1              | McA1982b | Sc      | 10      |
| 1978.1499  | 26.9           | 0.118                   | 0.001          | -                        | -                | -                   | 470                 | -                   | 3.8              | McA1980b | Sc      | 15      |
| 1978.3109  | 32.3           | -0.112                  | -               | -                        | -                | -                   | 470                 | -                   | 2.1              | McA1984b | Sc      | 10      |
| 1979.3622  | 38.3           | -0.085                  | -               | -                        | -                | -                   | 470                 | -                   | 3.8              | McA1982d | Sc      | 15      |
| 1983.0701  | 350.3          | -0.080                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1983.4332  | 355.4          | -0.093                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1984.0532  | 1.1            | -0.125                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1984.3752  | 5.6            | -0.115                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1984.3807  | 5.3            | -0.116                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1984.3835  | 5.9            | -0.116                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1985.1805  | 13.0           | -0.117                  | -               | -                        | -                | -                   | 600                 | 14                  | 6.0              | Bag1987   | S       | 20      |
| 1985.2438  | 14.0           | 0.126                   | 0.013          | -                        | -                | -                   | 625                 | 75                  | 1.9              | Bnu1986   | S       | 10      |
| 1985.3389  | 10.5           | -0.129                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.0              | Hrt2000a  | Sc      | 15      |
| 1985.4840  | 13.8           | -0.126                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1987b | Sc      | 15      |
| 1986.4067  | 20.3           | -0.127                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1989   | Sc      | 15      |
| 1987.2642  | 26.2           | -0.117                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1989   | Sc      | 15      |
| 1987.3800  | 27.5           | -0.108                  | -               | -                        | -                | -                   | -                   | -                   | 6.0              | Bag1989a  | S       | 20      |
| 1987.3800  | 27.5           | -0.108                  | -               | -                        | -                | -                   | -                   | -                   | 6.0              | Bag1991b  | S       | 20      |
| 1988.1655  | 35.5           | 0.088                   | -               | -                        | -                | -                   | 549                 | 22                  | 3.6              | McA1993   | Sc      | 15      |
| 1988.2524  | 36.8           | 0.080                   | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | McA1989   | Sc      | 15      |
| 1990.2759  | 33.8           | 0.053                   | -               | -                        | -                | -                   | 467                 | 16                  | 3.8              | Hrt1992b  | Sc      | 15      |
| 1991.3186  | 331.0          | -0.059                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | Hrt1994   | Sc      | 15      |
| 1992.3098  | 352.8          | -0.085                  | -               | -                        | -                | -                   | 549                 | 22                  | 3.8              | Hrt1994   | Sc      | 15      |
| 1992.4572  | 353.9          | -0.093                  | -               | -                        | -                | -                   | 549                 | 22                  | 4.0              | Hrt1996a  | Sc      | 15      |
| 1993.0905  | 1.5            | -0.105                  | -               | -                        | -                | -                   | 549                 | 22                  | 4.0              | Hrt1996a  | Sc      | 15      |

ASTROPHYSICAL BULLETIN  Vol. 72 No. 1 2017
Table 2. (Cont.)

