Analysis of *BVI* Photometry of the Eclipsing Binary EV Lyrae

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Abstract Differential photometry of the previously little-observed semi-detached eclipsing binary EV Lyr from the 2006 observing season is presented and analyzed. This study utilized a 25-cm SCT instrument to observe portions of 116 orbital cycles and obtain *B*-, *V*-, and *I*-band photometry. This allowed the development of a complete phase diagram of the system and determination of the period of 0.91847 ±0.0002 day and HJD epoch 2453894.71997. Visual band photometric observations were fit to a binary star model phase diagram using the binary star modeling program NIGHTFALL. Derived properties for the primary were $M/M_{\odot}$ = 1.6, $R/R_{\odot}$ = 1.64, spectral type F0 V, and effective temperature of 7300 K. Derived properties for the secondary were $M/M_{\odot}$ = 0.79, $R/R_{\odot}$ = 0.78, spectral type K0 V, and effective temperature of 5200 K. Inclination for the system was found to be 88°.

1. Introduction

As part of an informal, on-going project to clean up, correct, or complete entries in the *General Catalogue of Variable Stars* (GCVS) (Krajci 2006), an observational study of EV Lyr was begun in the 2006 observing season (northern hemisphere). EV Lyr is listed in the current on-line GCVS (Samus *et al*. 2007) as a semi-detached eclipsing binary star, although the period and associated epoch are not currently shown. Its variability was first described by Hoffmeister (1929) as an Algol-type star system that varies between 13.0 and 15.0 apparent magnitude, with this variability probably derived from visual observations. Since then, little has been published on this variable star system, except for a period determination from an automated survey by Hartman *et al.* (2004). As a type EA/SD binary, the surface of the less massive component of EV Lyr is close to its inner Roche lobe, and is likely ellipsoidal in shape. Typically for these types of binaries, the light remains constant between eclipses or varies very slightly because of reflection effects, surface features, and/or the shape of a component star. The GCVS gives periods of known semi-detached binaries which typically range from 0.4 day to 18 days or more, with an average of 2.4 days (Samus *et al*. 2007).

Because photometry of this type of system lends itself to modeling by binary star modeling software, detailed multi-band photometry of the system

can be used, in conjunction with the software, to derive the major parameters of the stellar system. In this manner, observable and deduced properties of incomplete entries in the GCVS can be obtained.

2. Observations

In the summer of 2006, EV Lyr was observed from JD 2453894.755 to JD 2454001.781 (6 June 2006 through 23 September 2006), encompassing 116 orbital cycles. The observations were made using a Meade LX200 10-inch (0.25-m) telescope, with a Starlight Xpress MX 716 CCD camera, which has a 550 × 720 pixel array. One-minute exposures were taken at an *f*-ratio of 6.3 (for an effective field of view of approximately 11 × 14 arcminutes) with Johnson *B*, *V*, and Cousins *I* filters. Typical seeing conditions for this low-altitude site were between 3.5 and 4.5 arc seconds FWHM for EV Lyr in each image. The airmass for observations ranged from 1.01 through 1.45. All exposures were dark current and bias subtracted, and also flat-fielded (using twilight sky flats) according to established procedures. The software tool AIP4WIN, Ver 2.0 (V2.1.0, Berry and Burnell 2000), was utilized for photometric measurements.

All exposures of EV Lyr included two comparison stars GSC 31345 (Tycho data: $V = 10.02$, $B = 11.03$) and GSC 31343 (Tycho data: $V = 10.09$, $B = 10.37$). To insure that the comparison stars were not variable, the difference between GSC 31345 and GSC 31343 was also measured for each exposure. The standard deviation of the *V*- and *B*-band magnitude difference over all observations was found to be 0.020 and 0.017, respectively.

The *B*, *V*, and *I* photometric data on each comparison star were normalized with measurements taken from Tycho observations of these comparison stars, corrected to the Johnson and Cousins system. Zero points were then determined from the comparison star photometry and applied to the EV Lyr photometry using AIP4WIN to produce standardized *B*–*V* and *V*–*I* measurements of EV Lyr. The calculated photometric error of observations of EV Lyr was at or below 0.04 magnitude.

