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The DDO Close Binary Spectroscopic Program

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Abstract. The survey of radial velocity orbits for short period ($P < 1$ day), bright ($V < 10$, with a few fainter stars) conducted at the David Dunlap Observatory in the last 9 years before its closure in 2008 included 162 binaries and resulted in 150 SB2 orbits and 5 SB1 spectroscopic orbits thus becoming one of the main legacies of DDO. The paper summarizes the main results from the survey.

1 The historical background

The David Dunlap Observatory, part of the Department of Astronomy and Astrophysics, University of Toronto, served as a major Canadian astronomy center between 1935 and 2008. In the late 1980's, a decision was made to close the observatory and reallocate the resources into more modern branches of astronomy. The radial velocity, short-period binary program described here was conducted during the last years of the DDO existence as a research facility, before its closure on 2 July 2008.

Radial velocities (RV) of binary stars were always in the center of research interests at DDO. The program described here continued these interests, but its main pragmatic rationale was to utilize the 1.9 m telescope for a useful program which could have tangible results in a limited amount of time. In the early 1990's, Dr. Hilmar Duerbeck and the author suggested to the DDO staff a simple service program of occasional observations of several tens of EW (also called W UMa or contact) binaries in order to provide the missing radial velocity component to combine with Hipparcos tangential velocities. The Telescope Operator of that time was Mr. Wen Lu; he went further and obtained full orbital coverage for several binaries. The author of this paper came back to Toronto from Hawaii in 1999 and helped Mr. Lu to analyze and publish the first batch of 20 orbits [DDO-1] and [DDO-2][1]. As the observatory kept on existing with a typically yearly horizon for its closure, the subsequent publications started to slowly acquire a shape of a more or less systematic survey; this took place at the time of the papers [DDO-4] or [DDO-5]. In addition to the DDO series, a number of additional papers dealt with special or unusual objects, but we did try to adhere to the 10-orbit per paper format and most orbits were published that way.

[1] For simplicity of referencing, papers based on DDO data will be marked below and in the reference list by square brackets.

2 Completeness of the survey

Given the haphazard organization and the uncertain time limit of the survey, it turned out to be surprisingly complete one exceeding the level of 90% completeness in terms of extant photometric discoveries. In the end, we tried to include all known contact (EW), semi-detached (EB) and detached (EA) binaries with periods shorter than one day, brightness above 10th magnitude and with accessibility limits of our telescope. Figure 1 shows the number distribution of our targets versus their celestial declination and brightness. Obviously, targets at negative declinations are under-represented, but this is not entirely due to difficulties of observing to the southerly direction, directly over the bright Toronto, but is also partly due to the smaller number of photometric discoveries in the southern sky for stars fainter than 8th magnitude. Some stars were simply never observed, either because we considered the literature data good enough or somehow did not observe them before the DDO closure. We are aware of 14 such objects[2]. Partial or inconclusive data for 12 binaries are described in the last, larger publication [DDO-15] which broke the 10 stars per paper format.

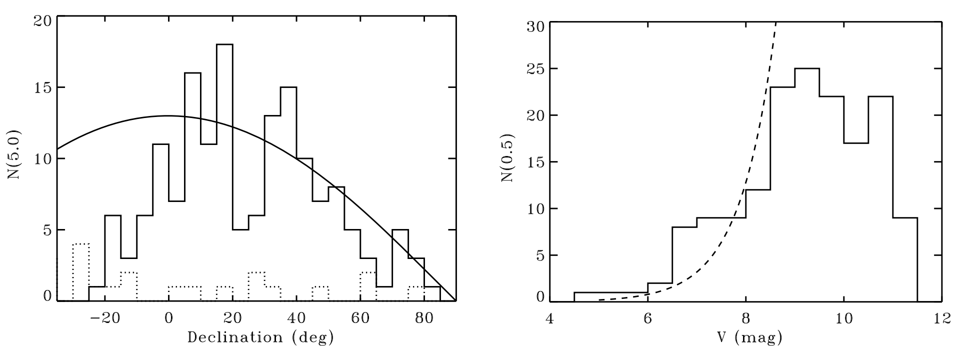

Figure 1. The known survey selection effects: The left panel shows the number of objects in 5 degree intervals of the declination. The expected shape of the distribution is given by the continuous cosine curve. The systems which were *not* observed are marked along the horizontal axis by a dotted line. The right panel gives the number of object per half-magnitude intervals. The continuous, broken-line curve approximates the expected 4× per magnitude increase rate.

