THE THREE-BODY SYSTEM δ CIRCINII

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ABSTRACT

Delta Cir is known as an O7.5 III eclipsing and spectroscopic binary with an eccentric orbit. Penny et al. discovered the presence of a third component in the IUE spectra. The eclipsing binary and the third body revolve around a common center of gravity with a period of 1644 days in an eccentric orbit with a semimajor axis of 10 AU. We demonstrate the presence of apsidal-line rotation with a period of ≈141 yr, which is considerably longer than its theoretically predicted value, based on the published radii of the binary components derived from the Hipparcos Hα light curve. However, our new solution of the same light curve resulted in smaller radii and better agreement between the observed and predicted period of the apsidal-line advance. There are indications that the third body is a binary. The object was resolved by VLTI using the PIONIER combiner; in 2012 June, the separation was 3.78 mas with magnitude difference in the H region 1σ=75. This result means that (assuming a distance of 770 pc) the inclination of the long orbit is 87°7.7.

Key words: binaries: general – stars: early-type – stars: individual (Delta Circini)

1. INTRODUCTION

There are not many known eclipsing binaries with such an early spectral type as δ Cir (HD 135240, HR 5664, HIP 74778). According to Walborn (1972), the integrated type is O7.5 III(f); however, see our discussion later in this paper. The period is 390 with a brightness of V = 5°05 − 5°20. The orbit is eccentric, and so rotation of the apside line is to be expected. Knowledge of the apse period is important, since there is only one other galactic binary of earlier spectral type with a known apsidal-line rotation period—HD 93205 (Morrell et al. 2001), and others of similar spectral types, such as δ Cir, VI007 Sco (Sana et al. 2001; Mayer et al. 2008), and HD 165052 (Ferrero et al. 2013).

The first three radial velocities (RVs hereafter) of δ Cir were previously obtained at the southern station of the Lick Observatory in 1915 (Campbell 1928). Additional RVs were secured by Feast et al. (1957); Buscombe & Kennedy (1965); Buscombe & Kennedy (1969), and Conti et al. (1977). RVs and orbits for δ Cir were published by Thackeray & Emerson (1969, TE), Stickland et al. (1993, ST93), and Penny et al. (2001, Pe01). The results of these studies were similar; they all found a small eccentricity of the orbit (≈0.06) and semiamplitude K1 ≈ 150 km s−1.

According to Pe01, the signature of a third body is present in the IUE spectra of δ Cir. Here, we analyze the spectra from the ESO archive. The third-body spectrum is present in these spectra as well. The mutual orbit of the eclipsing binary and the third body can be clearly observed.

We describe the spectroscopic data we used in Section 2, and how the RVs were measured and exploited for the orbital solutions in Section 3. We discuss the probable elements of the third body in Section 4, disentangle the spectra in Section 5, analyze the interferometric data in Section 6, present the results of the light curve solution in Section 7, and discuss the final results Section 8.

2. THE SPECTROSCOPIC DATA

The spectra in the ESO archive consist of two UVES spectra from 2000–2001, 29 FEROS spectra from 2007 to 2009, and 95 HARPS spectra from 2009 to 2012.4 We downloaded all of the HARPS and most of the FEROS spectra as pipeline products. We also compiled all available RV measurements from the astronomical literature5 and, whenever necessary, calculated HJDs for them. A list of all available RVs can be found in Table 1. Note that throughout this paper, we use the abbreviation RJD = HJD−2400000.0.

3. ANALYSIS OF RADIAL VELOCITIES AND ORBITAL SOLUTIONS

First, we inspected the existing photographic RVs of the primary component. Several published photographic secondary velocities are probably rather uncertain. We also used the IUE RVs from Pe01. There are 41 IUE spectra taken over the course of 17 yr. A large part of them, 29, was obtained over 10 days in 1992 September. ST93 used only the spectra from this short interval, and their solution of the primary RV curve has an rms = 2.3 km s−1. Pe01 used all IUE spectra together with the Hα RVs (they obtained 18 CAT/CES spectra at the ESO La Silla Observatory and three spectra at the Mount Stromlo

4 UVES, FEROS, and HARPS are echelle spectrographs. UVES is used with VLT at Paranal, and FEROS is used (Kaufer & Pasquini 1998) with the 2.2 m ESO/MPI telescope at the ESO La Silla Observatory and provides spectra in the region from 3625 to 9125 Å with a resolving power of 48,000. HARPS is a spectrograph connected to the 3.6 m ESO telescope, also at La Silla. Its spectral range is from 3781 to 6911 Å and the resolving power is 115,000.

