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THE AD BINARY IN THE MULTIPLE SYSTEM η Mus

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Introduction

An account of the multiple star η Mus (HD 114911, HIP 64661, HR 4993) was given by Budding et al. (2013). The light is dominated by the young close binary ($V \sim 4.8$-4.9, $B-V \approx -0.08$, $U-B \approx -0.34$), which is a B8V type partially eclipsing system composed of two stars of measurably the same mass though with apparently somewhat different rotation speeds (see also Bakış et al. 2007). The 7.3 magnitude visual companion η Mus B (CD -67 1384B) appears about 58″ NW of the close binary, while a 10th mag (J) closer companion (η Mus C = DUN 131C) is found $\sim$3″ SE of the main pair. Butland & Budding (2011) announced the likely presence of another, optically unresolved, star in the system, sufficiently close to the central binary to disturb its γ-velocity on a $\sim$2000 d period. The sky location, HIPPARCOS distance of 124 $\pm$ 9 pc, and proper motions ($\mu_\alpha \cos\delta = -36.92$; $\mu_\delta = -10.63$ mas y^{-1}), make the system a likely member of the Lower Centaurus Crux (LCC) concentration (Blaauw 1964; de Zeeuw et al. 1999) of the Sco-Cen OB2 Association, within the Gould's Belt giant star formation region (Nitschelm 2004), and so of interest in the context of stellar formation and dynamical interaction theory.

After considering HIPPARCOS data, other sources and background literature, Budding et al. (2013) gave an updated ephemeris for the eclipsing system as

$$\text{Min I} = 2453874.2708 + 2.396318E. \tag{1}$$

A brief discussion of the ($\sim$12 km s^{-1}) difference in radial velocity between the A and B components found by Bakış et al. (2007) was given by Butland & Budding (2011), who argued that this difference would probably disappear when averaged over the orbital period of the new star ('η Mus D'). Butland & Budding, however, appealed for further observations to clarify details of the poorly known properties of this inner system.

New data and analysis

The VSS group, affiliated to the RASNZ, responded with timings of the eclipse minima, summarized in Table 1. These findings are plotted in Fig. 1, together with a theoretical curve showing calculated times of minima for corresponding phases of the deduced orbit of the close binary η Mus A about the centre of gravity of the AD putative binary. Further details on these timings are available from the VSS via M.G.B.

Table 1: Adopted times of minimum with estimated errors

Date	Type	HJD (obs.)	Error
110610	Sec	2455723.0212	0.0024
110803	Pri	2455776.9387	0.0027
120402	Sec	2456020.1765	0.0020
120508	Sec	2456056.1213	0.0021
120607	Pri	2456086.0760	0.0020
130312	Pri	2456364.0529	0.0021
140515	Pri	2456792.9890	0.0016
150706	Pri	2457209.9407	0.0016
160228	Pri	2457447.1754	0.0014
160305	Sec	2457453.1664	0.0015

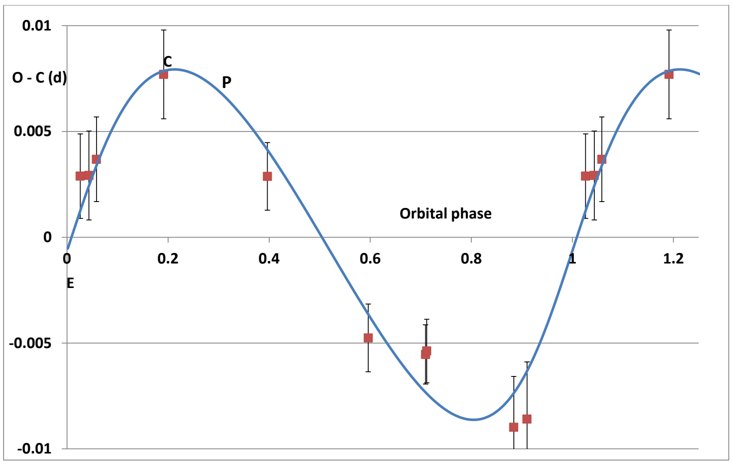

Figure 1. Optimal curve fitting applied to the O–C data for η Mus, as collected by M.G.B. The model orbit is phased from the reference epoch E. Its shape depends on the eccentricity parameters (e, M_0), which locate the periastron at P. Model phases are related to the observed times of minima, using the epoch and period given in Table 1, through the displacement $\Delta\phi_0$ from the conjunction at C.

In the meantime, further observations of the system were made using the HERCULES spectrograph and 1m McLellan Telescope of the Mt John University Observatory. These

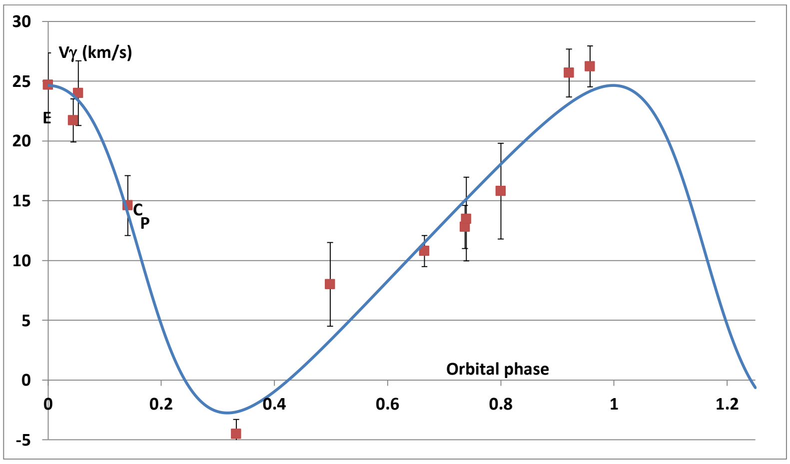

Figure 2. Optimal curve fitting applied to measured γ-velocities for η Mus over the last 10 years. Observational phases are reckoned from the epoch E, here at the origin, but displaced from the conjunction C by about the same shift $\Delta\phi_0$ as for the O–Cs. The periastron position P, dependent on the fitted eccentricity parameters, appears closer to the conjunction C than in the O–C fitting.

