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DIRECT DISTANCE ESTIMATION AND ABSOLUTE PARAMETERS OF Z DRACONIS

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Terrell (2006) briefly discussed the early observational efforts on the Algol-type binary Z Draconis and presented differential BVR_CI_C light curves, the first published light curves obtained on a modern photometric system. Since then, the availability of the AAVSO Photometric All-Sky Survey (APASS; Henden, et al. 2012) has made it possible to place the observations on the standard (absolute) system by using APASS standards in the field of Z Dra. We present a re-reduction of the BV images of Terrell (2006) that place the data on the standard system. We also present new spectroscopic observations that yield radial velocities of the primary star and, for the first time, the secondary star, thus enabling us to measure the mass ratio accurately. The combination of standard photometry (with flux calibrations, *viz.* Wilson, et al. 2010) and radial velocities allows for the inclusion of the distance to the binary as a solution parameter, yielding a distance estimate and corresponding error that includes the correlations with other adjusted model parameters directly, rather than being an after-the-fact estimate with simplifying assumptions (*e.g.* spherical stars). This Direct Distance Estimation (DDE) approach is described in Wilson (2008) and application examples are found in Wilson & Van Hamme (2009), Vaccaro, et al. (2010), Wilson & Raichur (2011) and Vaccaro, et al. (2015).

The equipment used to make the photometric observations is described in Terrell (2006). The BV images were bias/dark subtracted and flatfielded using the ccdproc routine in IRAF (Tody, 1993), and instrumental magnitudes were measured using PSF fitting with SExtractor (Bertin & Arnouts, 1996) and PSFEx (Bertin, 2011). The instrumental magnitudes were then transformed onto the standard system using the method described in Terrell, et al. (2016). The resulting BV magnitudes are available from the IBVS web site as file 6223-t3.txt. We chose to use the BV images and not the R_CI_C images for two reasons. First APASS does not provide R_CI_C magnitudes for standards directly, and transformations from the APASS passbands ($BVg'r'i'$) to R_CI_C are still preliminary. Secondly, the DDE approach is best suited to the analysis of light curves in two passbands when solving for the surface temperatures of both stars, as we do here (*viz.* Wilson, 2008). The addition of a light curve in a third passband would allow us to add the interstellar extinction as an adjustable parameter, but the extinction towards Z

Table 1: Radial velocity observations of Z Dra.

DAO image #	Mid time (HJD–2400000)	Exposure (sec)	Phase at mid-exposure†	V_1 ($km\ s^{-1}$)	V_2 ($km\ s^{-1}$)
11-02487	55666.7962	3600	0.275	–82.9 ± 2.3	140.8 ± 5.4
11-02532	55668.8275	1097	0.772	25.6 ± 2.7	–203.3 ± 3.2
11-02569	55670.7885	3600	0.216	–82.0 ± 2.3	143.0 ± 5.9
11-02710	55676.7913	3600	0.639	14.4 ± 2.3	–189.7 ± 7.6
11-02719	55676.9429	3600	0.750	25.9 ± 2.5	–205.4 ± 3.0
11-02752	55678.8829	3600	0.180	–75.8 ± 2.4	117.9± 5.6

† Phases computed using the ephemeris parameters in Table 2.

Dra appears to be very small (Terrell, 2006), as expected for its high galactic latitude and close distance. We did perform some solutions with BVI_C light curves, both adjusting the extinction directly and by doing solutions on a grid of fixed values for the extinction, but the results were not encouraging. The likely small value of the extinction combined with the uncertainties in the I_C calibration probably play a role in the inability to measure the extinction with our data.

In April of 2011, RHN secured a total of six medium resolution (R≈10,000) spectra of Z Dra at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada using the Cassegrain spectrograph attached to the 1.85 m Plaskett Telescope. The 21181 configuration was employed using a grating with 1800 lines/mm, blazed at 5000 Å, and giving a reciprocal linear dispersion of 10 Å/mm in the first order. The wavelengths ranged from 5000 to 5260 Å, approximately. Frame reduction was performed by software RaVeRe (Nelson 2013). See Nelson (2010) and Nelson et al. (2014) for further details. Radial velocities were determined using the Rucinski broadening functions (Rucinski, 2004, Nelson, 2010) as implemented in software Broad (Nelson, 2013; Nelson et al. 2014). A log of the spectroscopic observations is given in Table 1.

