ROTATION BROADENING AND THE SHAPES OF W URSAE MAJORIS STARS

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Abstract. We extract rotation broadening functions from the spectra of W Ursae Majoris Stars. Using a fast Fourier transform we deconvolve photographic spectra, covering some 500 A including dozens of strong lines, with equivalent spectra from non-rotating stars of similar spectral type. The resulting rotation functions contain information about global features such as the shape of the stellar surface (e.g. mass ratio and degree of contact), gravity brightening and limb darkening. We present preliminary data on the stars VW Cep and ER Vul. The rotation function of the former reveals the presence of the third component found visually by Heintz (1975), while that of the latter shows it to be detached and have mass ratio 0.9.

1. INTRODUCTION

It is now well recognized that W Ursae Majoris stars are pairs of main sequence or near main sequence stars in physical contact. The defining characteristics of the W UMa group are that the light curves exhibit curved maxima and nearly equal minima. The former characteristic indicates extreme aspherical distortion of the components while the latter indicates nearly equal effective temperatures for each component despite their having quite different masses. Nearly equal temperatures strongly suggests that a common envelope completely redistributes the energies generated in the separate cores (Osaki 1965; Lucy 1968a,b; Shu, Lubow, and Anderson 1976). Such a common envelope must have a photosphere which lies on an equipotential between the inner and outer critical surfaces of the Roche model for binary stars (Kuiper 1941). Unfortunately, the light curves alone do not provide the degree of contact (what we henceforth call the filled fraction, of the volume between the two critical surfaces filled by the common envelope) unambiguously. Specifically, an atlas of theoretical light curves (Anderson and Shu 1979) shows that there exist loci with nearly identical light curves running from a given mass ratio, low filled fraction, and radiative gravity brightening to higher mass ratio, higher filled fraction, and convective gravity brightening with reduced limb darkening (c.f. $q = 0.5$, $f = 0.0$, radiative →

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q = 0.6, f = 0.5, convective, zero limb darkening). In view of this ambiguity, we have chosen to investigate the shapes of W UMa stars through the rotational broadening of spectral features. (c.f. Shajn and Struve 1929, Rucinski 1971).

2. METHOD

We compare observed rotation broadening functions with the grid of theoretical functions by Anderson and Shu (1979). The calculations of the theoretical functions are thoroughly discussed in the reference. Both the calculations and the reduction of the observations share an important assumption which we refer to as the uniform profile model. We assume that, relative to the continuum, the spectral profile remains uniform over the projected view of the star except for the rotational Doppler shift (c.f. Gray 1976).

Each spectrum was recorded on baked 127-04 behind a Varo Mk II single stage image tube on the 20" spectrograph at the coudé focus of the Shane telescope at Lick Observatory. The dispersion was about 16 A/mm in the second order. The spectra were widened to about 0.7 mm. We then a) digitized each record to 4096 points spaced equally in $x = \ln(\lambda/\lambda_0)$ over the range λλ5000-5500 Å with the PDS microdensitometer at the U.C. Berkeley Astronomy Department, b) converted to intensities relative to the continuum $[(I_c(x) - I(x)) / I_c(x)]$, and c) determined complex fourier transforms of each spectral record.

Under the uniform profile assumption the observed spectrum of a W UMa star is a convolution of its rotation function with the spectrum of a non-rotating star of the same spectral type (Simkin 1974, Gray 1976). The Fourier transform of the rotation function is then the complex quotient of the W UMa transform divided by the appropriate standard transform, wavenumber by wavenumber. We chose for the denominator the non-rotating star which gave the cleanest "continuum" in the resulting functions. Slight variations in spectral type (±1/2 class) of the standard star do not alter the overall shape of the resulting rotation function, but do alter the "noise". Before transforming back into spectral wavelengths, we filtered the transform to provide a spectral resolution ~0.0002.

3. RESULTS

We present four observations of two stars classed EW in the Russian General Catalogue of Variable Stars (Kukarkin, et al. 1969): VW Cephei and ER Vulpeculae. The observational data are given in Table I. The rotation broadening functions appear in Figure 1. Zero phase is defined as the transit minimum. All plates were reduced with an average of the spectra of two non-rotating stars, the sun (a plate exposed to the day-light) and HR 483.

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TABLE I
Exposure Data (all plates 23 August 1978 UT)

Plate	UT	Exposure	Phase
VW Cep 027	06:21	6 min	0.27
VW Cep 037	09:52	6 min	0.79
ER Vul 026	05:58	4 min	0.73
ER Vul 033	08:19	4 min	0.87

The best fit theoretical broadening functions from Anderson and Shu (1979) also appear in Figure 1. For VW Cephei we found a mass ratio $q = 0.4 \pm 0.05$ and a filled fraction f not much larger than 0.0 (marginal contact). We also clearly detected spectroscopically the third component discussed by Hershey (1975). Its contribution to the rotation function, about 1/16 the area, agrees very well with Hershey's determination of the magnitude difference $\Delta m = 2.9$. Since this component is presumably not rotating, its width in the rotation function is a measure of our resolution. For ER Vulpeculae, we found that the components are actually detached with mass ratio $q = 0.9 \pm 0.05$. The EW classification results from the nearly unit mass ratio, rather than contact. Being detached, ER Vul lies outside the range of the grid of theoretical functions; each star rotates more slowly than it would if it were in contact with the same separation.