5 We have two remarks. (1) While inspecting local RV curves for the 3.9 day orbital period, we noted that two RVs derived by Buscombe & Kennedy (1965) on RJD 37043.2 and 37781.1 deviate very strongly from the RV curve. There is probably a date error: increasing both RJD by one day to 37044.2 and 37782.1 brings both RVs into agreement with the RV curve. (2) In the original paper, Feast et al. (1957) give RV = −84 km s−1 for RJD 35252.4, while Thackeray & Emerson (1969) tabulate −88 km s−1 without any explanation. We adopted Feast et al.’s original value.
Observatory) and got rms = 8.2 km s
\(^{-1}\). They found a third component in the IUE spectra. We will show that the radial velocity of this third body varies; the rms values cited above already indicate that the position of the third line must vary naturally due to the third-body motion around a common center of gravity with the 3.9 day binary. Such an explanation for the unexpectedly large rms has already been put forward by TE. ST93 also noted that their systemic velocity differs from that derived by TE and explained the difference as being due to the presence of a third body. Pe01 obtained different systemic velocities for the IUE and Hα spectra. For the primary RVs, the difference amounted to 19.6 km s
\(^{-1}\). Pe01 suggested that this difference might be due to the fact that the corresponding lines were formed in different layers in an expanding stellar atmosphere. However, we note that their Hα and IUE spectra were obtained at different times, and so in view of the results from the ESO spectra, the true reason for the difference might well be the orbital motion in the three-body system. In the Pe01 solution, the difference, 19.6 km s
\(^{-1}\), was added to the Hα velocities, and so we subtracted this value to use the originally measured RVs.

The ESO FEROS and HARPS spectra were always taken during rather short time intervals every year from 2007 to 2012. The contribution of the third body to the line spectrum is obviously also present in the ESO spectra; this contribution is needed to fill the observed He i line profiles. In this study, the FEROS and HARPS spectra were smoothed to a resolution of 0.06 Å and rectified using the program SPEFO (Horn et al. 1996, Škoda 1996). We also measured their RVs using a fit with three Gaussians, and—in the second step—we applied spectral disentangling (see Section 5).

In the He i lines 4541 and 5411 Å no traces of the secondary lines are present. Also, no contribution from the third body should be there since this object is—according to Pe01—cooler than the secondary. Therefore, we measured the primary RVs in these lines (in He i 4686 Å there is a weak contribution from the secondary). The secondary RVs were measured in the line He i 5876 Å, because the separation of the secondary from the primary lines at quadratures is best here. The secondary velocities were measured only in cases where their separation enabled a reliable Gaussian fit, i.e., close to quadratures.

The resulting RVs are listed in Table 2. In the first 13 HARPS spectra, a strong fringing was identified by Poretti et al. (2013). However, we succeeded in finding the period and amplitude of the fringes and removing them from the spectra.

We derived various orbital solutions from the measured RVs using the program FOTEL (Hadrava 2004a). When a joint solution for all primary RVs from the ESO spectra of δ Cir was derived, the result was quite disappointing: large deviations were present with rms 21 km s
\(^{-1}\). However, when we split the available RVs into subsets covering short time intervals and assigned individual systemic velocities Vγ to each of them (which is easy to do with FOTEL), we obtained a solution with a much lower rms. For instance, quite different Vγ velocities were obtained for the FEROS spectra from 2007 and from 2008, and for the HARPS spectra from 2010 and 2011.