The BV light curves and the new radial velocities were analyzed simultaneously with the 2013 version of the Wilson–Devinney program (WD; Wilson & Devinney, 1971; Wilson, 1979; Wilson, 2008). Since Z Dra is a semi-detached system with the lower mass secondary filling its Roche lobe (confirmed by initial experiments with the model using a detached configuration), we employed WD mode 5 in all of our solutions. We performed fitting experiments assuming both convective and radiative envelopes for the primary star, but found that models assuming a convective envelope gave superior fits in all cases, thus our best-fit model assumes a value of 0.32 for the gravity darkening exponents of both stars and a value of 0.5 for the bolometric albedoes. Limb darkening coefficients were automatically computed at each iteration from the Van Hamme (1993) tables. Weights for the various light and velocity curves were determined automatically by WD at each iteration.

In contrast to the traditional way of analyzing photometry using independently and arbitrarily scaled light curves in several passbands, the DDE approach uses standard magnitudes and preserves the color information found in the differences between the light curves in each passband at each point in the binary orbit. With two light curves in different passbands, it is therefore possible to allow the surface temperatures of both stars to adjust in the solution, as opposed to the traditional approach where the temperature of one star is fixed at a value derived from other sources such as spectral types or colors

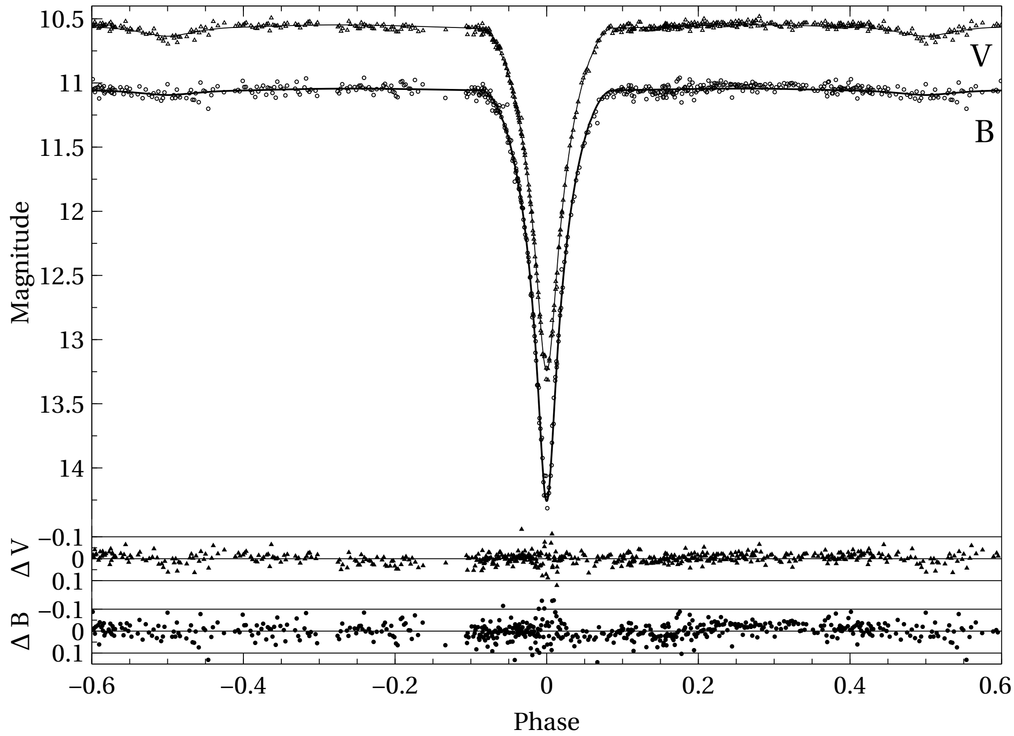

Figure 1. The fits to the B and V light curves of Z Dra. The residuals (observed - computed) from the fits are shown at the bottom.