As is visible in Fig. 1, at the bright end, the numbers of objects increase rapidly with magnitude, as expected, but only to about $8 - 9$ magnitude. The abrupt break in this rise is caused by an absence of fainter objects with amplitudes below $\simeq 0.02 - 0.03$ mag. The most complete photometric survey to this level of variability is that of the Hipparcos satellite, but it is complete only to about 8 magnitude. We note that we found many triple systems among the Hipparcos low-amplitude ("diluted") photometric variables which turned out to have large RV semi-amplitudes; we would never study them if we limited ourselves to large photometric amplitude objects only.

[2] The 14 binaries which were not observed: VW Cep, BW Dra, BV Dra, AC Boo, V1073 Cyg, ER Vul, V781 Tau, U Peg, DW Boo, VZ Psc, YY Eri, ES Lib, DX Aqr, PP Hya.

3 The observations

Although – in the end – we collected some 12,000 spectra, the yearly "horizon" for the DDO continuation forced us to survey only the shortest period ($P < 1$ day) and brightest ($V < 10$) binaries visible from Toronto, a task which seemed to be within reach in a few years and indeed was almost achieved. The first limit was just to confine the survey scope and thus its duration, but the second limit was driven by quality of the spectra ($S/N > 30 - 50$) at the required highest resolution power of the Cassegrain spectrograph ($R \simeq 12,000 - 15,000$) at $V \simeq 11$, with some margin for poorer quality nights.

In the middle of the program, the old, scratched grating of 1800 lines/mm was replaced by a new 2160 line/mm grating; this did not increase the resolving power (set by the spectrograph optics), but improved the sampling. We also changed the main CCD detector of 1024 pixels at 19 μm by a longer detector od 2048 pixels at 13.5 μm.

Most of the survey was done in the Mg I triplet region at 5184 Å, within a spectral window about 220 Å wide. This region is not only rich in spectral line in late-type spectra but its location in a city sky minimum gave another advantage in terms of the quality of spectra (Fig. 2).

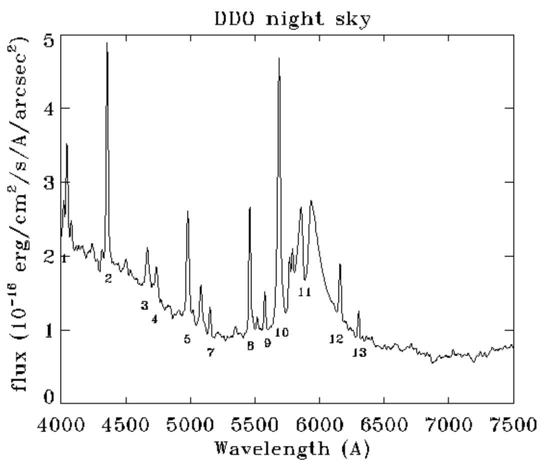

Figure 2. The Toronto sky is very bright. This calibrated, low resolution spectrum was obtained by Dr. R. M. Blake. It is dominated by the strong high-pressure lamp sodium feature. The Mg I 5184 Å triplet used in this program is situated in the brightness minimum, close to the feature marked as #7. This particular spectrum shows a weak lunar light contamination in the blue.

4 The broadening functions (BFs)

The broadening functions (BF) technique was developed and improved during the survey as we attempted to analyze progressively more complex spectra. Its first use dates back to an analysis of AW UMa using CFHT spectra (Rucinski

1992). Later, a short description (Rucinski 1999) stimulated further development by others, a technique utilizing model spectra known as the Least Squares Deconvolution (LSD). These techniques are not identical: The BF technique uses standard star spectra while the LSD technique uses model spectra. While the LSD gives smoother deconvolution results, we valued the ease of tying our RV's to the standard stellar velocities system as well as a simple reference to the spectral sequence: Integrated BF intensities at the Mg I triplet change monotonically with the spectral type and can be used as an independent check on the type of the star (in addition to the color and the Sp Type estimate). This interesting aspect will be discussed in a separate investigation.