We therefore only selected series of spectra that cover short time intervals, and we then derived individual Vγ velocities for them. Our selection and the results are listed in Table 3 and shown in Figure 1. The motion in the mutual orbit is clearly visible. Its period depends mostly on the ESO data, and it must be close to 4.5 yr with a semiamplitude of ≈24 km s
\(^{-1}\). These values fit the older data too, and both orbits, with periods of 3.9 days as well as 4.5 yr, can be solved. However, there is also another way to use the RVs. The program FOTEL allows us to solve both orbits in a hierarchic system simultaneously, with the advantage that all RVs, not only those in the time-limited groups, can be used. The solution including all old and new RVs is shown in Table 4. The RVs were weighted by weights inversely

| Spg. No. | RJD Range       | No. of RVs | Observatory/Instrument | Source                  |
|---------|----------------|------------|-------------------------|-------------------------|
| 1       | 20682.65-20740.49 | 3/0        | Lick 1-prism            | Campbell (1928)         |
| 2       | 34522.37-35284.38 | 3/0        | Radcliffe               | Feast et al. (1957)     |
| 3       | 36014.00-37781.10 | 3/0        | MtStromlo               | Buscombe & Kennedy (1965) |
| 4       | 38243.93-38628.87 | 4/0        | MtStromlo coude         | Buscombe & Kennedy (1969) |
| 2       | 39363.20-39906.62 | 24/5       | Radcliffe               | Thackeray & Emerson (1969) |
| 3       | 39703.87-39704.86 | 2/0        | MtStromlo               | Buscombe & Kennedy (1969) |
| 5       | 42115.81         | 1/0        | Cerro Tollolo           | Conti et al. (1977)     |
| 6       | 43756.92-49664.99 | 41/41      | IUE                     | Penny et al. (2001)     |
| 7       | 49867.54-49874.79 | 18/14      | ESO coude feed          | Penny et al. (2001)     |
| 8       | 50152.14-50155.08 | 3/3        | MtStromlo CCD           | Penny et al. (2001)     |
| 9       | 51653.86-52012.88 | 2/2        | ESO UVES                | This paper              |
| 10      | 54277.54-55698.72 | 29/16      | ESO FEROS               | This paper              |
| 11      | 55003.44-56136.47 | 95/50      | ESO HARPS               | This paper              |
Table 2
FEROS and HARPS Radial Velocities of δ Cir

