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Multiple Probes of the AS Cam Dynamical Problem

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Abstract. AS Camelopardalis is notorious for its apparent disregard for the theory of apsidal motion. The orbit of this 3.43-day double-lined eclipsing binary (B8V + B9.5V) rotates approximately 15° per century, which is only 0.3 to 0.4 as fast as predicted (classical + relativistic). Our dynamical program explores, as have others, the suggestion that a third star perturbs the orbit of the eclipsing pair and slows its apsidal motion, $d\omega/dt$. On the observational side, we unify the process of extracting apsidal motion and light-time effect parameters from eclipse minima by directly including a third body light-time effect along with the usual ephemeris parameters. By numerical experiment we identify third body parameters consistent with the eclipse timings and with the dynamics of third body perturbations. Results include the minimum third body mass required to produce the given retrograde apsidal rate. Finally, we use a general binary star light curve program that includes a light-time effect to solve for $d\omega/dt$ and ephemeris parameters together with other quantities, combining 21 years of radial velocities and light curves within one coherent analysis. The program has an improved stellar atmosphere routine based on Legendre polynomials that have been fitted to Kurucz atmosphere models. By analyzing whole light curves, the program has access to more information than only times of minima. Results agree well with those from eclipse timings over 100 years and attain smaller standard errors despite utilizing only one-fifth of the traditional method's baseline in time.

1. Introduction

AS Cam is an 8th magnitude double-lined eclipsing binary (B8V + B9.5V) in a 3.43-day orbit with eccentricity $e \approx 0.16$, and is one of the few apsidal motion binaries for which the general relativistic and classical effects are comparable.

Both DI Her and AS Cam show *too little* apsidal motion to match the sum of predicted classical and relativistic rates, $d\omega/dt$ (with ω the argument of periastron). For AS Cam, Maloney, Guinan, & Boyd (1989) estimated a total apsidal rate of $44^\circ\!.3 \pm 5^\circ\!.8/100\,\mathrm{yr}$, significantly larger than their observed $15^\circ\!.0 \pm 5^\circ\!.3/100\,\mathrm{yr}$. Wolf, Šarounová, & Diethelm (1996) found $18^\circ\!.2 \pm 2^\circ\!.6/100\,\mathrm{yr}$, about 0.4 times the expected value.

Guinan & Maloney (1985) and Maloney et al. (1989) were first to consider a third body hypothesis for AS Cam's anomalous apsidal motion. However, for several reasons they finally argued against the idea. For example, a third body would not only affect the periastron advance but also orbital inclination, which would alter eclipse depths. Because eclipse depth changes for AS Cam are very small or nonexistent, they considered a third body explanation unlikely. Khodykin & Vedeneyev (1997) revived the third body hypothesis and found that a nearby companion of moderate mass (0.78 to 1.45 $M_\odot$) in an inclined ($i_m > 32^\circ$, where i_m is the mutual inclination between the inner and outer orbits) short-period orbit, and with a period P between 0.6 and 2.9 yr, could sufficiently perturb the eccentricity of the eclipsing pair so as to alter the *apparent* apsidal motion *without* changing eclipse depths perceptibly. Kozyreva, Zakharov, & Khaliullin (1999) claimed to have detected the signal of a third body in photoelectric timings observed since the late 1960's. Their Fig. 1 shows a quasi-sinusoidal $O - C$ curve with an 805-day period and a 4.18-minute semi-amplitude that appears to represent the residuals.

Here we examine the third body hypothesis in a number of ways. First we apply the ordinary timing method of extracting apsidal motion from eclipse minima while including a third body light-time effect along with the usual ephemeris parameters and dP/dt, and adjusting ephemeris, apsidal, and third body parameters together. Then, by numerical experiment, we identify third body parameters that are consistent with the eclipse timings and with the dynamics of third body perturbations. This strategy leads to minimum third body masses that produce the given retrograde apsidal rates. Finally, we use a general binary star light curve program that includes a third body light-time effect to solve for $d\omega/dt$ and ephemeris parameters together with other quantities, combining radial velocities and light curves within one coherent analysis. The program has an improved stellar atmosphere routine based on Legendre polynomials that have been fitted to Kurucz atmosphere models. It also uses fluxes integrated over bandpasses instead of characterizing bands by effective wavelength. This procedure has been demonstrated to improve light curve fits, especially in the U band.