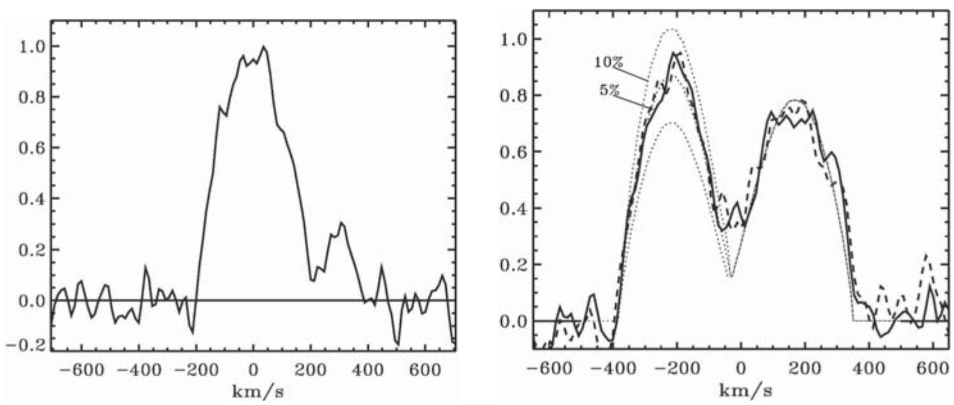

Figure 3. The broadening functions. The left panel: The BF for the extreme mass-ratio system SX Crv at its orbital quadrature. The value of $q \simeq 0.06$ is uncertain because of difficulties with measuring the minuscule RV shifts of the *primary* component. The right panel: The BF for SW Lac where we directly see the secondary-component surface-brightness enhancement (the taller, narrower peak), here parameterized by the relative temperature increase, $\Delta T/T$. The dash-dotted line without a label is for the unmodified "Lucy model" with $\Delta T/T = 0$.

The idea behind the BF is simple: With a template (standard star) spectrum representing all natural broadening effects, to de-convolve the binary spectrum for all effects caused by radial velocity effects of rotational broadening and orbital motion. The convolution of the template spectrum $T(n)$ with $B(m)$ ($n/m > 1$, preferably several times) into the broadened spectrum $P(n)$, is written as a set of linear equations and then solved using least squares. The convolution integral transform is written as an array operation:

$$P(\lambda') = \int B(\lambda' - \lambda)\, T(\lambda)\, d\lambda \quad \Rightarrow \quad \vec{P} = \mathbf{D}\, \vec{B} \tag{1}$$

where the rectangular array $\mathbf{D}$ contains the appropriately shifted vector $\vec{T}$ as its columns. The broadening function is represented by a vector of the unknowns, $\vec{B}$; the array $\mathbf{D}$ has dimensions m by $n - m + 1$. Thus, the system of over-determined linear equations for $\vec{B}$ is:

$$P_i = \sum_{j=0}^{m-1} T_{i+m-j}\, B_j \qquad \text{with} \qquad i = m', \ldots, n - m' - 1 \tag{2}$$

The result, the Broadening Function, looks and functions (Figure 3) very much like the cross-correlation function (CCF) but is in many ways superior to it: (1) it has better resolution, (2) it is linear, so that it is a simple mapping of stars into the RV domain, (3) the respective peaks can be integrated and do not require any calibration for the L_2/L_1 ratio (as does the CCF route), (4) does not show any fringing of the baseline which is characteristic for the CCF.

The BF technique is not as easy to use as the CCF though: The proper length of the BF window (not too long and not too short) should be adjusted beforehand by running a preliminary CCF; also, very long spectra are difficult to use in the array solution (with echelle spectra, it is better to work order by order). Details of the BF implementation and IDL scripts are available in author's Web page[3].