The position determined for EV Lyr was R.A. $19^h\,26^m\,36.45^s$ Dec. +39° 02' 17.6" (2000.0) based upon the reference coordinates in the *USNO-A V2.0 Catalog* (Monet *et al.* 1998), and is within 3.5 arcseconds of the position generated from the SIMBAD website (FK5 2000.0 coordinates: R.A. $19^h\,26^m\,36^s$ Dec. +39° 02' 06") and the coordinates in the GCVS.

Since there was limited knowledge of the parameters of the EV Lyr system, a sustained observation program had to be mounted to observe the variable on a regular basis for a significant number of hours per observing session. The binary system was initially observed nightly for a period of three weeks starting in June of 2006. Fortunately, during this initial observing campaign, multiple primary eclipses and several secondary eclipses were recorded.

3. EV Lyr period determination and phase diagram

To determine the period of EV Lyr, nine sets of *V*-band data taken during the initial observational campaign, each four to five hours in length, and including a primary eclipse in six such sets, were entered into the software program PERANSO (Vanmunster 2005). Using PERANSO's EA SOLVER analysis tool, the period for EV Lyr was determined to be approximately 0.9183 day, which allowed a complete phase diagram to be generated from the observational data. This phase diagram is seen in Figure 1. The phase diagram has the obvious characteristics of a semi-detached eclipsing binary, with a deep primary eclipse and a shallow secondary eclipse. Presumably, it is aspects of this phase diagram that allowed Hoffmeister to deduce this binary as an Algol type, but no such phase diagram was included in the original publication (Hoffmeister 1929), nor could be found in the literature. Multiple eclipses were recorded over the remainder of the summer and the midpoint of each eclipse identified. Utilizing the minima tool of Kwee and van Woerden (1956) in PERANSO, a more precise orbital period was calculated for EV Lyr as 0.91847 ± 0.00002 day, with a corresponding HJD epoch of 2453894.71997. The previously noted automated survey period determination (Hartman *et al.* 2004) was 0.9185 day.

4. Primary and secondary eclipses

The primary eclipse for EV Lyr was measured to be from 13.83 to 15.93 *V* magnitude, with the secondary eclipse measured from 13.83 to 14.04 *V* magnitude. The duration of the primary and secondary eclipses were measured to be 4.4 and 2.85 hours, respectively. A phase diagram of the primary eclipse in *B*, *V*, and *I* bands are shown in Figure 2. The average *B–V* color index of the non-eclipse light was found to be 0.68, while the *B–V* color index at maximum eclipse was measured to be 0.80. For the secondary eclipse, the *B–V* color index at maximum eclipse was measured to be 0.63.

5. Intrinsic variation

In order to detect any variability of EV Lyr during non-eclipse segments of its orbit, sets of twenty *V*-band exposures were averaged during seven six-hour observing runs. This averaging decreases the overall effects of scatter and scintillation. A plot of the light from EV Lyr for these non-eclipse averaged observations is shown in Figure 3. As can be seen, light from the binary star system varies up to approximately 0.1 *V* magnitude over a six hour period, and is present in both the early and later observational data sets. This variation could be the result of the ellipsoidal shape of the secondary star, surface spots/surface activity, heating effects on the primary or secondary star, and/or the result of low-volume mass transfer, although no flares or rapid brightening events were observed.

6. Spectral type and effective temperature

Although the graph of the primary eclipse does not have a flattened bottom, indicating that the eclipse is not total, the depth of the eclipse would still indicate that little of the primary star's light is present at eclipse maximum. Using the *B–V* color index of primary eclipse at this point allows computation of the probable effective temperature of the secondary star (Popper 1980).

McWilliam (1990) and Amado and Byrne (1996) have provided empirical relationships for effective temperature versus color indices (e.g., *B–V* or *V–I*) for stars of spectral types G to M. Using the color index of 0.80, this empirical relationship indicates an effective temperature of 5200 K. Using published tables of luminosity class and star effective temperatures from Meyer *et al.* (1998), this effective temperature would mean that the secondary star is likely a K0 V.