2. Analysis of Times of Minima

We analyze all available times of minima for AS Cam by Lacy's (1992) method, which avoids use of expansions in e, but we introduce some modifications. Cycle numbers are obtained with a subroutine that computes phases from Julian dates (and vice versa) by means of an ephemeris that includes not only T_0 and P_0, but also dP/dt. The phase of conjunction for a given cycle and the corresponding mean anomaly are calculated in the usual manner. With θ the angle in the orbital plane between the line of star centers and a plane normal to the orbit

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that includes the line of sight, the projected separation of centers, in units of $a = a_1 + a_2$, is

$$\delta = \frac{(1-e^2)(1-\sin^2 i \cos^2\theta)^{1/2}}{(1-e\sin(\theta-\omega))}. \tag{2}$$

Here $\omega = \omega_0 + (t - T_0)\, d\omega/dt$ is the argument of periastron at time of eclipse, and iteration is required. Minimum light occurs when δ reaches a minimum. This happens for two values of θ, one near 0 for a primary and the other near π for a secondary minimum. Lacy (1992) uses an iterative technique to minimize Eqn. 1, but actually iteration is unnecessary for this sub-problem, as solution of

$$\tan\theta = \frac{(-1)^{2-j} e \cos\omega \cos^2 i}{\sin^2 i - (-1)^{2-j} e \sin\omega} \tag{3}$$

yields the required angles ($j = 1, 2$ for the primary and secondary minima, respectively). Once θ for a given minimum has been obtained, the corresponding mean anomaly can be computed. Since a mean anomaly difference (divided by 2π) corresponds to a phase difference, the phase and hence the time of minimum can be predicted. Two to three iterations are sufficient to obtain a time of minimum that changes less than 0.00001 day per iteration. Least Squares fitting then estimates the ephemeris and apsidal parameters T_0, P_0, dP/dt, e, ω_0 and $d\omega/dt$, with results in Table 1. The solution with e adjusted would seem to

Table 1. Apsidal Motion Parameters from Minima

Parameter	Fixed e	Adjusted e
T_0 (HJD)	$2440204.39707 \pm 0.00074$	2440204.4065 ± 0.0015
P_0 (days)	3.4309689 ± 0.0000013	3.4309679 ± 0.0000013
dP/dt	$-0.29 \pm 0.24\, 10^{-9}$	$-0.25 \pm 0.24\, 10^{-9}$
i	$88.^\circ 4$	$88.^\circ 4$
e	0.16287	0.0982 ± 0.0028
ω_0 (°)	233.55 ± 0.27	188.1 ± 9.5
$d\omega/dt$ (°/100 yr)	13.5 ± 1.2	64 ± 24
P_{aps} (yr)	2675 ± 242	565 ± 212
σ (days)	0.002814	0.002786

reconcile the observed and theoretically expected apsidal motion if not for the low e. Values for e as low as 0.10 – 0.12 fail to yield acceptable solutions of the full light and radial velocity curves, as demonstrated by Maloney, Guinan, & Mukherjee (1991) and confirmed by our experiments. With e fixed at the larger value from the light and radial velocity solution, we find much slower apsidal motion, in agreement with Maloney et al. (1989), and significantly smaller than predicted.

