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UPDATED SPIN EPHEMERIS FOR THE CATACLYSMIC VARIABLE EX HYDRAE

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Recent satellite observations demonstrate that the phase of maximum flux of the 67 min spin modulation of the white dwarf in the cataclysmic variable EX Hya is drifting away from the optical quadratic ephemeris of Hellier & Sproats (1992, hereafter HS92). Relative to that ephemeris, the peak of the spin-phase extreme ultraviolet (EUV) flux modulation measured with the *Extreme Ultraviolet Explorer* (*EUVE*) was $\phi_{67} = 0.040 \pm 0.002$ in 1994 May (Mauche 1999) and $\phi_{67} = 0.115 \pm 0.001$ in 2000 May (Belle et al. 2002). Similarly, the peak of the spin-phase X-ray flux modulation measured with the *Chandra X-ray Observatory* was $\phi_{67} \approx 0.1$ in 2000 May (Hoogerwerf, Brickhouse, & Mauche 2004) and $\phi_{67} \approx 0.2$ in 2007 May (Luna, Brickhouse, & Mauche 2008). Because the discrepancy between the observed O and calculated C phases of the spin-phase flux modulation of EX Hya is now approaching a significant fraction of a spin cycle, we have undertaken the task of updating the ephemeris.

Toward that end, we have have combined the optical data of Vogt, Krzeminski, & Sterken (1980, hereafter VKS80), Gilliland (1982), Sterken et al. (1983), Hill & Watson (1984), Jablonski & Busko (1985), Bond & Freeth (1988), HS92, Walker & Allen (2000), and Belle et al. (2005) with the optical, EUV, and X-ray data listed in Table 1. The optical data were obtained by CS at ESO La Silla using the Danish 1.5-m telescope and the DFOSC CCD camera. Differential V-band magnitudes were obtained by aperture photometry extracted from flat-fielded and bias-corrected CCD frames. Other than the *EXOSAT* and *Ginga* data, which have been taken from the given references, all other times of spin maximum in the table have been derived by us from the various datasets. In the processes, we have corrected an error in the (spin *and* orbit) phases of the *ASCA* data published by Ishida, Mukai, & Osborne (1994) and the *RXTE* data published by Mukai et al. (1998). We note that our result for the second *EUVE* observation agrees within the errors with the result derived independently by Belle et al. (2002). Table 1 lists the observed times of spin maximum in Barycentric Julian Date, the corresponding cycle number derived from the HS92 quadratic ephemeris, and the $O-C$ residuals relative to the VKS80 linear ephemeris, the HS92 quadratic ephemeris, and our cubic ephemeris (eqn. 1).

Table 1. Times and cycles of spin maxima and $O-C$ residuals.

		$O-C$ (days)			
BJD(TT) − 2400000	Cycle	VKS80	HS92	Eqn. 1	Ref.[1]
45546.4450 ± 0.0010	168575	−0.013	−0.00090	−0.00039	1
46261.3044 ± 0.0026	183933	−0.014	+0.00160	+0.00181	2
46261.3471 ± 0.0025	183934	−0.017	−0.00225	−0.00204	2
46261.3928 ± 0.0021	183935	−0.018	−0.00310	−0.00289	2
46261.4450 ± 0.0014	183936	−0.013	+0.00256	+0.00277	2
46261.4905 ± 0.0017	183937	−0.014	+0.00151	+0.00172	2
46261.5353 ± 0.0029	183938	−0.015	−0.00024	−0.00002	2
46261.5789 ± 0.0019	183939	−0.018	−0.00318	−0.00297	2
46261.6239 ± 0.0015	183940	−0.020	−0.00473	−0.00452	2
46261.6730 ± 0.0018	183941	−0.017	−0.00217	−0.00196	2
46261.7218 ± 0.0022	183942	−0.015	+0.00008	+0.00029	2
46261.7636 ± 0.0014	183943	−0.020	−0.00467	−0.00446	2
46261.8148 ± 0.0016	183944	−0.015	−0.00001	+0.00020	2
46262.3707 ± 0.0018	183956	−0.018	−0.00267	−0.00246	2
46262.4227 ± 0.0017	183957	−0.012	+0.00279	+0.00300	2
46262.4668 ± 0.0014	183958	−0.015	+0.00034	+0.00055	2
46262.5130 ± 0.0016	183959	−0.015	−0.00001	+0.00020	2
46262.5552 ± 0.0020	183960	−0.020	−0.00435	−0.00414	2
47328.79044 ± 0.00154	206867	−0.024	−0.00279	−0.00319	3
47328.88757 ± 0.00322	206869	−0.020	+0.00125	+0.00084	3
47328.98132 ± 0.00253	206871	−0.019	+0.00190	+0.00150	3
47329.02481 ± 0.00155	206872	−0.022	−0.00115	−0.00155	3
47329.16375 ± 0.00097	206875	−0.023	−0.00185	−0.00225	3
47329.30569 ± 0.00149	206878	−0.021	+0.00045	+0.00005	3
49185.47425 ± 0.00023	246756	−0.031	+0.00182	−0.00014	4
49502.17402 ± 0.00010	253560	−0.033	+0.00186	−0.00043	5
50193.99031 ± 0.00019	268423	−0.037	+0.00358	+0.00051	6
51683.27876 ± 0.00010	300419	−0.049	+0.00447	−0.00067	7
51687.51537 ± 0.00005	300510	−0.048	+0.00539	+0.00025	5
52364.8102	315061	−0.050	+0.00908	+0.00283	8
52364.8608	315062	−0.046	+0.01314	+0.00688	8
52366.7276	315102	−0.041	+0.01810	+0.01184	8
52366.7759	315103	−0.040	+0.01985	+0.01359	8
54235.21476 ± 0.00007	355245	−0.068	+0.01024	+0.00035	7
54237.96000 ± 0.00011	355304	−0.069	+0.00927	−0.00063	7
54240.38080 ± 0.00006	355356	−0.069	+0.00968	−0.00022	7
54243.03427 ± 0.00007	355413	−0.068	+0.01004	+0.00013	7
54301.68235 ± 0.00045	356673	−0.069	+0.01023	+0.00019	9