| RJD       | Phase | Primary RV | Secondary RV | Tertiary RV |
|-----------|-------|------------|--------------|-------------|
| 54277.5318 | 0.915 | 36.6       | –261         | –45         |
| 54278.5352 | 0.172 | 181.4      | –261         | –45         |
| 54279.5359 | 0.428 | –22.2      | 288          | –59         |
| 54280.4936 | 0.674 | –130.9     | –238         | –38         |
| 54281.4853 | 0.928 | 47.5       | –238         | –38         |
| 54282.4858 | 0.184 | 180.3      | 274          | –23         |
| 54285.5075 | 0.958 | 82.0       | –250         | –31         |
| 54286.5188 | 0.218 | 156.9      | –213         | –35         |
| 54298.4766 | 0.282 | 109.1      | –213         | –35         |
| 54299.4835 | 0.540 | –102.3     | 239          | –38         |
| 54300.4733 | 0.793 | –83.2      | –268         | –19         |
| 54300.4752 | 0.794 | –82.2      | –268         | –19         |
| 54301.4741 | 0.050 | 162.7      | –230         | –53         |
| 54302.4761 | 0.306 | 86.0       | –230         | –53         |
| 54660.4685 | 0.042 | 136.5      | –249         | –34         |
| 54660.4707 | 0.042 | 135.0      | –250         | –31         |
| 54662.6006 | 0.588 | –139.5     | 258          | 26          |
| 54663.5865 | 0.841 | –66.0      | –5           | –5          |
| 54664.5370 | 0.084 | 161.3      | –268         | –19         |
| 54665.5846 | 0.353 | 35.3       | –268         | –19         |
| 54666.4724 | 0.580 | –137.0     | 240          | 24          |
| 54667.4764 | 0.838 | –68.3      | –4           | –4          |
| 54667.5368 | 0.823 | –51.1      | –5           | –5          |
| 54953.7739 | 0.201 | 136.1      | –264         | –14         |
| 55003.4383 | 0.927 | 15.8       | –268         | –19         |
| 55003.4419 | 0.928 | 16.9       | –268         | –19         |
| 55004.4810 | 0.194 | 129.1      | –268         | –19         |
| 55004.4871 | 0.196 | 129.0      | –268         | –19         |
| 55005.7396 | 0.517 | –116.0     | 201          | –31         |
| 55006.4428 | 0.697 | –158.0     | 265          | –31         |
| 55006.4463 | 0.698 | –157.4     | 265          | –31         |
| 55007.4539 | 0.956 | 45.6       | –259         | –59         |
| 55008.4769 | 0.218 | 119.9      | –259         | –59         |
| 55009.5571 | 0.493 | –103.2     | 159          | –59         |
| 55010.4657 | 0.728 | –148.6     | 249          | –59         |
| 55011.6215 | 0.024 | 105.9      | –244         | –59         |
| 55012.4466 | 0.236 | 111.1      | –244         | –59         |
| 55028.4563 | 0.338 | 34.7       | –268         | –19         |
| 55028.4584 | 0.339 | 34.3       | –268         | –19         |
| RJD       | Phase | Primary RV | Secondary RV | Tertiary RV |
| 55302.4521 | 0.593 | –147.6     | 240          | 70          |
| 55302.4547 | 0.594 | –147.5     | 239          | 70          |
| 55302.4568 | 0.594 | –147.9     | 240          | 70          |
| 5529.5183 | 0.610 | –153.4     | 245          | 70          |
| 5529.5204 | 0.611 | –153.1     | 245          | 70          |
| 5529.5912 | 0.629 | –153.3     | 245          | 70          |
| 5529.6397 | 0.641 | –153.9     | 248          | 70          |
| 5530.2900 | 0.664 | –155.4     | –305         | –9          |
| 5530.7379 | 0.923 | 17.6       | –305         | –9          |
| 5530.7400 | 0.923 | 17.5       | –305         | –9          |
| 5530.7428 | 0.924 | 19.0       | –305         | –9          |
| 5530.4652 | 0.112 | 150.4      | –305         | –9          |
| 5530.5292 | 0.432 | –56.6      | –305         | –9          |
| 5530.5325 | 0.432 | –58.9      | –305         | –9          |
| 5530.5377 | 0.434 | –58.2      | –305         | –9          |
| 5531.5137 | 0.684 | –162.3     | 231          | 52          |
| 5536.4813 | 0.444 | –70.6      | –305         | –9          |
| 5536.4873 | 0.700 | –155.5     | 224          | 27          |
| 5536.4825 | 0.701 | –157.6     | 226          | 34          |
| 5538.4988 | 0.474 | –94.9      | 50           | –50         |
| 5539.4953 | 0.729 | –147.7     | 210          | 52          |
| 5539.4614 | 0.283 | 71.1       | 12           | –50         |
| 5538.4548 | 0.537 | –134.5     | 191          | 44          |
| 5538.6112 | 0.090 | 145.1      | –304         | 22          |

Note. * Orbital phases are calculated for the final ephemeris of Table 3 of the 39# orbit: HJD 2454285.66 + 39#02463 × E.

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proportional to the squares of the rms errors of the individual data sets.

There is certainly a measurable increase in the longitude of the periastron over the time interval from the IUE spectra to the ESO spectra. However, the value obtained by TE disagrees
although strongest among the He i lines, is not suitable for Gaussian fitting. For the primary component, this line is blended with the He i 4025 Å line and would lead to an incorrectly measured RV of the tertiary. The He i 4026 Å line is suitable for disentangling, however, for which the line blending does not represent any problem.

The systemic velocities of the eclipsing binary (ESO data only), together with the measured RVs of the third line, are displayed in Figure 4. Clearly, the third line velocity varies in the antiphase with the systemic velocity, confirming the mutual orbital motion of both objects. The amplitude of the RV of the third line appears to be about 2.3 times larger than the amplitude of the orbital motion of the 3.9 day binary in the long orbit, as derived from its varying systemic velocity. Using the program KOREL (Hadrava 2004b), it was possible to estimate more accurately the semiamplitude of the third-body orbit $K_3$ (see Section 5 and Table 5).