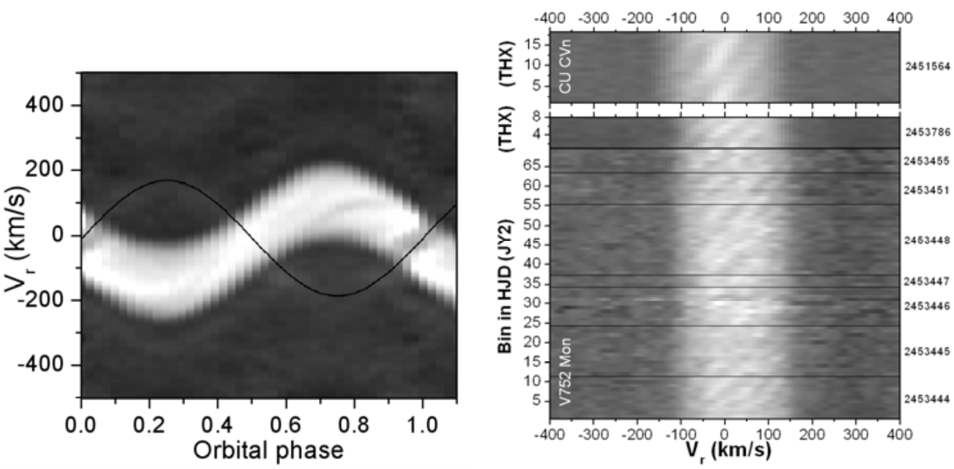

Figure 4. The temporal or orbital phase correlations in broadening functions are best visible when they are arranged into 2-D images. Left panel: The secondary's transit and photospheric spots on the primary of the detached binary XY UMa [DDO-12]. Right panel: Non-radial pulsations of $l \simeq 6-8$ manifest themselves on an apparently single stars (dominating primaries or third stars) in CU CVn and V752 Mon as slanted ripples [DDO-15].

5 Applications of BFs

The BF technique was certainly crucial in our ability to study so many double-line binaries: The number ratio of 150 SB2's versus 5 SB1's says it the best; the few SB1's are genuinely single-line binaries, most likely contain white or brown dwarfs or massive planets. Thanks to it, we have been able to detect several contact systems with very small mass ratio, $q = M_2/M_1$ at the level of 0.1 and below. Among them the system SX Crv [DDO-5] which appears to have the mass ratio even smaller than that of AW UMa, perhaps as small as $q = 0.06$ (Figure 3). Paradoxically, for such extreme systems, the difficulty is

[3] www.astro.utoronto.ca/∼rucinski

not in detection and velocity measurements of the low-mass component, but in determination of velocities from the large, wide lobe of the heavily broadened primary feature which does not move much. The only proper approach would be to model such BFs, to relate velocity centroid determinations to the velocity of the primary mass center.

Modeling of BFs has a potential of studying deviations from the assumed binary model. One such an application would be to look into the still unexplained cause of the W-type light curve deviations from the Lucy model, so well visible in the BFs of SW Lac [DDO-10] and apparently reproducible by a simple increase of the surface temperature by a few percent (Figure 3). Also, the BFs, when arranged in time or orbital phase can show features which are hard to detect in other ways, particularly weak, drifting photospheric dark spots and non-radial pulsations (Figure 4).