The light-time delay Δt due to a third body can be written as

$$\Delta t = \frac{a_3 \sin i_3}{c} \frac{q_3}{1+q_3} \frac{1-e_3{}^2}{1+e_3\cos f_3} \sin(f_3+\omega_3), \tag{4}$$

with a_3 the semi-major axis, i_3 the inclination of the outer orbit to the plane of the sky, e_3 the eccentricity, ω_3 the argument of periastron, q_3 a mass ratio

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$m_3/(m_1+m_2)$, and c the speed of light in vacuum. The true anomaly of the third body, f_3, is calculated as usual from the mean anomaly $M = \frac{2\pi}{P_3}(t-\tau_3)$ through Kepler's equation. P_3 is the orbit period and τ_3 the time of periastron passage. In principle, P_3, τ_3, e_3, ω_3 and the combination $a_3 \sin i_3\, q_3/(1+q_3)$ can be determined together with the ephemeris and apsidal motion parameters from the minima. However, for AS Cam, experience shows that including e_3 as a fitted parameter prevents the Least Squares program from converging because of strong correlations. Therefore, i_3, q_3, and e_3 were kept constant while a_3 was adjusted and essentially determined by the semi-amplitude of the third body signal. Fitted parameters a_3 and P_3 determine m_3 and a new q_3 that may not agree with the original q_3. So we step q_3, i_3 and e_3 and repeat the fitting procedure until consistency is obtained. Once consistent third body parameters are extracted from the times of minima, we check whether the configuration causes the line of apsides of the eclipsing pair to rotate in a retrograde direction at a rate of, say, 30°/century, as needed to bring the predicted and observed rates into agreement. For this purpose, we use the three body program by Wilson & Van Hamme (1999), developed specifically to examine third body effects on orbital parameters. Fig. 1 shows $d\omega/dt$ versus third body mass for sets of parameters that fit the AS Cam minima. Plausible third body masses are from 0.88 to 1.76 $M_\odot$, with semi-major axes between 680 and 720 $R_\odot$. With the Hipparcos parallax of 0″.0042 ± 0″.0011 (ESA 1997), the maximum angular separation between the eclipsing pair and the third body would be 0″.014 ± 0″.004. For $d\omega/dt = -0.30°/\mathrm{yr}$, m_3 would be at least 1.3 $M_\odot$. Table 2 lists a

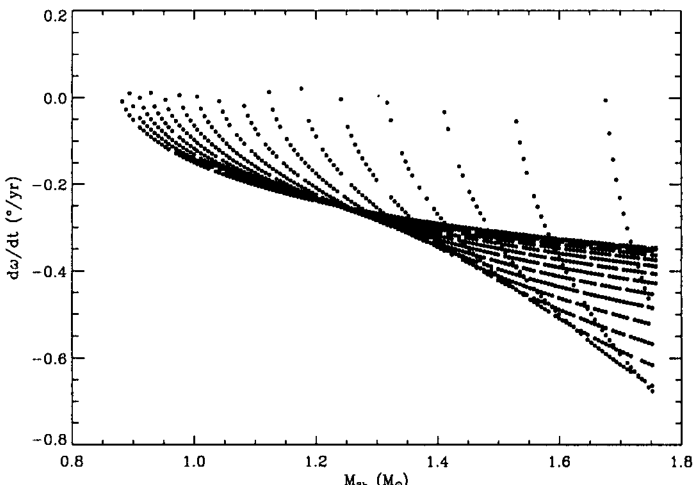

Figure 1. Apsidal rates versus third body mass for sets of ephemeris/apsidal/third-body parameters that fit AS Cam's times of minima.

final Least Squares fit to the times of minima with m_3 and i_3 such that the dynamical three-body program gives a 30°/century retrograde apsidal motion. For those parameters, the dynamical three-body program shows the inclination of the eclipsing pair to decrease 0°.3 per century, corresponding to an eclipse depth decrease of no more than 0ᵐ.004 in V. Fig. 2 shows the light-time effect

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Table 2. Apsidal Motion and Third Body Parameters from Minima

