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Observations and elements of the eclipsing binary FO Hydra

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ABSTRACT

Photometric observations in the *UBV* system are presented for the eclipsing binary FO Hydra (FO Hya). An analysis of the observed times of minimum light yields revised elements, with the times of primary minima given by Min I (JD) = 244 4717.7658 + 0.469 5571*E*. The light curve of FO Hya is shown to have the defining characteristics of the β Lyrae class of eclipsing binaries. The differential corrections program of Wilson & Devinney was used to model the light curve of FO Hya. A solution based on the assumption of an overcontact system is shown to provide an excellent fit to the light curves obtained with *V*, *B* and *U* filters. A comparison with two similar systems suggests that FO Hya is an evolved contact binary system.

Key words: techniques: photometric – binaries: eclipsing – stars: fundamental parameters – stars: individual: FO Hydra.

1 INTRODUCTION

The variability of the eclipsing binary system FO Hya was first noted by Hoffmeister (1936), and the first quantitative observations were made in 1944 by Tsessevich (Tsessevich 1954). Tsessevich identified three significant minima and used the times of these minima to obtain an estimate of the orbital period, 1.159 d. No other observations of FO Hya have been reported since the work of Tsessevich and FO Hya is absent from some of the usual catalogues. This is presumably because of its southern declination and the unexceptional orbital period reported by Tsessevich.

The General Catalogue of Variable Stars (Kholopov 1985) indcates the position of FO Hya ($9^h57^m23^s$, $-18°54'.2$, 1950.0 ≡ $9^h59^m45^s$, $-19°8'.6$, 2000.0) and lists an approximate magnitude range for FO Hya (9.5–10.0). This catalogue also contains the orbital elements determined by Tsessevich (1954) and classifies FO Hya as an eclipsing Algol-type system of early (O–A) spectral type.

The observations described here require a revised interpretation of FO Hya. First, it is shown that an orbital period value ~0.4696 d is required to account for the times of the primary minima reported here, and that a period of this magnitude is consistent with the times of the minima observed by Tsessevich (1954). Secondly, the light curve of FO Hya is found to have the defining characteristics of the β Lyrae class of eclipsing binaries (see below), rather than those of the Algol class. The current series of observations also indicates an approximate magnitude range ~11.0–11.5, rather than 9.5–10.0.

2 THE OBSERVING PROGRAMME

During photometric observing programmes on objects of special interest, there is often a spare hour or two, which can be filled by a background programme. Nearly 200 variables were selected from the General Catalogue of Variable Stars (Kholopov 1985) that were in need of observation and were accessible to the instrument. The observing procedure was to choose five or six variables near the meridian and take observations of each in a cycle. As soon as a variation occurred, that star was observed and all the others ignored. It was not the original intention, but this naturally led to the selection of a short-period variable. The first object to be adequately observed is FO Hya.

The observations were made on the Perth/Lowell 61-cm reflector at the Perth Observatory, Bickley, Western Australia, using an EMI 6256 S photomultiplier (Millis 1974). To relate to the standard Johnson *UBV* photometric system, a comparison star was selected from the USNO Photometric Catalogue. The comparison star used was HD 9339 ($9^h54^m.5$, $-23°28'$, 1900.0 ≡ $9^h59^m6^s$, $-23°57'$, 2000.0).

Preliminary plotting showed that the value that Tsessevich (1954) reported for the period was not sustainable and that a value near 0.4696 provided a much better fit to the observations. This plotting also allowed gaps in the light curve to be identified and sometimes filled.

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3 TIMES OF MINIMA AND THE ORBITAL PERIOD

A correction has been applied to the times of observation reported here, to yield heliocentric values. This is necessary because variations in the light travel time due to the Earth's orbital motion are a significant fraction, ~ 1 per cent, of the short orbital period of FO Hya.