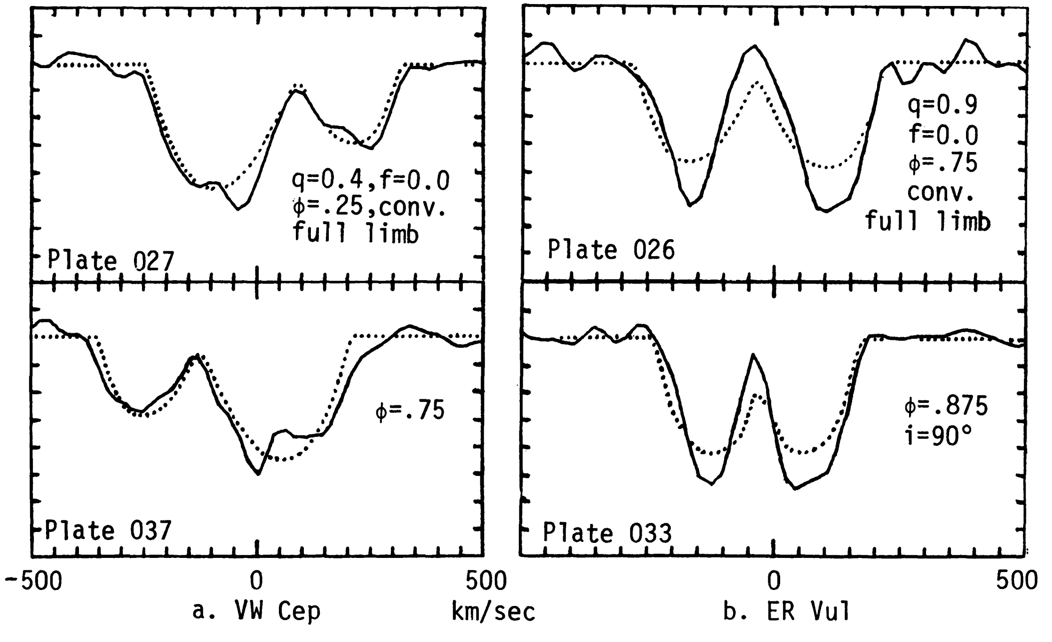

Fig. 1. Rotation broadening functions at phases given in Table I.
Solid lines: observed functions.
Dotted lines: best fit models from Anderson and Shu (1979).

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4. DISCUSSION

The mass ratios agree very well with previous determinations. Binnendijk (1967) gives q = 0.41 for VW Cephei (remarkably close to our value given that he was probably unaware of the third component). Northcott and Bakos (1956) give q = 0.93 for ER Vul.

We stress that the theory and observations are kept entirely separate until the final comparison is made; the observations are not reduced in some parametric form with a physical model in mind. The only assumption common to both calculation and reduction is the uniform profile assumption. To be consistent with our introductory comments about the light curves, we should mention that there are also loci of equivalent rotation broadening functions in Anderson and Shu's (1979) atlas. These loci run from low filled fraction and convective gravity brightening to higher filled fraction and radiative gravity brightening at constant mass ratio. If we assume the gravity brightening is fixed (as it ought to be) these loci present no problem. However, there is some question as to the value of the convective brightening exponent ($T_e^4 \propto g^{0.0}$ according to Anderson and Shu 1977, $\propto g^{0.32}$ according to Lucy 1967). If one lets this exponent be a free parameter, one must rely on the intersection of the light curve and rotation function loci.

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COMMENTS FOLLOWING ANDERSON, RAFF AND SHU

Collins: The use of the "standard line" approximation over such a distorted stellar system is an extremely dangerous one and probably will change the "ambiguity locus" of your line fits. Variations in the gravity, associated statistical equilibrium and local value of μ (i.e. cos θ) over the surface of the system can and do greatly affect line strengths and profiles. Various lines are affected differently and hence averages over many lines are subject to systematic error.

Anderson: Our uniform profile assumption is not really defensible, except on practical grounds. However, center-to-limb variations in line strengths are likely to be the most serious departures (consider your absorption line which reduces to virtually zero strength at the limb). Such variations mimic limb darkening in the rotation function. Comparing entries with and without limb darkening in the theoretical grid reveals little significant difference. Such variations would be buried in our observational "noise".

Wilson: Twigg and Robert (in press) have determined and collected values of the gravity darkening, limb darkening, and bolometric albedo parameters for at least several dozen contact binaries of both late and early type. Plotting these vs. surface temperature, they find much consistency in the results, thus indicating that they are finding the correct values. Therefore it seems that one can reliably determine these quantities from light curves alone if they are solved by a full differential correction procedure. Perhaps that would also happen with the velocity profiles if they were analyzed by differential corrections. In any case, it is clear that it is not necessary to continue light curve and velocity profile information to get unique answers.

Anderson (response and question to Wilson): I have a two-part answer, in part a comment in favor of light curve results, and in part a question about light curve fitting procedure. A) Although VW Cephei is an individual case, it is interesting that the rotation profile agrees with the general result of low filled fractions found for late-type W UMa stars through the light curves. B) Have you or others examined regions in parameter space other than the converged solution for solutions which also fit the data within the statistical error of the data?

Wilson: Twigg and Robert tell me that they have investigated "local minimum" problems rather thoroughly for most of their binaries, and find that their results are unique.

Rucinski: The problem of the limb darkening in the line being different than that in the continuum should be partially removed if you simultaneously use many lines formed by different mechanisms; how many lines contribute actually to your observational profiles?

Anderson: About one dozen strong lines and many more weaker ones.