are shown in Fig. 2, together with a model similarly derived from optimal curve-fitting procedures. The corresponding data are listed in Table 2. The masses of the components of η Mus being measurably the same, the system velocity can be easily determined by taking the average of line pairs towards elongation. Typically 4 HeI lines were used for this purpose, together with H_β; lines which are conveniently located in the échelle field (see Budding et al. 2013, for further details).

The two programs FITRV and FITOMC optimize separate sets of fitting parameters, but of course these should be related as they refer to the same orbit. Results are thus collected together in Table 3. The epoch of equation (1) was adopted as a reference point for both analyses, as was a period of 2090 d for the orbit of η Mus AD, derived from averages of preliminary fittings of both data-sets. Even so, small differences arise from the separate fittings: for example, the (projected) distance travelled in the period $P_{\rm AD}$ with the spectroscopic velocity amplitude $K_{\rm A}$ is greater than goes with the photometric light travel amplitude $A\sin i$. Parameter errors on the order of 10% may accommodate such differences, though the scale of errors estimated from the fitting programs (Table 1) are somewhat lower than that. Note that the inclination i is not derivable from O–C or radial velocity data. The value in Table 1 comes from photometric analysis of η Mus A given by Budding et al. (2013), and adopted for the η Mus AD orbit.

The fittings agree on a moderate eccentricity to the orbit, and the value $e = 0.29$, retained from Butland & Budding (2011), is supported by the present data-sets. The shapes of the curves are dependent on the orientation parameter (cf. Irwin 1952a,b), usually associated with the longitude of periastron ω, but the related mean anomaly at the conjunction phase (M_0: inferior conjunction of the less massive η Mus D) is more convenient in the computation. There is some difference in the preferred orientation of the ellipse between the two analyses, the v_γ periastron seemingly occurring $\sim$0.1 in phase before that of the O–Cs (Figs. 1 & 2). The values of M_0 and its corresponding ω given in Table 1 are then adopted means. The shift of the apsidal line with respect to the line

Table 2: Adopted system (γ) radial velocities with estimated errors at the listed (mean) heliocentric Julian dates. Also shown is the number (No.) of separate spectrograms used for each mean date of observation.

Mean HJD 2450000+	No.	γ vel.	Error
3874.27	16	24.7	2.7
3967.31	1	21.7	1.8
3985.88	1	24.1	2.7
5413.59	2	12.8	1.8
5418.79	3	13.5	3.5
5546.09	2	15.8	4.0
5797.82	3	25.7	2.0
5875.99	6	26.1	1.7
6258.11	2	14.6	2.5
6669.74	3	-4.5	1.2
7005.64	3	8.0	3.5
7354.35	3	10.8	1.3

of sight being set, the angle $\Delta\phi_0$ relates this latter reference direction to the epoch from which observational phases are initially reckoned. Both data-sets point to $\Delta\phi_0 \approx 300$ deg from the conjunction. The positive shift in the average line of sight position of the AD system to the focus of η Mus A's ellipse Δz_0 is about 0.001 light days greater than would correspond with Irwin's (1952a) formula ($Ae \sin\omega \sin i$). This is less than the O–C mean timing error ($\delta\tau$), but it may indicate a small error in the adopted period of η Mus A.

Although the separate data-sets and analyses produce comparable results, the scatter of the observed points in average-parameter curves is larger than expected and we cannot rule out some additional variation beyond a two-body model in the AD system. This point, and the minor inconsistencies in the present relatively small radial velocity and O–C data-sets, should be checked on the basis of more observations, and this interesting multiple star is worthy of continued review.

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Table 3: Orbital parameter set for η Mus A's projected orbit about the centre of gravity of the AD system from the combined O–C and γ-velocity data. The feasible datum error estimates δv_γ in velocity and $\delta\tau$ in time give rise to acceptable χ^2/ν values for the fittings shown in Figs. 1 & 2, but these would deteriorate to χ^2/ν ~2 or greater, with the average M_0 and $\Delta\phi_0$ values of the table, suggesting higher datum errors than assigned.

Parameter	Value	Error
Epoch E (HJD)	2453874.2708	
$P_{\rm AD}$ (d)	2090	50
$K_{\rm A}$ (km/s)	13.7	1.2
$v_{\gamma \rm AD}$	11.3	0.8
$A \sin i$ (AU)	1.50	0.13
i (deg)	77.9	
e	0.29	0.1
ω (deg)	40	20
M_0 (deg)	30	20
$\Delta\phi_0$(deg) (O–C)	300	10
Δz_0 (l.d.)	0.0028	0.0003
δv_γ (km/s)	2.5	
$\delta\tau$ (d)	0.002	
χ^2/ν (v_γ)	1.08	
χ^2/ν (O–C)	1.17	

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