A total of 14 primary minima were observed using the *V* filter during the period 1981–91. The time of each primary minimum was estimated by fitting a quadratic to the data in a small interval surrounding the minimum. The errors in the time of each primary minimum were estimated by analysing the effect on χ^2 of varying the assumed location of the minimum. The estimated times and associated errors of the 14 primary minima are shown in Table 1.

The period of the system was then estimated by fitting a straight line to the data in Table 1. This yields the following equation for the times of primary minimum:

$$\text{Min I (JD)} = (244\,4617.7658 \pm 0.0005) + (0.469\,557\,10 \pm 0.000\,000\,15)E. \qquad (1)$$

The procedure was repeated for the eight secondary minima observed using the *V* filter (the times and associated errors are listed in Table 2). The following equation for the times of the secondary minima is obtained:

$$\text{Min II (JD)} = (244\,4618.0001 \pm 0.009) + (0.469\,557 \pm 0.000\,002)E. \qquad (2)$$

Fig. 1 shows a plot of O − C values for the times of primary minima obtained using equation (1) and the data in Table 1. In all cases the residuals are comparable to the statistical errors in the times of the minima (see Table 1). Interestingly, the residuals are also comparable to the heliocentric light correction times.

We attempted to check the constancy of the orbital period by using the data obtained by Tsessevich (1954) (see Fig. 2). Unfortunately it is difficult to determine the times of the three primary minima observed by Tsessevich because each of the observing sessions that includes a minimum commences during that minimum (it seems that the faintness of FO Hya at minimum light may have prompted a new series of observations). We used the mean time of the observations within each minimum to obtain revised estimates of the times of the minima (the original times of the minima reported by Tsessevich do not appear to be consistent with the raw data that he published). The associated error was assigned a value of 0.035 d, which is roughly half the width of the primary minimum (see below). The combination of the resulting times of minimum yields an orbital period 0.471 ± 0.003 d.

Although this is consistent with the orbital period obtained from the observations described here, the times of these three minima are not consistent with the elements given in equation (1). Furthermore, when both the historical and current minima are included it is not possible to find a set of elements with residuals comparable to the statistical errors. This is true even if we make the assumption of a fixed rate of change in the orbital period by including a term quadratic in *E*. This suggests that there must have been some slight and irregular variation in the orbital period,

Table 1. Times of the primary minima observed with the *V* filter.

E	J.D.
1	2444618.2344 ± 0.0018
5	2444620.1111 ± 0.0018
31	2444632.3232 ± 0.0017
35	2444634.2005 ± 0.0015
48	2444640.3051 ± 0.0018
52	2444642.1827 ± 0.0016
67	2444649.2271 ± 0.0017
82	2444656.2698 ± 0.0018
88	2444659.0890 ± 0.0018
3236	2446137.2497 ± 0.0018
3238	2446138.1905 ± 0.0018
3251	2446144.2984 ± 0.0011
7148	2447974.1594 ± 0.0014
7149	2448303.3203 ± 0.0017

Table 2. Times of the secondary minima observed with the *V* filter.

E	J.D.
30	2444632.09 ± 0.015
33	2444638.19 ± 0.01
3250	2446144.07 ± 0.02
7139	2447970.18 ± 0.02
7141	2447971.11 ± 0.015
7843	2448300.27 ± 0.02
7844	2448301.21 ± 0.02
7846	2448302.14 ± 0.02