[1]References: 1: *EXOSAT* (Cordova, Mason, & Kahn 1985), 2: *EXOSAT* (Rosen, Mason, & Cordova 1988), 3: *Ginga* (Rosen et al. 1991), 4: *ASCA* (Sequence 20020000), 5: *EUVE* (Program IDs 93-067 and 99-009), 6: *RXTE* (ObsIDs 10032-01-01 through 10032-01-12), 7: *Chandra* (ObsIDs 1706 and 7449–7452), 8: optical, 9: *Suzaku* (ObsID 402001010).

The task of combining optical, EUV, and X-ray data into a single ephemeris presents a number of challenges. First, the published times of optical flux maximum typically do not include error estimates. Second, the times of flux maximum are typically determined in different manners in the optical and higher-energy wavebands. In the optical, the *times* of the flux maxima are typically estimated directly from the light curves, whereas in the EUV and X-ray wavebands, where the event rates are often fairly low, the events are typically phase-folded to produce a mean light curve, from which the *phase offset* relative to the assumed ephemeris is calculated from an analytic (typically, sine) fit to the mean light curve. From this, the effective time of flux maximum is derived, typically referenced to the start or mid-point of the observation. This approach is capable of producing very high signal-to-noise ratio light curves and hence error values on the fit parameters, particularly the times of flux maxima, that are formally very small.

Table 2. Spin ephemeris constants: $T_{\rm max} = \sum C_n E^n$.

Data Included	$C_0-2400000$	C_1	C_2	C_3
Optical	37699.89154	+0.046546479	-6.29×10^{-13}	. . .
	±0.00054	±0.000000007	$\pm 0.23 \times 10^{-13}$	
EUV & X-ray	37699.88930	+0.046546477	-6.19×10^{-13}	. . .
	±0.00165	±0.000000011	$\pm 0.17 \times 10^{-13}$	
All	37699.89301	+0.046546454	-5.85×10^{-13}	. . .
	±0.00041	±0.000000003	$\pm 0.05 \times 10^{-13}$	
All	37699.89165	+0.046546484	-7.34×10^{-13}	$+2.16 \times 10^{-19}$
	±0.00056	±0.000000009	$\pm 0.42 \times 10^{-13}$	$\pm 0.61 \times 10^{-19}$

Given these complications, we have taken a multi-step approach to calculate a revised spin ephemeris for EX Hya. First, we fit the optical data to a quadratic ephemeris without weights, producing the ephemeris constants listed in the first entry of Table 2. The standard deviation of this fit is 0.00361 days or 0.077 cycles (which, if used as a uniform error on the data, produces the same fit with a reduced $\chi^2 = 1$). Second, we fit the EUV and X-ray data to a quadratic ephemeris accounting for the errors listed in Table 1, producing the ephemeris constants listed in the second entry of Table 2. The two results, optical on one hand and EUV and X-ray on the other, are consistent within the errors and are as well close to (but different than) the optical quadratic ephemeris constants of HS92. Next, we fit the combined data sets, using 0.00361 days for the error on the optical data and the errors listed in Table 1 for the errors on the EUV and X-ray data, producing the ephemeris constants listed in the third entry of Table 2. The ephemeris constants are now significantly different than those of the previous fits, although it is apparent that the fit is not ideal ($\chi^2/dof = 646.0/428 = 1.51$), in part because the ephemeris rolls over too rapidly at early times. To remedy this deficiency, we fit the combined data sets to a cubic ephemeris, producing the ephemeris constants listed in the fourth entry of Table 2. The fit is now somewhat improved ($\chi^2/dof = 633.3/427 = 1.48$), the fit parameters are closer to the those of the earlier quadratic fits, the ephemeris is close to that of HS92 through 1991 January (230,000 cycles; Fig. 1*a*), and it reproduces well all of the available EUV and X-ray data (Fig. 1*c*). Finally, by setting a lower limit of 0.02 cycles or 0.00093 days on the size of the timing errors on the EUV and X-ray data, the reduced χ^2 of the fit is reduced to a very reasonable $\chi^2/dof = 465.8/427 = 1.09$. We note that the largest discrepancy between the data and the ephemeris is in the last group of optical data. While this is of some concern, and warrants future checking, we recommend that the following cubic ephemeris be used for recent past and future timings of the flux maxima of the spin modulation of the white dwarf in EX Hya:

$$T_{\rm max} = 2437699.8917(6) + 0.046546484(9)\,E - 7.3(4)\times10^{-13}\,E^2 + 2.2(6)\times10^{-19}\,E^3. \quad (1)$$

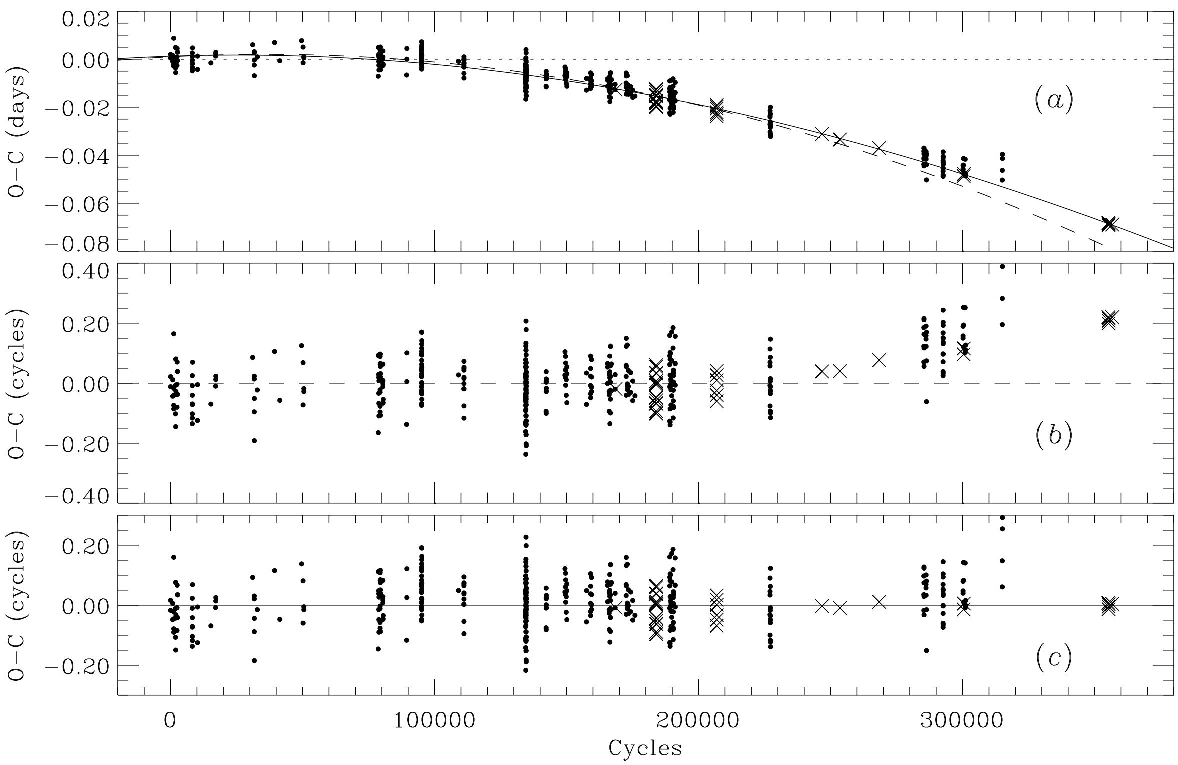

Figure 1. $O-C$ residuals for the optical (*filled circles*) and EUV and X-ray (*X*s) spin maxima of EX Hya relative to (a) the VKS80 linear spin ephemeris, (b) the HS92 quadratic spin ephemeris, and (c) the cubic spin ephemeris of equation 1. In the top panel, the HS92 quadratic and equation 1 cubic spin ephemerides are shown relative to the VKS80 linear spin ephemeris by the dashed and solid curves, respectively.

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