Parameter	Fixed e	Adjusted e
T_0 (HJD)	2440204.3969 ± 0.0012	2440204.402 ± 0.011
P_0 (days)	3.4309689 ± 0.0000011	3.4309685 ± 0.0000015
dP/dt	$-0.19 \pm 0.21\,10^{-9}$	$-0.17 \pm 0.22\,10^{-9}$
i	$88\overset{\circ}{.}4$	$88\overset{\circ}{.}4$
e	0.16287	0.118 ± 0.074
ω_0 (°)	233.31 ± 0.21	214 ± 54
$d\omega/dt$ (°/100 yr)	14.8 ± 1.0	28 ± 47
P_{aps} (yr)	2427 ± 167	1297 ± 2205
a_3 ($R_\odot$)	682 ± 119	680 ± 119
i_3	$56\overset{\circ}{.}44$	$56\overset{\circ}{.}44$
e_3	0.40	0.40
ω_3 (°)	31 ± 41	30 ± 42
P_3 (days)	805.4 ± 4.7	805.3 ± 4.8
τ_3 (HJD)	2444663 ± 89	2444661 ± 91
σ (days)	0.002278	0.002277

superimposed on the residuals with respect to the fitted ephemeris and apsidal motion curve.

3. Light and Velocity Solutions Including a Light-Time Effect

We made weighted simultaneous solutions of light and velocity curves with the model of Wilson (1979) including a light-time effect due to the presence of a third body. The Least-Squares fitting method is by differential corrections assisted by a Levenberg-Marquardt procedure (Levenberg 1944; Marquardt 1963) for improvement of convergence. We used time (instead of phase) as direct input and let the Least Squares process determine P, dP/dt, T_0 and $d\omega/dt$, including possible tradeoffs against other parameters. Radial velocities are from Hilditch (1972a); light curve references are Hilditch (1972b), Padalia & Srivastava (1975), Khaliullin & Kozyreva (1983), and Lines et al. (1989). Two solutions were carried out, one with dP/dt fixed from the times of minima analysis and one with dP/dt a free parameter. The V light curve by Padalia & Srivastava (1975) was not used because of a slight mismatch with the other V curves in differential magnitude level, despite use of the same comparison star and ostensibly the same kinds of standard filters. The simultaneous solution including dP/dt finds $d\omega/dt = 13.26 \pm 0.50\,°/100\,\mathrm{yr}$, which corresponds to an apsidal period of 2715 ± 102 yr. The $d\omega/dt$ agrees with the Maloney et al. (1989) and Wolf et al. (1996) $O - C$ solutions, but with standard errors 10 and 5 times smaller, respectively. Moreover, this result comes from only a 21 year data span, or less than 1% of the apsidal period. Our solutions find light of a third body at a level of 5 to 6 percent of system light at maximum. With $B - V = 0\overset{m}{.}00$ and $E_{B-V} = 0\overset{m}{.}08$, and from the amounts of B and V light at phase $0\overset{P}{.}25$ computed for each of the components by the light curve program, we determine a dereddened $B - V$ of $0\overset{m}{.}52$ for the third star, indicating a late-F spectral type and consistent with the

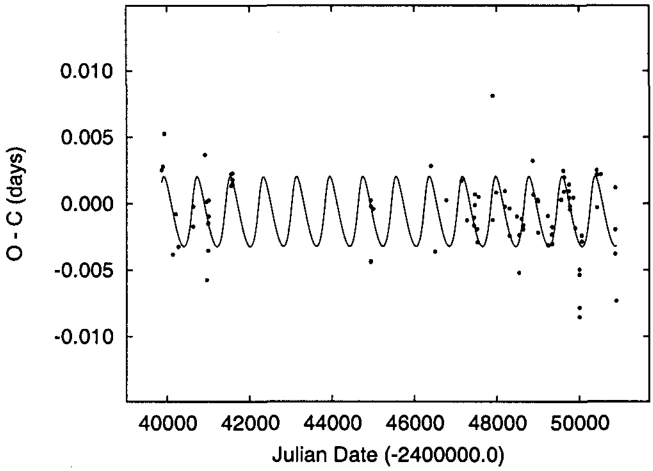

Figure 2. Third body light-time effect on $O - C$ residuals of minima with respect to the ephemeris and apsidal motion curve of Table 2 with e fixed.

1.3 $M_\odot$ minimum mass derived above. Full light/velocity solutions, including all parameters, will be given in a more detailed journal paper.

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