The third-body RVs shown in Figure 4 were obtained when only a single line was considered to represent the third body. However, it appears that in some cases, a two line representation of the third light is necessary. In Figure 5, we provide an example of such a profile. It is usually difficult, however, to decide

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**Table 3**

| RJD Range | Center of the Interval | Number of Measurements | $V_\gamma$ (km s$^{-1}$) | rms (km s$^{-1}$) | $\omega$ (deg) | Source of Data |
|-----------|------------------------|------------------------|---------------------------|-----------------|----------------|----------------|
| 39594 to 39723 | 1967.7 | 19 | 9.2 | 12.3 | 296 ± 17 | TE$^a$ |
| 44449 to 44460 | 1980.2 | 6 | 17.5 | 9.9 | 229 ± 10 | Pe01, IUE RVs$^b$ |
| 48885 to 48894 | 1992.8 | 29 | −8.3 | 4.9 | 257 ± 3 | Pe01, IUE RVs$^c$ |
| 49867 to 49874 | 1995.4 | 21 | −0.7 | 9.5 | 272 ± 3 | Pe01, Hα |
| 50152 to 50155 | 1996.2 | 3 | −16.5 | 8.8 | | |
| 54277 to 54302 | 2007.6 | 16 | 18.6 | 4.6 | 323 ± 4 | FEROS 2007 |
| 54660 to 54667 | 2008.7 | 9 | −0.8 | 4.9 | 305 ± 4 | FEROS 2008 |
| 55028 to 55031 | 2009.6 | 14 | −7.9 | 3.5 | 316 ± 4 | HARPS 2009 |
| 55360 to 55383 | 2010.5 | 13 | −14.7 | 2.4 | 310 ± 4 | HARPS 2010 |
| 55736 to 55762 | 2011.6 | 23 | 29.5 | 3.2 | 317 ± 3 | HARPS 2011 |
| 56103 to 56113 | 2012.5 | 21 | 13.6 | 2.7 | 312 ± 3 | HARPS 2012/1 |
| 56132 to 56136 | 2012.6 | 10 | 9.5 | 2.2 | 309 ± 3 | HARPS 2012/2 |

**Notes.**

$^a$ Only data from 1967.
$^b$ Data from 1979 and 1980.
$^c$ Only data from 1992 September.

**Table 4**

| Element | 3.9 day Orbit | 1644 day Orbit |
|---------|---------------|----------------|
| Sidereal period, $P$ (days) | 3.902463(6) | 1644(3) |
| Epoch of periastron (RJD) | 54285.66(5) | 37482(27) |
| Eccentricity, $e$ | 0.0601(48) | 0.415(32) |
| Longitude of periastron, $\omega$ (deg) | 308.3(4.7) | 106(6) |
| Semiamplitudes, $K_1$ and $K_3$ (km s$^{-1}$) | 153.9(1.5) | 23.6 |
| Semiamplitude, $K_2$ (km s$^{-1}$) | 284.17 | |
| Systemic velocity, $V_\gamma$ (km s$^{-1}$) | 3.5 | 3.1 |
| Apsidal advance, $\dot{\omega}$ (deg day$^{-1}$) | 0.00696(15) | |
| Mass ratio, $m_2/m_1$ | 0.546(3) | |
| $m_1 \sin i$ (M$_\odot$) | 22.21 | |
| $m_2 \sin i$ (M$_\odot$) | 12.13 | |
| $a \sin i$ (R$_\odot$) | 33.90 | |

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**Figure 2.** RVs measured in HARPS spectra corrected to a common systemic velocity. Full circles correspond to primary RVs and open circles correspond to secondary RVs.
which option is better as the fit qualities of both—three and four Gaussians—are quite comparable. Nevertheless, the possibility exists that the third body is a binary. Aside from the cases where a two line representation is clearly better, that possibility is also indicated by the large scatter of all the measurements of the third line RVs. Despite all of our effort, we have not succeeded in finding the period of the putative second binary. However, from the cases where a four Gaussian fit appears to be superior, we suspect that the period should be of the order of several days.

5. DISENTANGLING SPECTRA

Although the RVs measured using Gaussians provided acceptable results, more reliable elements can be obtained via spectral disentangling. We used the program KOREL (Hadrava 2004b; for details about the application, see Mayer et al. 2013) and applied it to three different spectral segments containing the lines He\(\text{I}\) 4026, He\(\text{I}\) 4922, and He\(\text{II}\) 5411 Å. In the case of the He\(\text{II}\) 5411 Å line, no traces of the secondary or tertiary components were detected, and so only the line of the primary was disentangled. Since the RVs that were used by the program FOTEL cover a longer time interval, we assumed the values of both orbital periods derived by this program (Table 4) when applying KOREL.

