Changes in the Light Curves of Short-Period W Ursae Majoris Binaries: Program Summary

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Presented at the 94th Spring Meeting of the AAVSO, March 25, 2005; received June 1, 2005; revised June 25, 2005; accepted June 25, 2005

Abstract We are observing and analyzing changes in the light curves of a few W Ursae Majoris binaries. This paper summarizes the objectives of our program and the rationale behind our choice of stars and observational strategy. It also describes, briefly, our approach to the seasonal optimization of our reductions, and our two primary analytic approaches (phase-bin and Wilson-Devinney).

1. Program objectives

The W UMa stars, overcontact binaries of late spectral type, are fascinating laboratories for understanding stellar structure and evolution. They typically consist of two stars of very different masses in physical contact, with mass ratios higher than ten-to-one in some cases. Despite nearly forty years of research on these stars, we still do not understand the details of their internal structure. New three-dimensional modeling codes are being developed that will enable researchers to make progress in understanding both the internal structure and evolution of these stars. Developing and testing these models fully will require observations of a magnitude heretofore unseen.

The primary science objective of our program is to characterize the nature and time scales of changes—even very subtle changes—in the shapes of the light curves of several magnetically-active stars. Rather than providing a few disjointed "snapshots" of such systems, it is our intent to provide "movies" of their behavior over yearly, monthly, weekly, and even daily time scales. Such observations should provide powerful feedback to theoretical hydrodynamic models of the behavior and evolution of magnetically active stars.

The secondary science objective of our program is to search for transits of large close-in planets, i.e. “hot Jupiters,” across those binaries in our program that have high orbital inclinations. If hot Jupiters are orbiting W UMa binaries, there are several reasons why their transits have not yet been detected. Although essentially all known W UMa systems are eclipsing binaries, their orbital inclinations are, in the main, nowhere near 90 degrees. Thus one would only expect to observe transits on a small subset of W UMa binaries and, even then, only for close-in orbits. To further compound observational difficulties, hot Jupiter transits of W UMa binaries would produce quasi-periodic rather than truly periodic transits since the binaries are orbiting around each other as the planet moves across our line-of-sight (Doyle *et al.* 2000). Also, the ever-changing star spots and other surface photometric phenomena would mask subtle transit signatures. Thus it is not surprising such transits have not yet been discovered, although their evidence may already exist unrecognized in some high-precision observations.

Our planned multi-year observations of the same binaries led us to adopt, as a tertiary science objective, the search for “cold Jupiters” (Jupiter-mass planets in Jupiter-distance orbits), brown dwarfs, or other third bodies via the light-travel-time effect on eclipse times-of-minima (Deeg *et al.* 2000). Since Jupiter shifts our own solar system’s barycenter by five seconds peak-to-peak over the course of six years, one might be able to detect a similar shift in an eclipsing binary’s barycenter caused by a third body if the precision of the September–December (2004) seasonal eclipse timing was 1 second or better (3 sigma). Intermittent mass loss, drifting star spots, and other transient phenomena may mask subtle third-body effects, although separation may be possible (Kalimeris *et al.* 2002).

Supporting our three science objectives are two technical objectives. The first is fine tuning our reduction process for each of our major sets of observations. While such optimization would not be worthwhile under ordinary circumstances, our large data sets and the full automation of our reduction and analysis processes allow us to parametrically explore and optimize such reduction decisions as ensemble star inclusion, weighting strategies, etc.

Our second technical objective is to develop our phase-bin analysis process for detecting and evaluating small changes in light-curve shapes, including those that could be caused by the transits of hot Jupiters. Our phase-bin technique has been developed specifically for the analysis of a sizeable number of complete orbit-in-one-night light curves.

2. Choice of stars

To meet our primary science objective, we needed to select stars that were highly active magnetically. This suggested stars with a high Rossby number—i.e., stars with rapid rotation and long convective turnover times (Noyes *et al.* 1984). Long convective turnover times require deep convective envelopes, hence late-type stars. For single stars, the speed of rotation tends to fall off as one goes from early to late spectral type. However, as first noted by Eggen (1961), the opposite is true for W UMa binaries . The fastest rotators (those with the shortest period) are of the latest spectral type. It might be noted that at a period of 0.22 day and a spectral type of K5V, the "end of the line" is reached, as the primary component has reached full convection (Rucinski 1992). Thus the shortest period W UMa binaries have the highest Rossby numbers and hence the greatest magnetic activity. They are ideal magnetic activity laboratories. Also, late-type systems have the low masses required for measurable offsets by planetary third bodies detectable by periodic eclipse minima timing offsets, our tertiary objective.