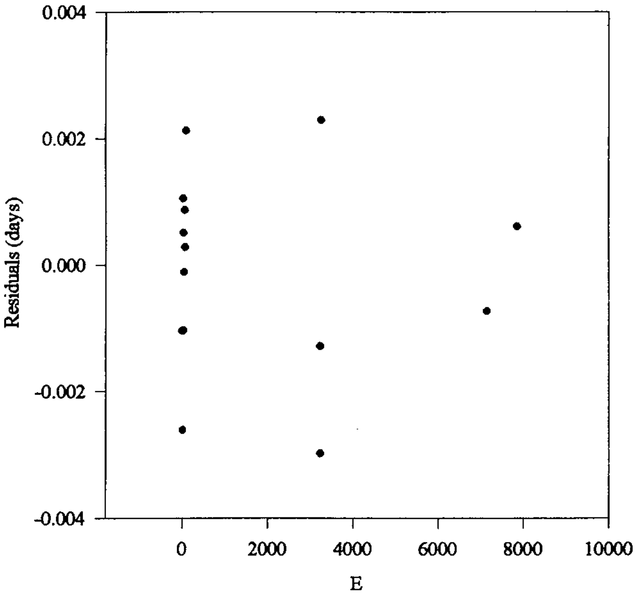

Figure 1. The difference, O − C, between the observed and calculated times of the primary minima for FO Hya, assuming the elements given in equation (1).

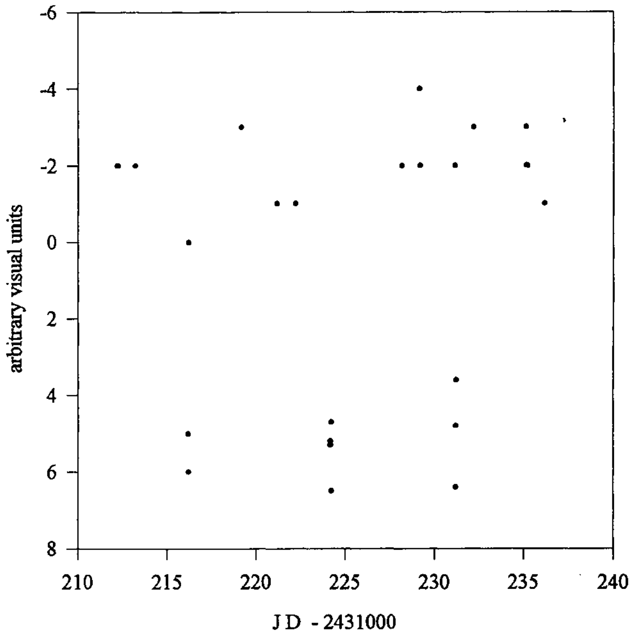

Figure 2. A subset of the raw data reported by Tsessevich (1954). The three significant minima identified by Tsessevich are apparent. The units of the vertical axis are the arbitrary visual units used by Tsessevich.

presumably caused by mass transfer between the components at an uneven rate.

The mean phase difference between a primary minimum and the following secondary minima can be obtained by combining the mean time interval between a primary minimum and the following secondary minimum, 0.2343 ± 0.009 d, with the rotation period 0.469 5571 d. The resulting mean phase difference, 0.499 ± 0.004, is consistent with a circular orbit. This is not surprising given the tidal forces that will act to reduce the eccentricity of the orbit of such a close binary (e.g. Zahn 1977, Giuricin, Mardirossian & Mezzetti 1984). It should be noted, however, that the mean phase difference between primary and secondary minima obtained here does not preclude an eccentric orbit aligned with the major axis in the line-of-sight direction.

The orbital period obtained here for FO Hya, 0.469 5571 d, is of interest as it is at the short-period end of the distribution for *β* Lyrae systems (e.g. Linnaluoto & Vilhu 1973).

4 THE LIGHT CURVES

The light curve of FO Hya varies smoothly at all phases with strong curvature in both maxima. The primary and secondary minima have significantly different depths: 0.5 and 0.2 mag respectively (see Fig. 3). The light curve of FO Hya lacks the flat maxima that characterize the Algol-type eclipsing binaries (e.g. Binnendijk 1960, Kopal 1978). By contrast, the light curve does display the key defining features of the *β* Lyrae class of eclipsing binaries: strong curvature in both maxima and light curve minima of unequal depths (e.g. Binnendijk 1960, Kopal 1978). It is clearly more appropriate to place FO Hya in the *β* Lyrae class of eclipsing binaries.