7. Fit to a binary star model

The binary star modeling software tool NIGHTFALL (Wichmann 1999) was used to model the EV Lyr system. This program utilizes the Djurašević (1992) binary star model. A phase-based data file for the entire phase diagram was created from the observations that included both the intrinsic variation and eclipse data points and this file was input to the modeling program.

Before beginning the phase diagram matching routine, certain parameters need to be input from known values from the observations or assumed from astrophysically reasonable numbers (Wilson 1994). The orbital period has been determined, as well as the probable effective temperature of the secondary star. Although the effective temperature of the primary star can not be similarly directly measured, it is possible to infer a range of spectral types from the overall EA/SD binary type and eclipse data. As the primary eclipse is quite deep—slightly more than two magnitudes—this should mean that the primary is several thousand degrees hotter than the secondary, and is probably a late A- or early F-type star, with an approximate effective temperature of 7500 K. This stellar type was used for the initial temperature and corresponding mass of the primary star parameters.

In turn, using common masses for these type stars the initial mass ratio would be 0.5 for the EV Lyr system. The (Roche Limit) fill factor was set to 0.6 and 1.0 for the primary and secondary, respectively. The initial inclination was assumed to be 89°. The linear cosine relationship was utilized in the model for limb-darkening.

The data-fitting routine of the software was started, and most system parameters (inclination, primary mass, primary fill factor, etc.) were allowed to vary from their initial conditions. After multiple iterations, the best match for the data (i.e., the smallest χ-square value = 0.95) was found. The NIGHTFALL software model output for *V*-band photometry is shown in Figure 4. This same

output, mapped together with the observational data, is shown in Figure 5. It should be noted that the output of the NIGHTFALL program positions the primary eclipse at the 0.5 phase point and the phase diagram is drawn from –0.25 to 0.75 phase. Figure 6 shows the residual values of the EV Lyr observation data subtracted from the binary star model data for the same orbital phase points. Using this best-fit solution to the observational data, the probable physical parameters for the EV Lyr star system are shown in Table 1.

8. Conclusions

This paper has presented new *B*-, *V*-, and *I*-band photometry of EV Lyr, which included multiple observations of the primary and secondary eclipses, and uncovered some intrinsic variability of the system. From these observations, it has been possible to determine the orbital period of EV Lyr and the associated epoch, and deduce the other principle parameters of the binary star system, which can be added to the data of the GCVS for this system. The analysis, together with the EV Lyr phase diagram, confirms that this stellar system is a typical semi-detached eclipsing binary. The period of EV Lyr, at 0.91847day, is shorter than approximately 80% of similar EA/SD binaries listed in the current online GCVS (Samus *et al.* 2007), although the derived stellar types, radii, and masses are very similar to other Algol-type systems (Popper 1980).

9. Acknowledgements

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Table 1. Observed and derived EV Lyr system properties. From observations by the author in 2006.

Parameter	*Value*
Primary Spectral Type	F0V
Primary Star Mass	$1.6\ M_{\odot} \pm 0.08\ M_{\odot}$
Primary Star Radius	$1.64\ R_{\odot} \pm 0.1\ R_{\odot}$
Secondary Spectral Type	K0V
Secondary Star Mass	$0.79\ M_{\odot} \pm 0.08\ M_{\odot}$
Secondary Star Radius	$0.78\ R_{\odot} \pm 0.08\ R_{\odot}$
Mass Ratio (q_0)	0.43 ± 0.1
Orbital Inclination (i)	$88° \pm 1.0°$
Stellar Separation	$5.31\ R_{\odot} \pm 0.07\ R_{\odot}$
Orbital Period	0.91847 ± 0.0002 day
HJD Epoch	2453894.7199 ± 0.0007
Duration of Primary Eclipse	5.9 ± 0.03 hours

