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AN IMPROVED EPHEMERIS FOR Z CAMELOPARDALIS

Z Cam is the prototype of a class of dwarf novae that show standstills in their light curves. Kraft et al. (1969; henceforth KKM) first established its ephemeris. They combined radial-velocity information with observations of periodic features in the light curve to derive a period of $0.289840 \pm 1 \times 10^{-6}$ d. Two studies by Robinson (1973a and 1973b), one photometric and the other using Hα emission velocities, did not yet show any significant error in the KKM ephemeris as of the early 1970s. Szkody & Wade (1981) obtained a cycle of emission-line velocities in early 1979, when Z Cam was in standstill: they also found no difference from the KKM ephemeris. Even so, the formal error in the KKM ephemeris has now accumulated to greater than 0.1 cycle, so we re-established the phase.

We obtained spectra of Z Cam using the Michigan-Dartmouth-MIT Observatory 1.3-m McGraw-Hill telescope. We used the Mark III transmission-grating spectrometer and a TI 4849 CCD chip (Luppino 1989); our 300 line/mm grating gave 10 Å FWHM resolution from 6400 to 9000 Å. On 1991 October 17 UT we obtained thirteen 15-minute exposures covering three hours; the next night we obtained three exposures, and the night after this we obtained a single spectrum. Reduction followed the procedures described in Thorstensen et al. (1991) and the references therein. The emission lines within our spectral range were strong; Hα had an equivalent width of 37 Å in the sum of our spectra, and at its center stood about twice as high as the adjacent continuum. The FWHM of Hα was 30 Å. Our first night was photometric, and we reduced our spectra to absolute flux using an observation of the white dwarf G191B2B; with a modest extrapolation to shorter wavelengths, we derive for Z Cam $V = 13.5 \pm 0.3$ (estimated error). This is close to the mean minimum magnitude (Szkody & Mattei 1984). Thus the magnitude and spectrum both show that Z Cam was not in outburst or standstill. There were no evident changes in the spectrum or flux during our brief observations.

Unfortunately, the red-star features were not measurable in our spectra, unsurprising given its rather early spectral type (G1: KKM). We therefore measured the strong Hα emission line using a double-Gaussian convolution technique (Shafter 1983). The Gaussians in the template were separated by 34 Å (full width), equivalent to 1500 km s^{-1}. In effect, this measured the steep sides of the line profile. Table 1 lists the resulting velocity time series. We fit to our emission-line velocities a least-square sinusoid of the form

$$v(t) = \gamma + K \sin[2\pi(t - T_0)/P],$$

with the period P fixed at the KKM value. With this convention, T_0 is the epoch of apparent inferior conjunction of the line source. This gave $\gamma = -36 \pm 3$ km s^{-1}, $K = 138 \pm 4$ km s^{-1}, and $T_0 =$ HJD 2448547.0174 ± 0.0014, where the uncertainties are 1-σ. The choice of T_0 is arbitrary *modulo* the period; the epoch given here corresponds to the night of our most extensive observations. The 1-σ error of a single measurement, derived from the goodness of fit, was only 11 km s^{-1}. We also re-fit the Hα velocities from Robinson (1973b); this gave $\gamma = -44\pm6$ km s^{-1}, $K = 135\pm9$ km s^{-1}, and T_0 = HJD 2441355.7828$\pm$ 0.0028; the goodness-of-fit implies $\sigma = 25$ km s^{-1}. The good agreement between the K and γ velocities in the two studies gives us confidence that our phases may be compared directly. We are further emboldened since we are measuring the same line (Hα emission) in the same state (quiescence) and using a broadly similar centering, which emphasizes the outer parts of the line profile.

The two values of T_0 above are 7191.2346 days apart. This is 24811.05 cycles of the KKM period. There is no ambiguity in the cycle count; KKM's quoted error does not allow it, and the adequacy of the KKM ephemeris for the intervening epochs of Robinson (1973a and 1973b) and Szkody & Wade (1981) makes a cycle-count error even more unlikely. Adopting 24811 cycles for the interval gives a refined period $P = 0.2898406(2)$ d, where the quoted uncertainty is inflated a bit from the formal 1-σ value (1.2×10^{-7} d) and is in units of the last quoted digit. In Figure 1 we show the data of Robinson (1973b), folded together with ours on this best period. Extending this analysis back to the original KKM radial-velocity data does not improve the accuracy much, since their velocities show much more scatter than ours or Robinson's, and the extension of the time base is modest; in any case, the epoch of emission-line conjunction given in KKM's Table 2 agrees with our phase to within 0.01 cycle. Given how well our period agrees with the KKM ephemeris, which was adequate through the 1970s, there is no evidence yet of any period change.

The KKM study did, however, define a phase tied to the red star in the system; this red-star phase should have a more direct physical interpretation than the emission-line phase. KKM noted that the emission lines are not precisely 180 degrees out of phase with the absorption (presumed to represent the red star), but rather lag by an additional 0.017 d (some 20 degrees of phase). The ephemeris quoted in KKM's equation (1) is for the inferior conjunction of the red star; if we assume that the 0.017 d offset still holds, we find for an updated red-star ephemeris

$$\text{Red star inferior conjunction} = \text{JD}_{\odot}2448546.855 + 0.2898406(2)E,$$

where E is the integer cycle count. For completeness we give here

$$\text{Emission-line inferior conjunction} = \text{JD}_{\odot}2448547.0174 + 0.2898406(2)E.$$

Table 1: Hα Emission Velocities in Z Cam

HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})
8546.881	−52	8546.936	−171	8546.981	−124	8547.943	79
8546.891	−84	8546.948	−190	8546.993	−109	8547.954	106
8546.903	−124	8546.959	−171	8547.004	−60	8547.965	99
8546.914	−132	8546.971	−148	8547.016	−42	8548.958	−186
8546.926	−159						

[a] Heliocentric Julian Date of mid-integration, minus 2 440 000.

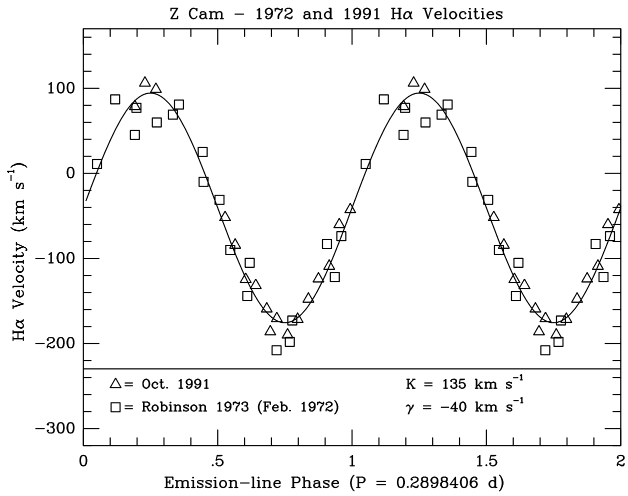

Figure 1. Hα radial velocities from Robinson (1973b; squares) and this work (triangles) folded on the refined period. All data are plotted twice for continuity. The curve shown is the least-squares best fit, and its parameters are given in the figure. For the horizontal axis, phase zero is apparent inferior conjunction of the emission line source; inferior conjunction of the red star should be at phase 0.44 in this convention (KKM).

The emission-line epoch has rather better internal precision than the absorption-line epoch. Since the emission lines form in or above the accretion disk, it seems surprising that the ephemerides from such widely separated epochs can be phased together, and that there is no obvious phase change between quiescence and standstill.

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