| Date     | \(\theta\), deg | \(\sigma\theta\), deg | \(\rho\), arcsec | \(\sigma\rho\), arcsec | \(\delta m\), mag | \(\sigma\delta m\), mag | Filter \(\lambda\), nm | \(\delta\lambda\), nm | Telescope size, m | Ref.   | Method | Weight |
|----------|------------------|------------------------|------------------|------------------------|-------------------|------------------------|---------------------|-------------------|-------------------|---------|---------|--------|
| 1993.1973 | 1.6              | 0.114                  | -                | -                      | 549               | 22                     | 3.8                 | Hrt1994          | Sc                | 15      |         |        |
| 1995.1495 | 17.8             | 0.120                  | -                | -                      | 549               | 22                     | 2.5                 | Hrt1997          | Sc                | 10      |         |        |
| 1995.3109 | 17.2             | 0.121                  | -                | -                      | 549               | 22                     | 2.5                 | Hrt1997          | Sc                | 10      |         |        |
| 1996.1840 | 24.2             | 0.116                  | -                | -                      | 549               | 22                     | 4.0                 | Hrt2000a         | Sc                | 15      |         |        |
| 2001.2708 | 350.3            | 0.8                    | 0.078            | 0.003                  | 550               | 14                     | 6.0                 | Bag2006b         | S                 | 20      |         |        |
| 2001.2708 | 350.2            | 0.6                    | 0.079            | 0.003                  | 600               | 30                     | 6.0                 | Bag2006b         | S                 | 20      |         |        |
| 2001.2708 | 350.3            | 0.7                    | 0.078            | 0.003                  | 750               | 35                     | 6.0                 | Bag2006b         | S                 | 20      |         |        |
| 2002.3224 | 1.8              | 0.100                  | -                | 0.62                   | 550               | 40                     | 3.5                 | Hor2008          | S                 | 15      |         |        |
| 2002.3224 | 3.1              | 0.106                  | -                | 0.48                   | 754               | 44                     | 3.5                 | Hor2008          | S                 | 15      |         |        |
| 2004.1960 | 11.8             | 0.141                  | 0.002            | -                      | 550               | 24                     | 1.55                | Hrt2008          | Su                | 10      |         |        |
| 2006.1915 | 32.1             | -                      | 0.092            | -                      | 550               | 24                     | 4.0                 | Msn2009          | Su                | 15      |         |        |
| 2007.0105 | 222.2            | 0.0716                 | -                | 0.99                   | 550               | 40                     | 3.5                 | Hor2011b         | S                 | 15      |         |        |
| 2007.3286 | 238.8            | 0.0456                 | -                | 0.58                   | 550               | 40                     | 3.5                 | Hor2011b         | S                 | 15      |         |        |
| 2007.3286 | -                | -                      | -                | 1.63                   | 698               | 40                     | 3.5                 | Hor2011b         | S                 | 0       |         |        |
| 2009.2601 | 305.5            | 0.0383                 | 0.0002           | 0.4                    | 551               | 22                     | 4.1                 | Tok2010          | S                 | 15      |         |        |
| 2009.4462 | 320.8            | 0.0318                 | -                | 0.46                   | 562               | 40                     | 3.5                 | Hor2011b         | S                 | 15      |         |        |
| 2009.4462 | -                | -                      | -                | 0.31                   | 692               | 40                     | 3.5                 | Hor2011b         | S                 | 0       |         |        |
| 2009.4462 | 322.6            | 3.2                    | 0.044            | 0.003                  | 562               | 40                     | 3.5                 | Hor2012a         | S                 | 15      |         |        |
| 2009.4462 | 322.2            | 3.2                    | 0.044            | 0.003                  | 692               | 40                     | 3.5                 | Hor2012a         | S                 | 15      |         |        |
| 2012.1843 | 8.0              | 0.1214                 | 0.0002           | 0.6                    | 543               | 22                     | 4.1                 | Tok2012b         | S                 | 15      |         |        |
| 2013.4026 | 16.5             | 0.1258                 | -                | 0.36                   | 692               | 40                     | 3.5                 | Hor**            | S                 | 15      |         |        |
| 2013.4026 | 16.7             | 0.1264                 | -                | 0.35                   | 880               | 50                     | 3.5                 | Hor**            | S                 | 15      |         |        |
| 2014.3005 | 23.0             | 0.1204                 | 0.0002           | 0.6                    | 534               | 22                     | 4.2                 | Tok2015c         | St                | 15      |         |        |

* The abbreviations and weights are given as in the Fourth Catalog of Interferometric Measurements of Binary Stars [25]
(http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/int4).

** Unpublished measurements.

The orbital elements and the masses determined in the present work together with their estimated standard errors are included in Table 3.

Table 4 lists the RMS residuals and mean arithmetic residuals of the position angles and separations for the orbits calculated in this work as well as for previously determined orbits. Table 5 presents the ephemerides for each orbit for the period between 2014 and 2020. Keeping in mind the ephemerides of both solutions, it will be possible to discriminate between the two calculated orbits in the very near future.