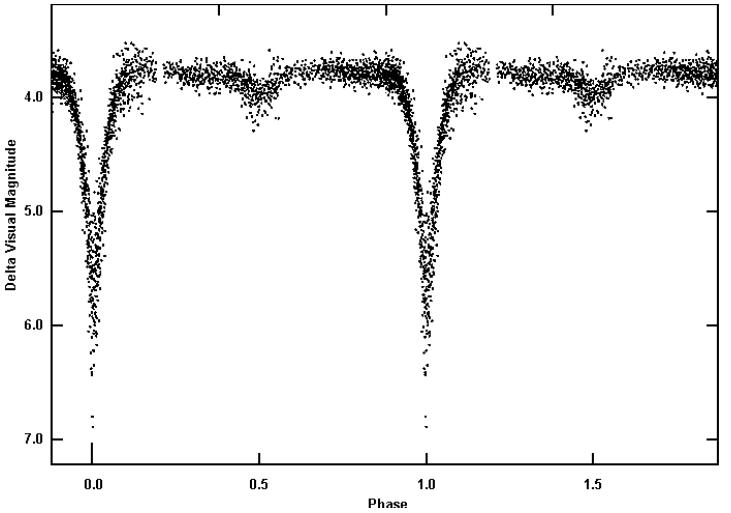

Figure 1. Phase diagram for EV Lyr. From observations by the author in 2006.

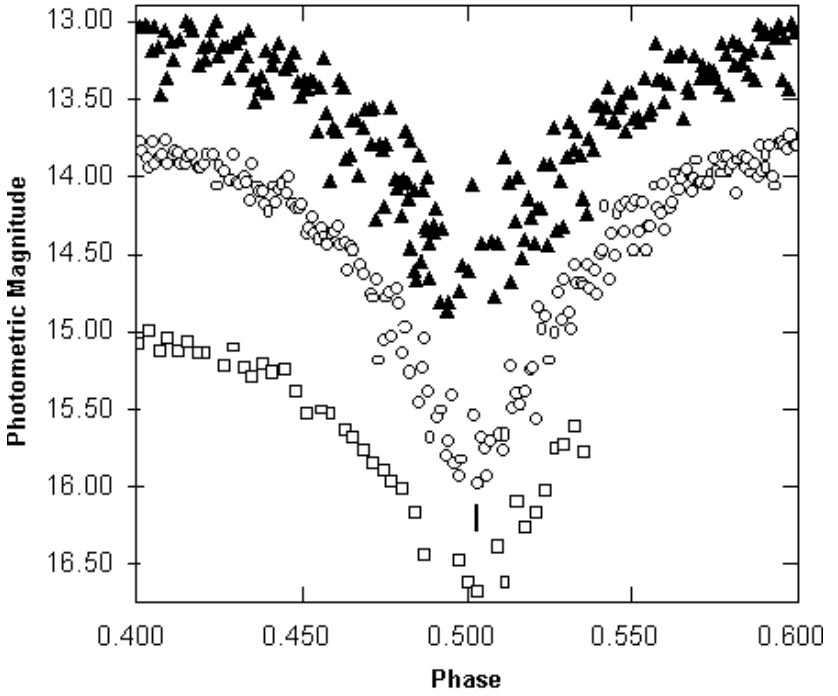

Figure 2. Phase diagrams of the primary eclipse of EV Lyr. From observations by the author in 2006. Circles denote *V* band; squares, *B* band; triangles, *I* band.

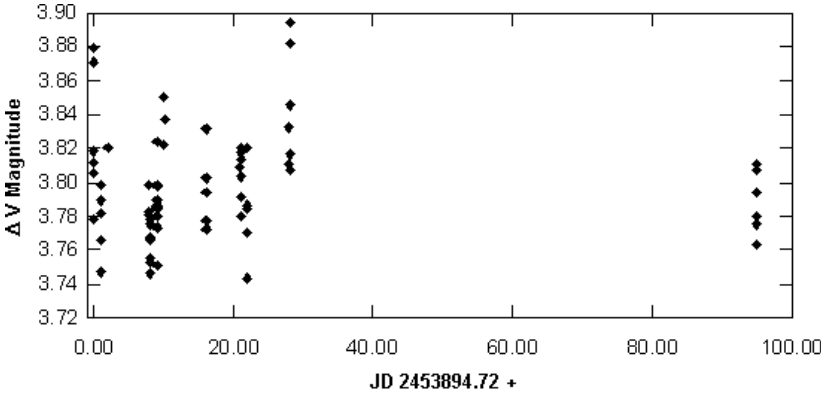

Figure 3. Intrinsic variability of EV Lyr. Each diamond is an average of 20 individual observations, with a *V* magnitude uncertainty of 0.02. From observations by the author in 2006.