We first investigated the dependence of the sum of the squares of residuals on various elements, namely, the semiamplitudes and mass ratios of both recognized subsystems, keeping the orbital periods and the value of the apsidal advance of the 3.9 day orbit fixed at values obtained from the FOTEL triple-star solution. After finding the values of the semiamplitudes and mass ratios corresponding to the lowest sum of residuals in each studied region, we used them as starting values and ran a number of solutions for all of the elements (except for the periods and the apsidal advance), kicking the initial values in different directions. The solutions with the lowest sum of the residuals are summarized in Table 5 and the corresponding disentangled line profiles are in Figure 6.

The values of the mass ratios could not, of course, be derived for the He\(\text{II}\) 5411 Å region. The equivalent widths (EWs) of several lines as measured on the disentangled spectra are listed in Table 6.

Since KOREL does not provide an estimate of the errors of the elements, Table 5 also contains the mean values for all three solutions and their rms errors. While there is satisfactory

![Figure 3](image1.png)

**Figure 3.** Differences of observed and expected velocities in the third-body system.

![Figure 4](image2.png)

**Figure 4.** Systemic velocities of the eclipsing binary (short horizontal lines) and measured RVs of the third line (full circles) according to the FEROS and HARPS spectra.

![Figure 5](image3.png)

**Figure 5.** Example of an He\(\text{I}\) 4922 Å profile where the two line fit of the third-body contribution is necessary. The dashed curve shows the best one line fit.

| Table 5: KOREL Solutions |
|--------------------------|
| Element | Line 4923 Å | Line 4026 Å | Line 5411 Å | Mean |
|----------|---------|---------|---------|------|
| 3.9 d Orbit |
| \(T_{\text{periastr}}\) (RJD) | 54285.612 | 54285.634 | 54285.672 | 54285.639 |
| \(e\) | 0.066 | 0.072 | 0.067 | 0.068 |
| \(\omega\) (deg) | 304.6 | 307.0 | 309.6 | 307.1 |
| \(K_1\) (km s\(^{-1}\)) | 157.4 | 156.3 | 156.6 | 156.8 |
| \(K_1/K_2\) | 0.558 | 0.560 | 0.559 |
| \(K_2\) (km s\(^{-1}\)) | 282.1 | 279.1 | - | 280.4 |
| \(a\sin i\) (R\(\odot\)) | 33.84 | 33.51 | - | 33.65 |
| 1644 day Orbit |
| \(T_{\text{periastr}}\) (RJD) | 37469.4 | 37485.0 | 37497.5 | 37484.0 |
| \(e\) | 0.440 | 0.468 | 0.339 | 0.416 |
| \(\omega\) (deg) | 284.9 | 286.7 | 280.5 | 284.0 |
| \(K_{1+2}\) (km s\(^{-1}\)) | 22.2 | 23.0 | 22.2 | 22.4 |
| \(K_{1+2}/K_3\) | 0.362 | 0.452 | - | 0.407 |
| \(K_3\) (km s\(^{-1}\)) | 61.3 | 50.9 | - | 55.0 |
| \(a\sin i\) (AU) | 11.33 | 9.87 | - | 10.64 |
agreement on the values of the majority of the orbital elements among the three solutions, there is a striking difference for the value of the mass ratio of the outer orbit between the solution based on the He\textsc{i} 4026 Å and He\textsc{i} 4922 Å lines. In our opinion, this might indicate that the third body is indeed a binary and that the line blending between the components of this pair of stars is different for the two investigated lines. This implies that before the resolution of this pair of stars, the mass ratio of the 1644 day system must be considered uncertain.

The plots of the disentangled line profiles show that the secondary He\textsc{i} 4922 Å line is asymmetric due to the blend with the O\textsc{ii} line 4925 Å. However, the tertiary line is symmetric (although originating in a component/components with a similar temperature) and of a different shape. As a matter of fact, its shape is a perfect sinusoid. Such a profile would result as an integration of the orbital motion in the putative second binary system. Therefore, this supports our suspicion that the third body is indeed another binary. Guided by the opinion reached when these lines were measured using Gaussians, the EW ratio of the putative second binary lines might be about 2/3 with a similar mass ratio; therefore, the theoretical curve has been calculated as a sum of two sinusoids. Apparently, the contribution of the “secondary” also well represents the wings of the profile.