The similarity between the value of the HIPPARCOS parallax (12.28 ± 0.77 mas) with the dynamical parallaxes obtained for each orbit (short period: 13.12 ± 0.31 mas, and long period: 13.38 ± 0.46 mas), demonstrates the robustness of the first as well as its use as a referent value in this work.
Fig. 1. The apparent short period orbit ($P \sim 9$ yr). Stars represent the measurements made by Finsen; open circles, dots, and rectangles are the measurements carried out with $1–2$, $3–4$, and $6$-m telescope class respectively. Dates of several observations (rounded to the nearest integer) are included.

Fig. 2. The apparent long period orbit ($P \sim 18$ yr). Stars represent the measurements made by Finsen; open circles, dots, and rectangles are the measurements carried out with $1–2$, $3–4$, and $6$-m telescope class respectively. Dates of several observations (rounded to the nearest integer) are included.

We concluded that the true orbit is that of the short-period because the long-period orbit gives unacceptable residuals in the position angle regarding the observations of 1990.2759 and 2007.0105. Even if we give 0 weight to those observations, the rms in the position angle is worse in the long-period orbit (see Table 6).

3. ATMOSPHERIC MODELING

In order to estimate the physical and geometrical parameters of the individual components of the system, we follow Al-Wardat’s complex method for analyzing CVBS [8]. The method makes use of the measured magnitude difference $\Delta m$ between the subcomponents, their composite visual magnitude $m_V$ and the parallax of the system to calculate preliminary input parameters to model atmospheres of the individual components. Model atmospheres are then used to calculate their spectral energy distributions (SEDs), which then combined together (according to specific criteria) to build the entire synthetic SED of the system. The observational SED is used as a reference guide to the synthetic one in an iterated way of the aforementioned steps by changing the input parameters until the best fit between them achieved.

The magnitude difference between the two components $\Delta m = m_B - m_A = 0^m59$ was taken as the average value of all measurements under the filters 550/40, 551/22, 562/40, 543/22 and 534/22 (given in Table 2), which are the closest to the $V$-band filter.
Table 3. Calculated orbital elements and masses of the system with standard errors

| Parameters                       | Short period | Long period  |
|----------------------------------|--------------|--------------|
| Period $P$, yr                  | 9.130 ± 0.030 | 18.442 ± 0.200 |
| Periastron epoch $T_0$           | 2017.487 ± 0.050 | 2009.328 ± 0.900 |
| Eccentricity $e$                 | 0.622 ± 0.007 | 0.021 ± 0.007 |
| Semi-major axis $a$, arcsec      | 0.0795 ± 0.002 | 0.129 ± 0.002 |
| Inclination $i$, deg             | 57.0 ± 0.5    | 73.5 ± 0.5    |
| Position angle of nodes $\Omega$, deg | 18.8 ± 1.5 | 15.8 ± 1.0 |
| Argument of periastron $\omega$, deg | 170.8 ± 3.5 | 279.3 ± 18.0 |
| Mass sum* $\sum M_{A,B}, M_\odot$ | 3.255 ± 0.332 | 3.408 ± 0.311 |
| Mass sum** $\sum M_{A,B}, M_\odot$ | 3.173 ± 0.152 | 3.146 ± 0.149 |
| Mass sum*** $\sum M_{A,B}, M_\odot$ | 2.665 ± 0.125 | 2.637 ± 0.122 |

* Using HIPPARCOS parallax: 12.28 mas.
** Using dynamical parallaxes: 12.39 ± 0.31 mas (short period) and 12.61 ± 0.36 mas (long period), and the calibration for main sequence stars.
*** Using dynamical parallaxes: 13.13 ± 0.43 mas (short period) and 13.38 ± 0.46 mas (long period), and the calibration for subgiants given in [26].