The light curve of FO Hya is similar to the light curves of two evolved contact systems: V1010 Ophiuchi (Leung & Wilson 1977) and TT Herculis (Kwee & van Genderen 1983). One interesting feature of the light curve of FO Hya that is not shared by these other systems is the significant difference in height of the light curve maxima, which is apparent in the observations with the *V*, *B* and *U* filters. This point is discussed further below.

5 DETERMINATION OF THE PHOTOMETRIC ELEMENTS

The curved maxima and the smooth variation in the light curve of FO Hya indicate that the dimensions of the components are comparable to their orbital separation. As a result the components of FO Hya will fill Roche equipotentials that are significantly distorted from a spherical shape. For this reason we have used a computer program developed by Wilson & Devinney (1971) and Wilson (1979; 1992, private communication), which is based on the shape of Roche equipotentials, to model the light curve. This program has been used successfully in modelling systems with similar light curves (Leung & Wilson 1977; Kwee & van Genderen 1983).

The starspot facility of the Wilson & Devinney program was used to model the differing heights of the light curve maxima of FO Hya. This facility allows the user to determine the effect on the light curve of a localized region on the stellar surface where the surface temperature is increased or decreased by a specified factor. To simulate a spot on a star, the user specifies the following four properties of the spot: the latitude (measured from 0° at the North pole to 180° at the South pole), the longitude (measured counterclockwise, reviewed from above the North pole, from the line of star centres), the angular radius and the 'temperature factor'. The temperature factor is the ratio of the local temperature within the spot to the unperturbed local temperature. Here we have attributed the greater brightness of the maximum following the primary minimum to a region of greater than average temperature on the primary component. We assumed that the spot has a latitude 90°, and included the longitude, angular radius and temperature factor as free parameters.

Our earliest attempts to model the light curve of FO Hya were based on the assumption that only one of the binary components filled its Roche Lobe. This required the use of modes 4 and 5 in the Wilson & Devinney program (in mode 4 the primary is assumed to fill its Roche Lobe and in mode 5 the secondary is assumed to fill its Roche Lobe). A good fit to the observed light curve data was obtained in both modes, but only with parameters corresponding to a system in near contact. This led us to try mode 3 of the Wilson & Devinney program, which is used for overcontact systems and which has the advantage of fewer free parameters.

To reduce the number of free parameters we assume that limb darkening in FO Hya is adequately described by the standard linear limb-darkening law.

$$I/I_0 = 1 - x(1 - \cos\gamma), \tag{3a}$$

where x is considered a free parameter and γ is the angle between the observer's line of sight and a vector that is normal to the stellar surface. In effect, we assume that the