6. INTERFEROMETRY

Independent of its spectroscopic detection, the third body was discovered by interferometry. δ Cir was observed in 2012 June (RJD 56090.554) with VLTI and the PIONIER combiner (Le Bouquin et al. 2011); the separation was 3.87 mas with a magnitude difference of 1.75 in the \textit{H} band.

The observed separation \( \rho \) can be calculated as

\[
\rho^2 = \left( \frac{a(1-e^2)}{(1+e \cdot \cos \nu)} \right)^2 \left( 1 - \sin^2(\omega + \nu) \cdot \sin^2 i \right).
\]

Using the elements of the 1644 day orbit (Table 5), the true anomaly \( \nu \) equals 150° for the given date, and the inclination can be calculated as \( i = 87.7 \). A large inclination is needed to satisfy the solution of the long orbit, as will be discussed in the next section.

7. LIGHT CURVE SOLUTION—PHYSICAL ELEMENTS OF THE SYSTEM, AND THE APSIDAL ADVANCE

The light variability of δ Cir was first reported by Cousins & Stoy (1962). However, the only published light curve (lc) of δ Cir is based on the \textit{Hipparcos} \( H_p \) photometry (Perryman & ESA 1997). We noted that Thackeray & Emerson (1969) mentioned receiving unpublished Cape \textit{V} photometry of δ Cir from Dr Cousins that was indicative of binary eclipses. At our request, Dr. David Kilkenny very kindly searched in the archival materials remaining from the late Drs. Cousins and Thackeray. Regrettably, he was unable to find the original photometric observations, but he did find a plot of the \textit{V} magnitude versus phase in the folder with the correspondence of Dr. Thackeray. To preserve this previous piece of information, we reproduce the original plot in Figure 7.

Assuming the Thackeray & Emerson (1969) ephemeris, we were able to reconstruct the light curve and use it along with the \textit{Hipparcos} \( H_p \) photometry. In doing so, we took into account the remark of Thackeray & Emerson (1969) that the Cousin’s photometry covers an interval of 5000 days. We therefore assumed that the mean epoch of the photometry falls in the year 1960 and created artificially fictitious Julian dates corresponding to the phases of the observations for RJDs 37000-37004.
Figure 7. Reproduction of the original phase diagram based on Dr. Cousins’ V photometry found in the correspondence of Dr. Thackeray by Dr. Kilkenny.

A solution of the Hipparcos LC was derived by Pe01, but they used a program designed for circular orbits only. It can be seen in Figure 4 of Pe01 that the observed widths of the 3.9 day binary eclipses are narrower than the calculated LC and the observed maxima are flatter. It was therefore deemed useful to obtain another light curve solution based on a modern program. We used the program PHOEBE (Prša & Zwitter 2005). The projected semimajor axis \( a \sin i \) and the binary mass ratio following from the mean KOREL solution were fixed in PHOEBE. Since all of the components of \( \delta \) Cir are hot stars, we fixed both the albedos and the gravity darkening coefficients equal to 1. We also used the square-root limb darkening coefficients. The value of the sidereal orbital period was kept fixed from the final FOTEL solution of Table 4. After a few trials, we found that the scarcely covered eclipses cannot guarantee a unique solution; the space of the possible solutions with nearly identical quality for the fit was immense. To circumvent this unpleasant situation, we simply assumed the temperatures and relative photometric radii corresponding to the known spectral classification of the eclipsing components, and also the light contribution of the third body as found from the interferometry, and fixed them in the light curve solution. The only free parameters in the solution were the epoch, the longitude of the periastron passage, the orbital inclination, and the relative luminosity of the primary. Keeping the inclination of the orbit fixed from this solution, we then also derived an independent solution for the reconstructed V light curve from Cousin’s observations. The results are summarized in Table 8 and the theoretical and observed light curves are compared in Figure 8.