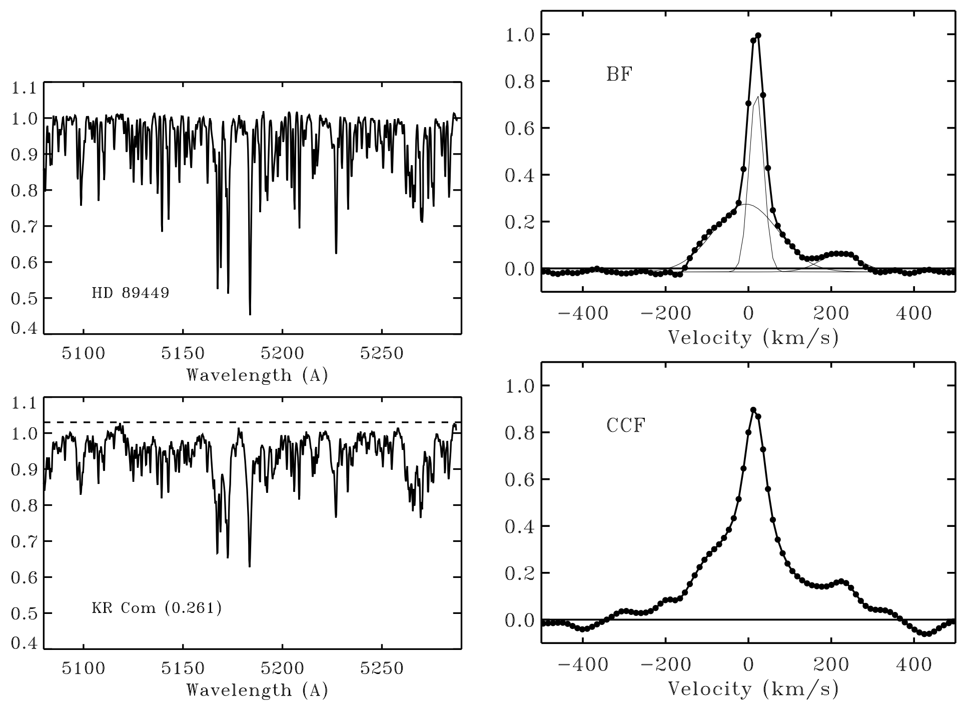

Figure 5. A typical triple system, KR Com. The left panel shows spectra of the template and of KR Com at the orbital phase 0.261. The star was previously considered chemically peculiar because of its strange continuum, now explainable by heavy blending of the close binary lines. The BF and CCF functions are compared in the right panel. Note, that the BF baseline is slightly negative. This is due to the necessity to use the pseudo-continuum for spectral normalization/rectification. This does not affect the intensities because the BF is linear, but does affect estimates of $\beta = L_3/L_{12}$: The slowly rotating component and the binary have spectral continua whose hight ratio does not correspond to the luminosity ratio; thus, usually, $\beta_{obs} > \beta_{true}$. For the KR Com spectra shown here, $\beta_{obs} = 0.56$ so that the third star has a comparable brightness to components of the binary, but certainly dominates in the appearance of the spectrum.

6 Triple systems

At first, we had so many SB2 spectra that we did not analyze any triple and multiple systems, but later we realized that the BF approach is particularly useful for situations when more spectral features are visible together because it offers very high fidelity of the information extraction. Also, with the Hipparcos low photometric amplitude binary detections, we were confronted with the increasing number of systems with relative large K_i semi-amplitudes but showing two or more BF additional peaks of stationary or semi-stationary components.

Realization that triple systems are so common in our survey led to resurrection of the old idea (Rucinski & Kaluzny 1982) that close binaries exist *because* they are in triple/multiple systems. This has led to a survey of literature data [Triples-1] and to an adaptive-optics search for close companions [Triples-3]. In the present context, the most interesting of the DDO data utilization was the project involving averaging of several of co-aligned spectra to detect stationary RV components of companions [Triples-2]. Because of the limited space, we refer the reader to the papers of this series for details. We only note that we have indications that binary systems with periods shorter than one day show the apparent frequency of companions $> 60\%$ which is consistent with 100% incidence.

7 The mass ratios

Among 150 SB2 orbits of the DDO program, 121 were of contact (EW) systems; the rest were semi-detached (EB; 14), detached (EA; 10) and uncertain in type, ellipsoidal variables (Ell, 5). The semi-amplitudes K_1 and K_2 for the SB2 binaries, although probably the best currently available, may be affected by the way we measured them. Both, the Gaussian (used up to [DDO-10]) and rotational profiles (used from [DDO-11]) are symmetric functions, while peaks in the BFs are certainly not symmetric. The only proper approach would be to model the BFs in full, assuming a contact, semi-detached or detached model. But, for many systems, the photometric data were not available; besides, we simply had no resources for complex, combined radial-velocity and photometric solutions.

The mass ratios, determined from $q = K_1/K_2$ seem to be least affected by the way we determined the radial velocities. A plot of mass ratios versus the orbital period (Figure 6) shows an unexpected avoidance of moderate values of the mass ratio (roughly $0.3 < q < 0.8$) for periods longer that 0.6 day. One can even see two sequences, (1) of detached (EA) and perhaps semi-detached (EB) systems with large mass ratios and (2) of contact systems with mass ratios approaching smallest detectable values. If one were brave, one can notice a convergence of both sequences at the very short-period end where they tend to the same mass ratio of $q \simeq 0.5$. Of course, the number of binaries remains small so that a statistical fluke is not excluded. But, if confirmed, the relation shown in Figure 6 is a new, unexpected and important result.