To meet our secondary science objective, we needed to select at least one of our binaries with high enough inclination angle to allow a hot Jupiter to transit in a close, yet dynamically stable orbit (Holman and Wiegert 1999). With an inclination angle of 83.8 degrees, V523 Cas is, at best, a borderline candidate. We are in the process of determining, from our photometric observations, the inclination angle of V1191 Cyg. Although a radial velocity curve for V1191 Cyg is not available, a fairly accurate determination of its inclination should be possible via photometry alone as both primary and secondary eclipses are total (Terrell and Wilson 2005). In addition to the above science selection criteria, there were a number of practical criteria. The binaries had to be sufficiently bright, considering our modest-aperture telescopes, to provide a large number of photometrically-precise observations. A brightness between 9th and 12th magnitude is optimal for our systems. Binaries also needed to have short enough periods to allow complete light curves to be gathered in a single night for a reasonable time (at least a couple of months). For a given binary, these few months then become its "observing season" each year. Those binaries with the shortest periods and most northerly declinations have the longest observing seasons. Finally, W UMa binaries needed to be appropriately situated in the sky with respect to our observing season (May–December), sky obstructions, and telescope declination constraints. Although there are over 300 known W UMa binaries (Pribulla *et al.* 2003), only 35 met our overall criteria. Of these 35, only two had known inclinations greater than 85 degrees (CC Com at 87.9 degrees and BX Peg at 87.5 degrees). EK Com, at 88.5 degrees and magnitude 12.7, almost made the cut.

3. Observations and reduction

Observations were obtained at Dark Ridge Observatory with a 14-inch Meade LX-200GPS telescope, and at the Orion Observatory with a 10-inch Meade LX-200 telescope. Both observatories utilized SBIG ST-7XE CCD cameras, and were operated in a semiautomatic mode. The systems were initialized (manually) in the early evening on a binary in the east, and then left to run themselves (auto-guiding) throughout the night, turning themselves off when encountering a western limit switch. During our first observing season with (so far) preliminary, non-ensemble reduction, our overall photometric precision for over 21,000 observations of

V523 Cas was slightly better than 5 millimagnitudes. Our O–C residuals for V523 Cas were 4.4 seconds (1 sigma) and the error of the seasonal mean (with 32 times of minima) was 0.8 second.

Since we observe the same fields all night long, night after night, we can afford to take somewhat extraordinary measures to optimize our photometric reduction. This includes characterization of the 40 or so brighter stars in the field with respect to standard magnitude and color, spectral type, and variability. We plan, in essence, to establish each field as a set of secondary standards. There is no uniform agreement among variable star observers with respect to the optimal choice and weighting of ensemble comparison stars, nor is it even clear that there is a best "one-size-fits-all" approach. Some observers only use ensemble stars which closely match the variable star in color (or color and magnitude). Proximity of the ensemble stars to the variable may be a factor. Surrounding the variable with ensemble stars may improve precision under cirrus conditions. A number of observers include all stars without regard to magnitude, color, or proximity; simply weighting each star by its (estimated) signal-to-noise ratio (Gilliland and Brown 1988; Honeycutt 1992; Everett and Howell 2001). In any event, care must be taken because differential extinction due to color variations of the stars can look like transit events and are of similar durations (a few hours). An entirely different approach, image subtraction, may be worth considering, although its primary application, to date, has been in crowded fields (Alard 2000).

While observers generally agree that variable stars should not be included in comparison ensembles, at some magnitude level and time scale many stars are variable (Henry 1999). If one is employing nightly zero point adjustments (renormalization), the use of stars varying on the time scale of months might be appropriate, particularly if they are the only bright comparison stars in the field. To explore and choose between these alternatives, we are taking an empirical approach, varying the possibilities in a methodical, parametric manner; noting the effects on "overall performance" for the entire season. For "classical" variable/check/comparison (VCK) star photometry, the performance measure is, typically, the one-sigma standard deviation of the C–K values over the observational period. Of course there is no guarantee that the actual V–C performance might not be significantly different than that of C–K. In ensemble photometry, where a number of stars form the "C," and "K" can be variously defined, one needs to consider different measures of performance. We are employing three.

First, we are choosing, from the field, a non-variable "stand-in" for the variable, a star as closely matched in magnitude, color, and position to the real variable as possible. Given the relatively small fields we observe, this will have to be a significant compromise. Second, the variable star can, under appropriate circumstances, be used as its own stand-in. The trick is to make it non-variable. In the case of our W UMa eclipsing binaries, we will select a small portion of the light curve about a maximum which is quite "flat." Over a short time period, it should not vary so much that it cannot provide us with a useful performance measure.

Finally, it is known that the temporal precision with which times of minima can be determined are proportional to photometric precision (Doyle and Deeg 2003). In turn, the standard deviations of the observed minus calculated (O–C) residuals for best-fit seasonal ephemerides are proportional to the times-of- minima precision. Thus it follows that the standard deviations of the seasonal best-fit O–C residuals are proportional to photometric precision. Although this measure is computationally intensive, the full automation of our reduction and analysis processes allows us to utilize this performance measure in our parametric explorations.