Table 4. RMS and mean arithmetic residuals for the new and old orbits

| Epoch | Short period | Long period |
|-------|--------------|-------------|
| $\Delta \theta$ | $\Delta \rho$ | $\Delta \theta$ | $\Delta \rho$ | Source |
| 2016.0 | 42.6 | 0.070 | 35.4 | 0.087 |
| 2017.0 | 110.6 | 0.024 | 54.1 | 0.057 |
| 2018.0 | 259.6 | 0.027 | 102.3 | 0.037 |
| 2019.0 | 338.9 | 0.059 | 154.2 | 0.054 |
| 2020.0 | 357.1 | 0.095 | 174.8 | 0.084 |

This magnitude difference, along with the composite photometry of the system $m_V = 6^m358$ (Table 1), was used as an input to the equations:

$$m_A = m_V + 2.5 \log (1 + 10^{-0.4 \Delta m}),$$

$$m_B = m_A + \Delta m,$$

to calculate the apparent magnitudes of the individual components as: $m_A = 6^m87$ and $m_B = 7^m42$.

These individual apparent magnitudes, along with the corresponding Main Sequence relations and standard values [14, 27]:

$$M_V = m_V + 5 - 5 \log d - A_V,$$

$$\log (R/R_\odot) = 0.5 \log (L/L_\odot) - 2 \log (T/T_\odot),$$

$$\log g = \log (M/M_\odot) - 2 \log (R/R_\odot) + 4.43$$

were used to calculate the preliminary input parameters (effective temperatures and surface gravity accelerations) needed to build model atmospheres for the individual components. We used bolometric corrections of [14] as well as $T_\odot = 5777$ K and extinction $A_V$ given in Table I by NASA/IPAC.
### Table 6. Residuals of the orbits

| Date   | Long period | Short period | Date   | Long period | Short period |
|--------|-------------|--------------|--------|-------------|--------------|
|        | $\Delta \theta$, $\Delta \rho$, deg | $\Delta \theta$, $\Delta \rho$, arcsec |        | $\Delta \theta$, $\Delta \rho$, deg | $\Delta \theta$, $\Delta \rho$, arcsec |
| 1959.47 | 2.5 0.015 4.4 0.011 | 1987.3800 | 2.9 -0.006 0.7 -0.003 |
| 1960.55 | -4.8 0.036 -3.2 0.030 | 1988.1655 | 4.2 -0.007 0.3 -0.000 |
| 1964.530 | -10.4 0.025 -4.2 0.032 | 1988.2524 | 4.6 -0.012 0.4 -0.005 |
| 1965.545 | 2.5 0.019 5.6 0.022 | 1990.2759 | -61.2 0.017 -0.8 0.023 |
| 1966.520 | 11.1 -0.124 12.8 -0.122 | 1991.3186 | -3.8 0.007 2.8 0.011 |
| 1966.527 | 12.7 0.010 14.4 0.012 | 1992.3098 | -3.2 0.002 -0.5 -0.001 |
| 1967.5447 | 12.2 0.011 12.8 0.012 | 1992.4572 | -4.0 0.005 -1.4 0.002 |
| 1968.545 | -1.2 0.016 -1.5 0.016 | 1993.0905 | -2.7 0.000 -0.6 -0.003 |
| 1976.2959 | -2.4 0.003 -0.6 0.004 | 1993.1973 | -3.4 0.007 -1.5 0.004 |
| 1976.3697 | -1.5 -0.014 0.3 -0.014 | 1995.1495 | 0.6 -0.008 0.9 -0.008 |
| 1976.4570 | -0.8 0.000 0.8 0.001 | 1995.3109 | -0.9 -0.007 -0.8 -0.006 |
| 1977.0877 | -0.8 0.005 0.3 0.004 | 1996.1840 | 0.8 -0.003 0.1 -0.001 |
| 1977.1751 | -4.0 -0.006 -2.9 -0.006 | 2001.2708 | -0.3 0.003 -0.4 -0.002 |
| 1977.3280 | -0.9 -0.005 0.0 -0.006 | 2001.2708 | -0.4 0.004 -0.5 -0.001 |
| 1978.1499 | 0.6 0.007 0.9 0.005 | 2001.2708 | -0.3 0.003 -0.4 -0.002 |
| 1978.3109 | 4.8 0.004 4.9 0.003 | 2002.3224 | -1.0 -0.004 -1.2 -0.010 |
| 1979.3622 | -0.4 0.006 -2.1 0.009 | 2002.3224 | 0.3 0.002 0.1 -0.004 |
| 1983.0701 | -3.9 -0.002 -1.4 -0.002 | 2004.1960 | -3.1 0.012 -4.6 0.013 |
| 1983.4332 | -3.2 0.000 -1.3 -0.001 | 2006.1915 | 4.7 -0.014 -0.1 -0.004 |
| 1984.0532 | -3.2 0.017 -1.9 0.015 | 2007.0105 | 6.2 -0.011 -3.8 0.007 |
| 1984.3752 | -1.0 0.000 -0.1 -0.001 | 2007.3286 | 18.0 -0.027 2.0 -0.003 |
| 1984.3807 | -1.4 0.001 -0.4 0.000 | 2009.2601 | -6.4 -0.001 -2.0 0.003 |
| 1984.3835 | -0.8 0.001 0.2 0.000 | 2009.4462 | -1.1 -0.012 -0.3 -0.010 |
| 1985.1805 | 1.3 -0.009 1.5 0.009 | 2009.4462 | 0.7 0.001 1.5 0.002 |
| 1985.2438 | 1.9 -0.001 2.1 0.000 | 2009.4462 | 0.3 0.001 1.1 0.002 |
| 1985.3389 | -2.1 0.001 -2.0 0.002 | 2012.1843 | -0.9 0.003 -0.8 -0.001 |
| 1985.4840 | 0.4 -0.002 0.3 -0.002 | 2013.4026 | 0.4 -0.003 -0.4 -0.002 |
| 1986.4067 | 1.8 0.000 0.8 0.001 | 2013.4026 | 0.6 -0.002 -0.2 -0.001 |
| 1987.2642 | 2.4 0.001 0.4 0.004 | 2014.3005 | 1.7 -0.003 -0.0 0.001 |
| 1987.3800 | 2.9 -0.006 0.7 -0.003 |
Table 7. Comparison between the observational and synthetic magnitudes of the entire system