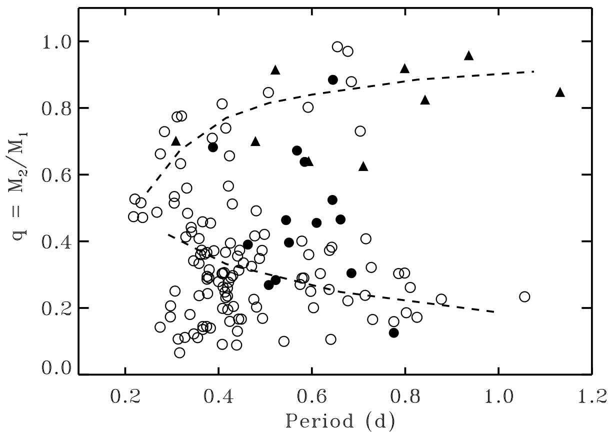

Figure 6. The spectroscopic mass ratio versus the orbital period for all SB2 systems of the survey. The symbols are: open circles for EW, filled circles for EB and triangles for EA systems. The high frequency of contact systems is well known for orbital periods around $P \simeq 0.3 - 0.4$, but note the absence of binaries for $P > 0.6$ days and moderate mass ratios. The two sequences, as marked approximately by the broken lines, correspond to preferred mass ratios of EW + a few EB (lower) and EA + a few EB (upper) types.

8 Center of mass velocities

Are contact systems old? Many lines of evidence suggested that it takes long time for initially close, but detached binaries to come into contact and to live a new "contact" life. Previous kinematic investigations by Guinan & Bradstreet (1988) and Bilir et al. (2005)[4] indicated that center-of-mass velocities of EW binaries have a large dispersion, a property which could be interpreted as due to the advanced age.

The new statistics based on all 121 contact systems of the survey does not confirm any excess in the velocity dispersion. The velocity dispersion is $\sigma V_0 = 29.0 \pm 2.1$ km s^{-1} which is *not different* from the dispersion of Main Sequence stars in the field, as based on the data given in Dehnen & Binney (1998). We cannot exclude a possibility that the picture is more complex with two contributing distributions of different widths, as indicated by the actual shape of the V_0 histogram in Figure 7.

[4] DDO results up to and including [DDO-9] were used in the Bilir et al. (2005) study, in addition to data from other, generally poorer sources. Such studies can now benefit from subsequently published DDO data.

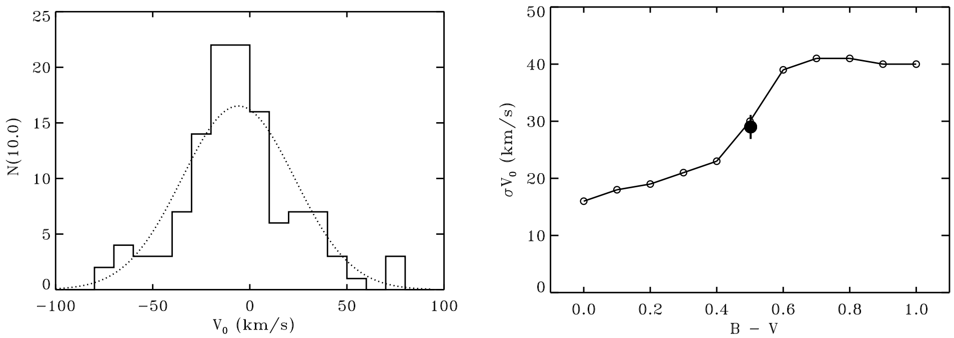

Figure 7. The distribution of the V_0 (center of mass) velocities of contact binaries is shown in the left panel. The right panel gives the field, Main Sequence one-dimensional velocity dispersion versus the $B-V$ color index based on the Dehnen & Binney (1998) study. The dispersion for EW systems is shown for their mean $B-V$ as a filled circle; the numbers of EW systems per color bin are small but the MS progression appears to be present there. This result indicates that W UMa binaries are not substantially older than most of the field (old disk) stars.

9 The AW UMa system; is the contact model right?

The AW UMa binary, known also as Paczynski's star[5] has been crucially important for our understanding of contact binaries. In spite of the extreme mass ratio ($q_{ph} \simeq 0.07-0.08$), its light curve beautifully agrees with the "Lucy model" of a contact binary which fills the Roche common equipotential and is subject to standard limb and gravity darkening description. Wilson (2008) singled out this binary as one which can serve as an excellent indicator of the distance, comparable in quality to best trigonometric parallax determinations[6].