One can see that the fit is very good and in this sense it confirms that the light curves do not contradict the temperatures and radii we adopted. More notably, the values of the longitude

Figure 8. Comparison of observed light curves and PHOEBE model light curves. Upper panel: Cousins Cape V photometry. Bottom panel: Hipparcos \( H_p \) photometry.
of the periastron basically confirm the rate of apsidal advance deduced from the spectroscopy. It is clear, however, that a really accurate determination of the rate of apsidal advance will require a new, more accurate light curve (and/or continuing spectroscopic observations). Currently, it is regrettable that no good photometry exists. The ASAS data (Pojmanski 2002) are quite noisy (as is common for such bright stars), and only a rough estimate of a normal minimum can be deduced: RJD 54601.383 (according to our ephemeris, a secondary minimum should appear at RJD 54601.381). Any shift of the phase of the secondary minimum from 0.5 (as observed in the Hipparcos photometry) is uncertain.

8. DISCUSSION AND CONCLUSIONS

From the elements of the mutual orbit presented in Table 4, the minimum mass of the eclipsing binary is 43.6 $M_\odot$ and the mass of the third body is 18.7 $M_\odot$. However, the total mass of the eclipsing binary (see Section 5) is only 36 $M_\odot$. Therefore, $K_3$ is very probably smaller than 55 km s$^{-1}$; e.g., with 51 km s$^{-1}$ the minimum mass of the eclipsing binary is 36 $M_\odot$. The inclination certainly has to be large, which would be in agreement with the interferometry.

The mass of the third body, as follows from the solution of the long orbit, is large (larger than the mass of the secondary) even with the assumed $K_3 = 51$ km s$^{-1}$. It would agree better with the interferometric magnitude difference as well as with the spectroscopic evidence if this body is a binary.

We calculated the expected apside-line period using the evolutionary models by Claret (2004). The theoretical period depends strongly on the radii, and with the radii derived by Pe01 ($R_\text{pri} = 10.2$ and $R_\text{sec} = 6.4$ $R_\odot$; polar radii), the apsidal period should be $\approx 62$ yr (including the general relativity contribution, which is 0.00247 per cycle). In order to reproduce the observed apsidal period, the radii would have to be smaller. With our radii (Table 7), the corresponding theoretical apside-rotation period is 85 yr, closer to but still shorter than the observed one.

The apside-line period can, of course, be affected by the third body. From theoretical considerations, it is clear that the effect increases if the ratio of the semimajor axis $d_\text{long}/d_\text{short}$ becomes smaller and if the mutual inclination increases. In the case of $\delta$ Cir, the ratio of the axes is 66, the inclination is $11^\circ.8 < i < 16^\circ.4$ (since $i_\text{long} = 87^\circ.7$ and $i_\text{short} = 75^\circ.9$), and $e_1$ is small. Then, the formula by Söderhjelm (1984, Equation (25)) might provide an approximate idea concerning the magnitude of the effect (although it is valid for $e = 0$ and $i = 0$ only). According to the formula, the apsidal period — due to the third body only — would be $\approx 1500$ yr. As the expected period is $\approx 100$ yr, the effect might be only of the order of several percent, which is smaller than the present errors for the theoretical estimates as well as of the observational value.

Once more, we repeat that a new, accurate, and complete multicolor light curve is highly desirable and crucial for a reliable determination of the basic properties of the binary.

We also note that our new radius for the primary is not consistent with the radius expected for the O7.5 III classification, for which, e.g., Martins et al. (2005) give $R \approx 14$ $R_\odot$. Another classification was published by a team from the Yerkes Observatory (Hiltner et al. 1969): O8.5 V. Pe01 classified the primary component using IUE spectra as O7 III-V. We measured the 4471/4541 ratio as log $W' = +0.21$ (Conti & Alschuler 1971), and the corresponding type is O8. Therefore, we suspect that the individual classification of the primary is O8 IV; such a luminosity class is also supported by the He $\lambda$ 4143 Å line when compared with a synthetic spectrum. Pe01 claimed that the primary mass of $\delta$ Cir is smaller than would correspond to the given spectral type. We obtained larger semiamplitudes of RVs, and so now the mass is fully consistent with the value obtained by Martins et al. (2005).

There are several early B-type stars closer than 10 arcmin to $\delta$ Cir (HD 135160, 135241, 135332), however, their distances are not well known and it is not possible to suggest that $\delta$ Cir is a member of a group.

Despite some uncertainties in the solutions of the RV and light curves, we obtain an acceptable model of the system of $\delta$ Cir. Further interferometric data are needed to see if the separation and change of the position angle follow the prediction.

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