|  | Obs. | Synth. (this work) |
|---|---|---|
| $V_J$ | 6.36 | 6.36 |
| $B_T$ | 6.66 | 6.68 |
| $V_T$ | 6.38 | 6.40 |
| $(B-V)_J$ | 0.26 | 0.252 |
| $\Delta m$ | 0.543 | 0.548 |
| $b-y$ | 0.164* | 0.16 |

* Danziger and Faber [30].

Hence, the calculated parameters were used as input parameters to construction model atmospheres for each component using grids of Kurucz’s 1994 blanketed models (ATLAS9) [28]. Here, we used solar-abundance line-blanketed model atmospheres to build the spectral energy distribution for each component.

The total energy flux received from the binary star is calculated depending on the net luminosity of the components, A and B, located at a distance, $d$, from the Earth. This is represented by the following equation [5]:

$$F_\lambda d^2 = H_\lambda^A R_\lambda^A + H_\lambda^B R_\lambda^B$$

where $H_\lambda^A$ and $H_\lambda^B$ are the fluxes from a unit surface of the corresponding component and $F_\lambda$ represents the total SED of the system.

Now, the goal is to achieve the best fit between the computed total SED with the observed one. So, in order to achieve that fit, dozens of different sets of parameters were tested by different ways; the first way is the direct correspondence as can be seen in Fig. 3, which includes the maximum values of the absolute flux, the shape of the continuum, and the profiles of the absorption lines. The second way is by comparing synthetic magnitudes and color indices with the observational ones (see Table 7).

It is worthwhile to mention here that two of the input parameters have the same effect on the maximum values of the absolute flux, these are the radii of the components and the parallax of the system according to Equ. (6). Hence, the radii of both components were set subject to change according to the parallaxes of different sources. Table 8 gives these radii using the following atmospheric parameters:

$$T_\text{eff}^A = 7820 \pm 75 \text{ K}, \quad T_\text{eff}^B = 7250 \pm 75 \text{ K},$$

$$\log g_A = 4.10 \pm 0.40, \quad \log g_B = 4.25 \pm 0.40.$$
Fig. 3. Best fit between the entire observational SED of the system taken from [29] and the entire synthetic one of the two components built in this work. The figure also shows the SEDs of the individual components built using the parameters given at the end of Section 3.