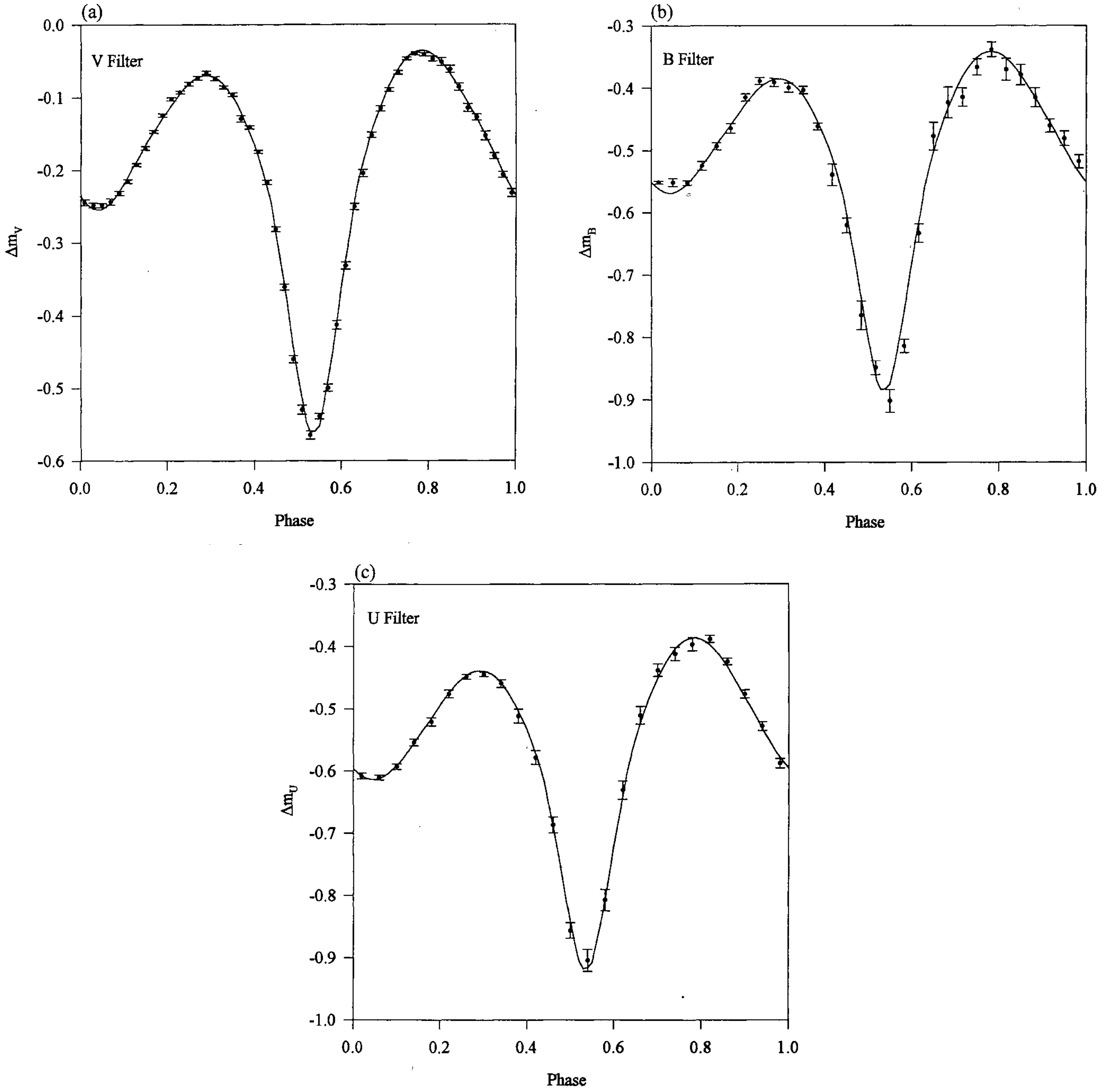

Figure 3. The light curves of FO Hya for (a) the *V* filter, (b) the *B* filter and (c) the *U* filter. The error bars are standard errors of the mean for each normal point.

coefficient $y = 0$ in the limb-darkening equation used by the Wilson & Devinney program (Wilson, private communication):

$$I/I_0 = 1 - x(1 - \cos\gamma) - y\cos\gamma(\ln\cos\gamma). \quad (3b)$$

We also assumed that the eccentricity of the orbit is 0.0 (as suggested by the above analysis of the times of minima) and that the third light contribution is 0.0 for all filters.

Preliminary solutions for an overcontact binary were obtained by trial and error variation of the 17 remaining parameters available in mode 3 for the light curve generating program. When a reasonable fit had been obtained, the differential corrections program was used to refine the estimates of the free parameters. After a small number of iterations the corrections procedure converged and the parameter corrections became small compared with the probable error in the parameters. The best-fitting parameters and estimates of the probable errors are given in Table 3. The resulting theoretical light curves are compared to the observed light curves from the *V*, *B* and *U* filters in Figs 3(a), (b) and (c). The theoretical light curves provide an excellent fit to the observed light curves.