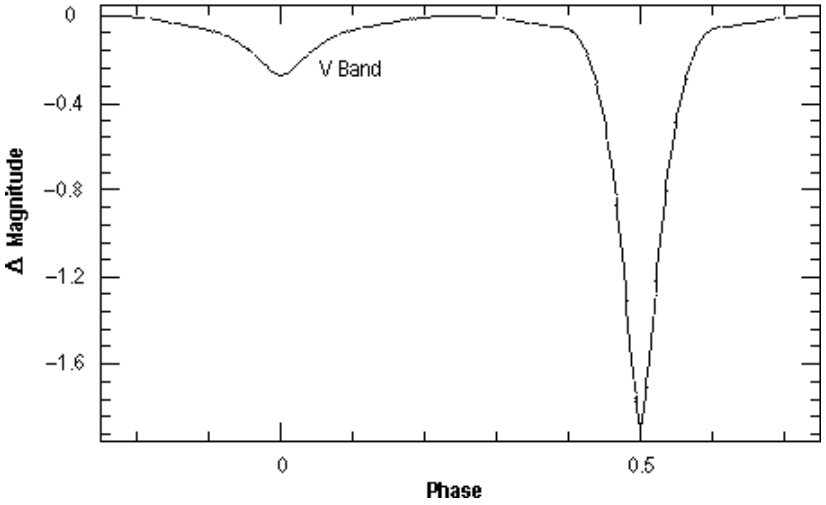

Figure 4. EV Lyr NIGHTFALL Binary Model phase diagram.

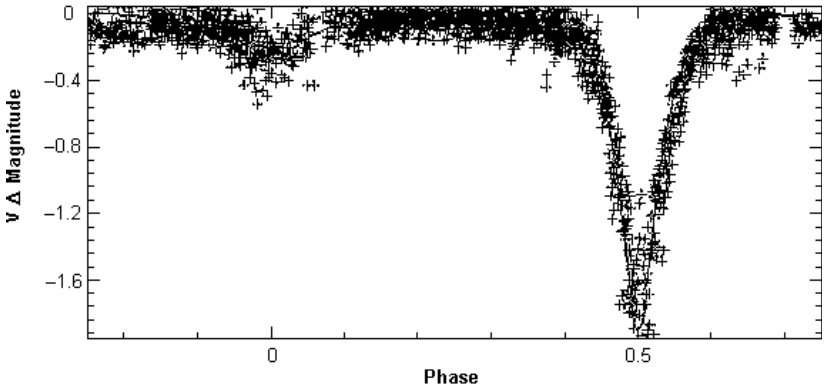

Figure 5. EV Lyr observational data fit (pluses) to binary model (line) shown in Figure 4. From observations by the author in 2006.

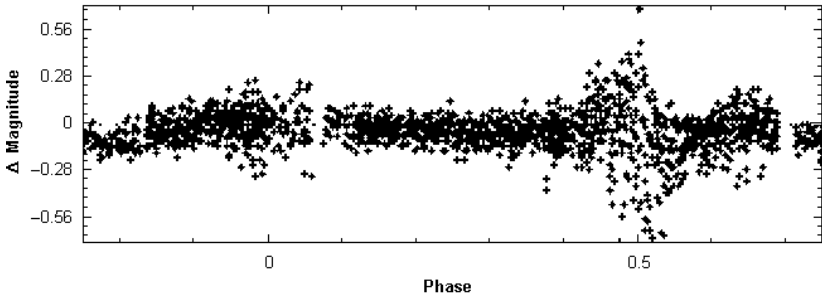

Figure 6. Residual values of EV Lyr observed minus fit data. From observations by the author in 2006.