Table 8. Estimated radii and luminosities of the individual components according to different parallaxes

| Source of Parallax          | $\pi$, mas | $R_a \pm 0.07$ | $R_b \pm 0.07$ | $L_a/L_\odot$ | $L_b/L_\odot$ |
|-----------------------------|------------|---------------|---------------|---------------|---------------|
| HIPPARCOS (new) [17]        | 12.28      | 1.92          | 1.71          | 12.38         | 7.25          |
| Dynamical parallax          |            |               |               |               |               |
| (short period, MS)          | 12.39      | 1.88          | 1.67          | 11.87         | 6.92          |
| (long period, MS)           | 12.61      | 1.86          | 1.65          | 11.62         | 6.75          |
| Dynamical parallax          |            |               |               |               |               |
| (short period, Subgiant)    | 13.13      | 1.79          | 1.60          | 10.76         | 6.35          |
| (long period, Subgiant)     | 13.38      | 1.76          | 1.57          | 10.40         | 6.11          |
| HIPPARCOS (old)             | 13.45      | 1.75          | 1.56          | 10.28         | 6.04          |

$\Sigma M = 2.869 M_\odot \pm 0.684$, $M_A = 1.616 M_\odot \pm 0.422$ and $M_B = 1.253 M_\odot \pm 0.345$ using $\Delta m = 0.010 \pm 0.15$ and $\pi = 12.92 \pm 0.95$ mas.

The estimated mass sum using atmospheric analysis, $\Sigma M = 3.30 M_\odot$, $M_A = 1.75 M_\odot$ and $M_B = 1.55 M_\odot$, (Table 9) supports that of the short period orbit solution as 3.255 $M_\odot$.

The comparison between the observational and synthetic magnitudes of the entire system (Table 7) gives a good indication about the reliability of Al-Wardat’s complex method in analyzing CVBS.

Figure 4 gives the positions of the two components on the evolutionary tracks and isochrones for low- and intermediate-mass stars of [31]; the error bars in the figure represent the effect of the parallax and radii uncertainty.

Depending on the estimated parameters of the system’s components and their positions on the evolutionary tracks with age around 0.79 Gyr (Fig. 4), fragmentation is the most likely process for the formation of such system. Bonnell [36] concluded that fragmentation of rotating disk around an incipient central protostar is possible, as long as there is continuing infall, and Zinnecker and Mathieu [37] pointed out that hierarchical fragmentation during rotational collapse has been invoked to produce binaries and multiple systems.

5. CONCLUSIONS

Al-Wardat’s complex method along with Do- cobo’s analytical method for orbit calculation were
used to analyze the speckle interferometric close visual binary star FIN 350 (WDS 13175-0041, HIP 64838, HD 115488). The physical and geometrical parameters of the system’s components were estimated depending on the orbital solution of the system and the best fit between the entire observational SED and the synthetic ones built using model atmospheres.

The dynamical parallax ($\pi = 12.39 \pm 0.31$ mas, which lies between the old and new HIPPARCOS measurements) gives the best coincidence between Al-Wardat’s complex analysis and Docobo’s analytical solution for this system, and it was adopted as the parallax of the system.

New orbits (short and long-period) of the system were calculated. The 9.130 yr short-period improves the earlier orbits while the 18.442 yr long-period solution was calculated for the first time. Nevertheless,
in this work it was demonstrated that the short-period is the orbit that better fits the observations.

The synthetic magnitudes and colors of the entire system and individual components were computed in different photometric systems as given in Table 10. In addition to their importance as parameters, these synthetic magnitudes and colors show the accuracy of the method.

The spectral types and luminosity classes of the components of the system were concluded as A7V for the component A and F0V for the component B, which assured the Main Sequence phase of both components.