It should be noted that the probable errors given in Table 3 are formal statistical estimates and may not reflect the

Table 3. Photometric parameters of FO Hya.

Filter independent parameters

inclination	$68^{\circ}.6 \pm .4$
mass ratio	$0.552 \pm .005$
surface equipotential	$2.968 \pm .007$
Phase of primary conjunction	$.5372 \pm .0008$
Temperature of primary	6950 ± 230
Temperature of secondary	4260 ± 90
Reflection coefficient	$.55 \pm .13$
Gravity darkening coefficient	$.52 \pm .20$

Filter independent parameters of spot

latitude of spot	$90^{\circ}.0$[a]
longitude of spot	$268^{\circ}.2 \pm .1$
angular radius of spot	$35^{\circ} \pm 16$
Temperature factor of spot	$1.024 \pm .02$

Filter dependent parameters

	V(λ ~5500)	B (λ ~4400)	U(λ ~3600)
Luminosity of primary $L_1/(L_1+L_2)$	$0.952 \pm .006$	$0.972 \pm .006$	$0.986 \pm .005$
Limb darkening over envelope	$0.63 \pm .07$	$0.68 \pm .08$	$0.52 \pm .08$
Third light	0.0[a]	0.0[a]	0.0[a]

System configuration

r_1 (pole)	.4101[b]
r_1 (side)	.4358[b]
r_1 (back)	.4667[b]
r_2 (pole)	.3140[b]
r_2 (side)	.3291[b]
r_2 (back)	.3652[b]
inner contact equipotential	2.9915[b]
outer contact equipotential	2.6606[b]

[a] Not adjusted.
[b] Calculated.

overall uncertainty in the various parameters. For example, making the assumption of an eccentric orbit with its major axis in the line-of-sight direction might lead to revised estimates for some of the parameters significantly outside the probable error range quoted. Furthermore, the differential corrections procedure can only guarantee to converge to a local minimum of the weighted sum of the squares of the residuals. We tested for the presence of other local minima by repeating the differential corrections procedure with different starting points in parameter space. In all cases the corrections procedure converged to the solution reported here.

6 DISCUSSION

The solution given in Table 3 corresponds to a system in near contact, with the surface equipotential very close to the inner contact equipotential. The configuration of the solution, as viewed from the orbital equatorial plane, is shown in Figs 4 and 5 (the views from the poles of the orbit are very similar). In Fig. 4 the shape of the surface equipotential is compared to the inner and outer contact equipotentials. In Fig. 5 a schematic view is shown.

Wilson & Devinney (1973) argue that the inclusion of third light values as free parameters allows a stringent test of the degree to which the best-fitting parameters reflect the real properties of the binary under consideration. Wilson & Devinney suggest that a physically unrealistic set of parameters may still produce a good fit to the observations if a spurious third-light contribution is allowed. They suggest that a solution can be accepted with greater confidence if the best-fitting third light values are small (i.e. comparable to the probable error values). We performed this test for FO Hya by including the third-light values as free parameters and repeating the differential corrections procedure. In all cases the resulting third-light values were found to be small compared to the probable errors.

There seems little reason to expect a real third-light contribution for FO Hya if, as is sometimes assumed, third light must be attributed to the presence of a large amount of heated gas in the vicinity of the system (e.g. Kwee & van Genderen 1983). The common envelope lies well inside the outer contact equipotential so that there is no reason to expect significant mass loss from the system.