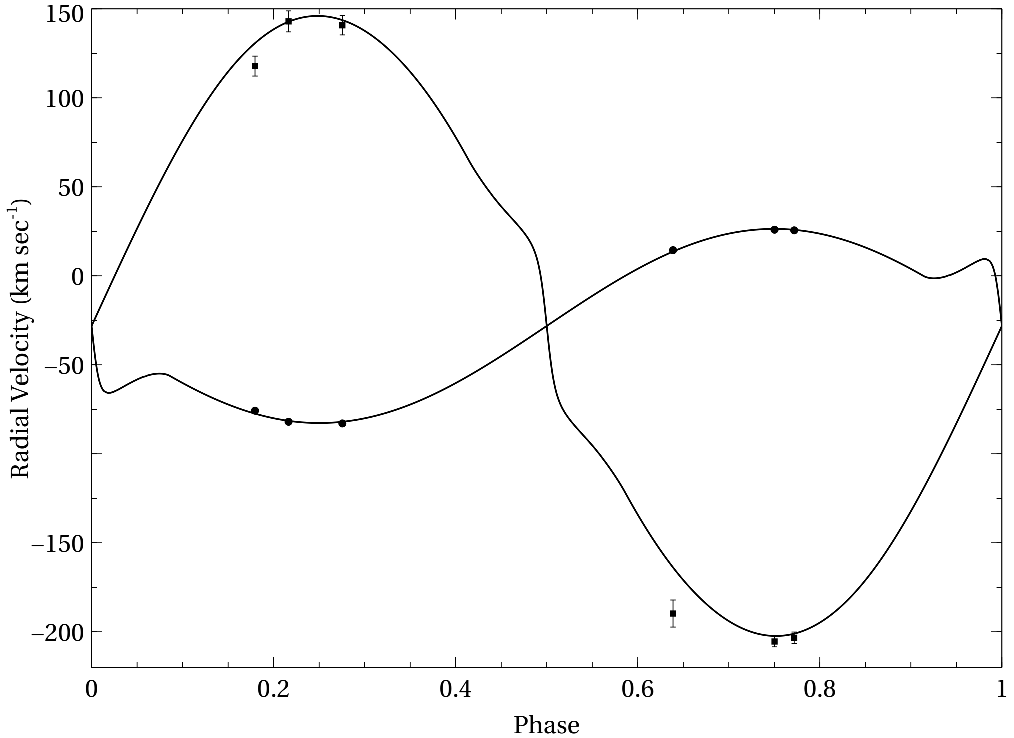

Figure 2. The fits to the radial velocity curves curves of Z Dra. The sizes of the error bars on the primary star velocities are approximately the same size as the points.

Table 2: Parameters from the light/velocity curve solution.

Parameter	Value	Std. error
a	6.29 $R_\odot$	0.08 $R_\odot$
V_γ	-28.2 km sec^{-1}	0.5 km sec^{-1}
i	$86\overset{\circ}{.}94$	$0\overset{\circ}{.}06$
T_1	6446 K	11 K
T_2	3936 K	14 K
q	0.304	0.002
Ω_1	4.56	0.02
Ω_2	2.475	(lobe filling constraint)
HJD$_0$	2453430.71668	0.00006
P	$1\overset{\mathrm{d}}{.}3574226$	$0\overset{\mathrm{d}}{.}00001$
$\dot{P}$	2.0×10^{-8}	1.1×10^{-8}
$log(d)^\dagger$	2.441	0.005
M_1	1.39 $M_\odot$	0.05 $M_\odot$
M_2	0.42 $M_\odot$	0.02 $M_\odot$
R_1	1.48 $R_\odot$	0.02 $R_\odot$
R_2	1.77 $R_\odot$	0.02 $R_\odot$
$L_{V,1}$	4.0 $L_\odot$	0.1 $L_\odot$
$L_{V,2}$	0.134 $L_\odot$	0.004 $L_\odot$

† Distance d to the binary in parsecs.

as, for example, in the solution for Z Dra of Terrell (2006).

Table 2 shows the adjusted parameters which includes the distance to the system in addition to the expected parameters for a semi-detached solution with light and radial velocity curves. Figure 1 shows the fits to the light curves, and Figure 2 the radial velocity fits. There are clearly small asymmetries present in the light curves, probably due to spots, and we did attempt a few fits with a single cool spot on the primary, but the improvement in the fit was marginal and the question of the uniqueness of such solutions with modest-precision light curves led us to abandon the spot fits. As noted in Terrell (2006), the derived value of $\dot{P}$ is not particularly informative given the complex period changes in the system, but it was included to allow for the change in period between the epochs of the photometric and spectroscopic observations so that they could be analyzed simultaneously. Previous studies of the eclipse timings (*viz.* Khaliullina, 2016 and references therein) conclude that a third star may be present in the system and we included third light as an adjustable parameter in our solutions, but this led to physically unrealistic (negative) values.The estimated distance to the system is 276 ± 3 pc and that compares well to the value of 283^{+19}_{-17} pc from Gaia Data Release 1 (Gaia Collaboration, et al. 2016). If there were third light in the system that was unaccounted for in the model, the distance to the system would be understimated because the system would be too bright for its actual distance. The good agreement with the distance from Gaia supports the argument that any third light in Z Dra must be negligible.

With a mass of 0.42 $M_\odot$ and a radius of 1.77 $R_\odot$, the secondary component is clearly evolved, making Z Dra a short-period Algol. Still unresolved is the nature of the period changes in the system. A period increase due to mass transfer from the lobe-filling secondary seems to be a reasonable conclusion but the somewhat periodic changes on top of that are still debated. The light time effect, the Applegate (1992) mechanism, or a combination of both, are plausible explanations at this point. Further observations, standardized photometry in particular to measure luminosity changes predicted by the Applegate mechanism, will be needed to decide between the various possibilities.

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