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REFERENCES

1. I. I. Balega, Y. Y. Balega, K.-H. Hofmann, et al., Astron. and Astrophys. 385, 87 (2002).
2. N. I. Shatskii and A. A. Tokovinin, Astronomy Letters 24, 673 (1998).
3. J. A. Docobo, V. S. Tamazian, Y. Y. Balega, et al., Astron. and Astrophys. 366, 868 (2001).
4. M. Salaris and S. Cassisi, Evolution of Stars and Stellar Populations (Wiley, Chichester, 2005).
5. M. A. Al-Wardat, Bull. Spec. Astrophys. Obs. 53, 51 (2002).
6. M. A. Al-Wardat, Astronomische Nachrichten 328, 63 (2007).
7. M. A. Al-Wardat, Astronomische Nachrichten 330, 385 (2009).
8. M. A. Al-Wardat, Publ. Astron. Soc. Australia 29, 523 (2012).
9. M. A. Al-Wardat and H. Widyan, Astrophysical Bulletin 64, 365 (2009).
10. M. A. Al-Wardat, H. S. Widyan, and A. Al-thyabat, Publ. Astron. Soc. Australia 31, e005 (2014).
11. M. A. Al-Wardat, Y. Y. Balega, V. V. Leushin, et al., Astrophysical Bulletin 69, 58 (2014).
12. M. A. Al-Wardat, Astrophysical Bulletin 69, 454 (2014).
13. H. M. Jeffers, W. H. van den Bos, and F. M. Greeby, Index Catalogue of Visual Double Stars, 1961.0, Vol. 21 (Lick Observatory, Mount Hamilton, 1963).
14. D. F. Gray, The Observation and Analysis of Stellar Photospheres, 3rd ed. (Cambridge Univ. Press, Cambridge, 2005).
15. M. A. C. Perryman, L. Lindegren, J. Kovalevsky and et al., Astron. and Astrophys. 323, L49 (1997).
16. E. Høeg, C. Fabricius, V. V. Makarov, et al., Astron. and Astrophys. 355, L27 (2000).
17. F. van Leeuwen, Astron. and Astrophys. 474, 653 (2007).
18. S. Malaroda, Astron. J. 80, 637 (1975).
19. A. P. Cowley, Publ. Astron. Soc. Pacific 88, 95 (1976).
20. P. Baize, Astron. and Astrophys. Suppl. 74, 507 (1988).
21. W. I. Hartkopf, B. D. Mason, and H. A. McAlister, Astron. J. 111, 370 (1996).
22. E. P. Horch, W. F. van Altena, S. B. Howell, et al., Astron. J. 141, 180 (2011).
23. J. A. Docobo, Celestial Mechanics 36, 143 (1985).
24. J. A. Docobo, in Proc. Workshop on Orbital Couples: Pas de Deux in the Solar System and the Milky Way, Obs. Paris, 2011, Ed. by F. Arenou and D. Hestroffer (2012), pp. 119–123.
25. W. I. Hartkopf, H. A. McAlister, and B. D. Mason, Astron. J. 122, 3480 (2001).
26. J. Docobo and M. Andrade, Monthly Notices Royal Astron. Soc. 428, 321 (2013).
27. K. R. Lang, Astrophysical Data I. Planets and Stars. (Springer-Verlag, Berlin, Heidelberg, New York, 1992).
28. R. Kurucz CD-ROM No. 19 (Smithsonian Astrophys. Obs., Cambridge, MA, 1994).
29. M. A. Al-Wardat, Bull. Spec. Astrophys. Obs. 53, 58 (2002).
30. I. J. Danziger and S. M. Faber, Astron. and Astrophys. 18, 428 (1972).
31. L. Girardi, A. Bressan, G. Bertelli, and C. Chiosi, Astron. and Astrophys. Suppl. 141, 371 (2000).
32. M. P. Fitzgerald, Astron. and Astrophys. 4, 234 (1970).
33. J. M. Apellaniz, Astron. J. 131, 1184 (2006).
34. J. Maiz-Apellániz, ASP Conf. Ser. 364, 227 (2007).
35. C. Martin and F. Mignard, Astron. and Astrophys. 330, 585 (1998).
36. I. A. Bonnell, Monthly Notices Royal Astron. Soc. 269, 837 (1994).
37. H. Zinnecker and R. Mathieu, IAU Symp., 200 (2001).