Although the origin of the FO Hya system cannot be inferred directly from the data reported here, it is possible

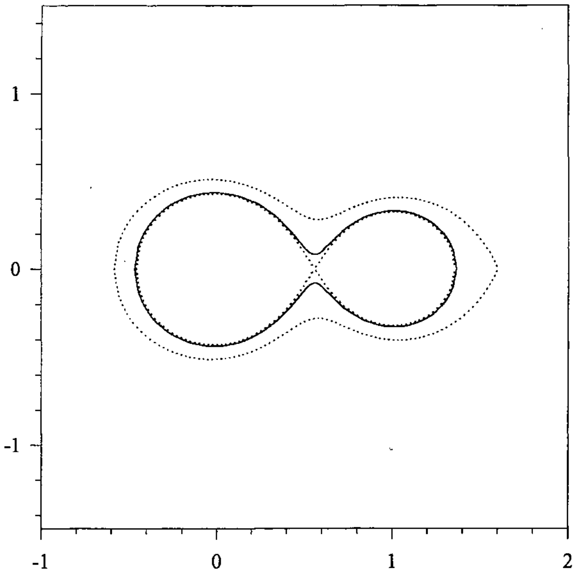

Figure 4. A diagram showing the outline of the critical equipotentials of FO Hya. The system is viewed from the orbital plane. The dotted lines represent the inner and outer contact equipotentials.

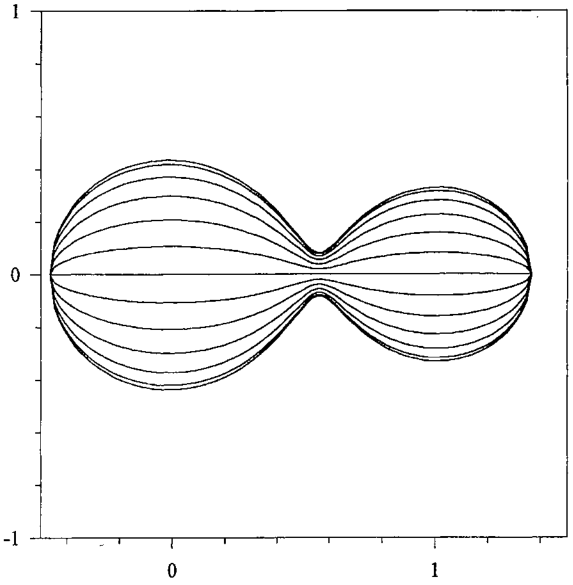

Figure 5. A schematic diagram of the configuration of FO Hya from the orbital plane.

to draw some tentative conclusions. Spectroscopic data has been used to determine the origins of V1010 Ophiuchi and TT Herculis, which both have light curves similar to that of FO Hya. The spectroscopic data suggests that V1010 Ophiuchi and TT Herculis are evolved contact binaries (Leung & Wilson 1977; Kwee & van Genderen 1983) that formed after one of the components has expanded sufficiently to fill its Roche equipotential. Given the similarity of the light curves it seems reasonable to suggest that FO Hya is also an evolved contact binary. Some support for this suggestion is provided by the gravity darkening and reflection coefficient of FO Hya (see Table 3), which have values suggestive of a convective envelope (Wilson & Devinney 1973; Wilson 1992, private communication).

It will be possible to analyse the FO Hya system more completely when velocity curves become available through spectroscopic analysis. The following simple analysis suggests that the relative radial velocities are likely to be quite large. Assuming that the surface temperatures can be related to the spectral types of the components, in spite of the contact relationship, then the spectral types of the primary and secondary are F3 and K4, respectively. A conservative estimate of the size of the components can be obtained by assuming that they lie close to the main sequence. This yields estimates of the radii of the primary $\sim 1.25\,\mathrm{R}_{\odot}$ and of the secondary $0.75\,\mathrm{R}_{\odot}$ (e.g. Allen 1976). The stellar centres will then traverse a circle of approximately solar radius (7×10^5 km) in a period of 4×10^4 s. Allowing for the inclination of the orbit, this leads to relative radial velocities of about 200 km s^{-1}.

The system will pass through at least one maximum in the relative radial velocity on each observing night. The times of maximum velocity, halfway between primary and secondary minima, can easily be predicted using the elements presented here. A large telescope will obviously be required in order to keep exposure times short.

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