To our surprise, the DDO detailed spectroscopic analysis [AW UMa] revealed large deviations from the contact model (Figure 8): (1) As seen in the BFs, the spectral lines are too narrow, but they do have broad bases; (2) The spectroscopic mass ratio estimated from centroid motion and from modeling cannot be reconciled with the photometric one and it cannot be smaller than $q_{sp} \simeq 0.10$; (3) The secondary component appears small and asymmetric when projected against the primary; large changes in its shape are apparent when the orbital quadratures are compared. The latter variability is particularly large at phases around 0.64. It should be noted that the contact binary V566 Oph with $q_{sp} = 0.26$ does not show any systematic deviations from the contact model (but except for an unexpectedly large scatter in the secondary BF, also at phases of about 0.64).

These results are puzzling and hard to explain. Is the domain of contact binaries populated by objects with various adherence to the contact model with

[5] Paczynski (1964) discovered AW UMa in 1964 and immediately recognized its importance; this star accompanied him until his last publication (Paczynski, Sienkiewicz, & Szczygiel 2007).

[6] This view has been confirmed in a private conversation with Dr. Wilson during this conference.

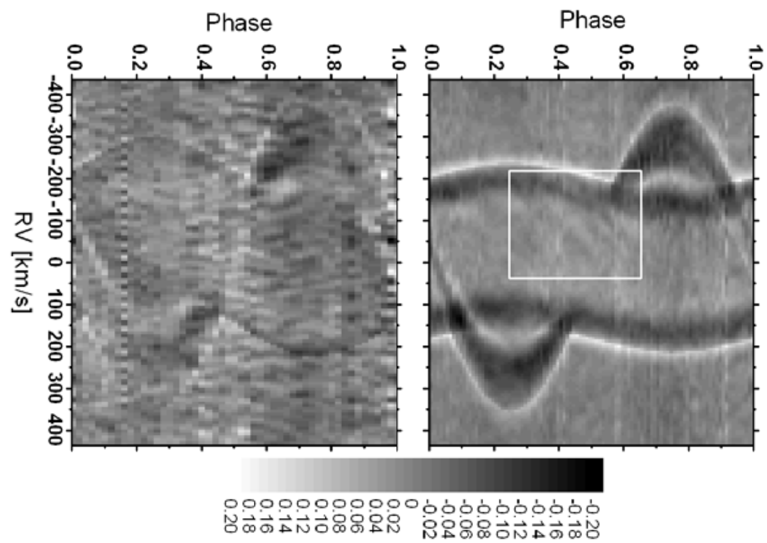

Figure 8. The grey scale figure shows deviations from the model BFs arranged in orbital phase (horizontal) for V566 Oph (left) and AW UMa (right); the vertical scale gives velocities. The box marks the region where spots or non-radial pulsations on the AW UMa primary are visible as inclined ripples.

some semi-detached systems “pretending” to be contact binaries. What controls the discrepancies? As a caution: We should remember that the BFs give us information about velocities only; these should not be mistaken for spatial positions as these must involve models.

10 Conclusions

The DDO radial velocity survey of close binaries is the most complete among such surveys with more than 90% of the currently photometrically recognized close binaries with $P < 1$ day and < 10 mag. The survey will not be continued; the DDO has been closed. The high success in determination of many SB2 orbits and in detection of many companions is partly due to the Broadening Function (BF) approach which is a much better analysis tool than the Cross Correlation Function (CCF). Among the new results, the unexpected bifurcation of the P versus q relation requires confirmation. The case of the AW UMa binary is probably the most interesting and intriguing: The light curve beautifully agrees with the contact model yet – spectroscopically – we see very serious deviations from it.

Many further studies will utilize the DDO data. Here, a plea to those who will use them: Please do not do photometric improvements to our mass-ratios. There is plenty of room for other investigations, but tiny changes to the mass ratio, based on light-curve fits are the least important and meaningful of all what can be done... The case of AW UMa should be taken as a warning on how incomplete may be the picture based on light curves alone.

Acknowledgments. The David Dunlap Observatory binary-star survey would not be possible without the hard work and dedication of many individuals. I would like to express my sincere thanks to Mel Blake, George Conidis, Bryce Croll, Chris Capobianco, Heide DeBond, Cosmas Gazeas, Toomas Karmo, Krzysztof Kaminski, Piotr Ligeza, Wenxian Lu, Stefan Mochnacki, Waldemar Ogloza, Bogumil Pilecki, Theodor Pribulla, Wojtek Pych, Archie de Ridder, Matt Rock, Piotr Rogoziecki, Michal Siwak, Greg Stachowski, Jim Thomson.

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