4. Phase-bin analysis

Phase-bin analysis is a straightforward procedure that is especially applicable to the analysis of a season of nights where each night has at least one complete orbital cycle. The first step in the analysis is determining a best-fit seasonal ephemeris. One then converts, for each night, the observation times (in HJD) into phase and, after deciding how many bins per phase cycle to use, assigns each observation a bin number based on its phase.

The strength of phase-bin analysis lays in its merger capabilities. All the observations on one night can be merged into a single phase curve. Similarly, multiple nights can be merged together. One can even take all the nights in an entire observing season and merge them into a single "seasonal master." In the case of our V523 Cas seasonal master, the average number of observations in each of our 100 bins is over 200. In the final step of any phase-bin analysis, multiple observations within each bin are simply averaged. Phase bins averages can be subtracted from one another to yield phase-bin differences. For instance, one can merge all the nights in a season together to form a seasonal master, as suggested above, and then, one night at a time, subtract each night in a season from the seasonal master. The resulting phase-bin difference plots, one for each night throughout the season, can then be strung together, serially, to form a "movie" of how each individual night varies from the seasonal master. This process, in effect, removes the major underlying variation (the eclipse curve and any non-varying star spots, and so on), leaving just the small differences (changes) within the season which, with the amplitude scale now greatly magnified, can be readily seen. In the case of V523 Cas, our "movie" of four months of observations showed minor variations in the light curve for the first couple of months, followed by a dramatic change in the fourth month.

A number of other "experimental designs" are possible. As both observatories, on many occasions, observed the same binary on the same night, we are binning the observations from each observatory together on those nights and taking the difference to closely examine any instrumental differences. We are using a modified phase-bin approach to search for transits. Several nights on either side of the night in question are being binned together to form a comparison template. The "middle night," i.e. the "night in question," is phased and then binned (although not in the normal way, as its temporal sequence must be preserved). A phase-bin difference is then taken over the "phase" range of the middle night. With the main eclipse (and star spot) flanking-nights variation removed, any changes of the middle night with respect to the flanking nights will now stand out, exposing any hot Jupiter transits. A much more sophisticated matching filter analysis may eventually be applied (Deeg *et al.* 1998). For a discussion of the potential confusion of planetary transits and star spots, see Queloz *et al.* (2001).

Phase-bin analysis is a method for removing the average (and hence major) features of light curves so that non-average, much smaller differences become apparent. Its strength is that it makes no assumptions about the nature of the average, "comparison" light-curve shape and hence can be very sensitive to any real differences. This is also its weakness, however, as it is difficult to interpret the astrophysical meaning of any differences (with the exception of a transit event). Used in conjunction with an astrophysical model, however, the two should provide complementary insights.

5. Wilson-Devinney analysis

The Wilson-Devinney (WD) program (Wilson and Devinney 1971; Wilson 1979) is the most widely used program for analyzing eclipsing binary star data. We will use WD to analyze our photometric data on both V523 Cas and V1191 Cyg. Radial velocities have been measured for V523 Cas (Rucinski *et al.* 2003) and we will analyze them simultaneously with our photometry. To our knowledge, no radial velocities have been measured for V1191 Cyg, but it has complete eclipses which enables a determination of its mass ratio (Terrell and Wilson 2005). The WD analysis of the binaries will determine basic system parameters such as the orbital inclination, relative radii of the stars (absolute radii for systems with radial velocities), and the temperature and luminosity ratios of the stars.

The WD program models surface inhomogeneities with circular spots. The spot parameters that can be specified are the latitude and longitude, spot radius, and spot temperature factor (the ratio of the spot temperature to the temperature of the photosphere if the spot were not there). We will use this capability to model star spots on the binary components and follow them over time to see if they move in a coherent fashion. The independent variable can be the traditional phase quantity, computed with given ephemeris quantities, or the data can be analyzed with time as the independent variable. In the latter case, the ephemeris parameters are among the adjusted parameters. Thus, rather than using times of minimum to estimate the ephemeris parameters, they are found from the analysis of entire light curves.

We are also working on modifications to WD that will enable it to model the transits of circumbinary planets. This capability will enable us to explore the light curve morphology of planetary transits in binary systems and search for potential transits in our data. It will also enable us to explore morphological differences between planetary transits and spot phenomena that may mimic transits.

6. Acknowledgements

Genet acknowledges a NASA grant obtained through the AAVSO for travel to Las Cruces. We thank Robert Nelson for the automation of his MINIMA23 program and Erick Betz at Cuesta College for his work on W UMa transits.

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