II. DETACHED SYSTEMS

DETERMINATION OF ABSOLUTE DIMENSIONS OF MAIN SEQUENCE BINARIES

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ABSTRACT

Determinations of absolute dimensions of main sequence binaries are no longer useful unless random and systematic errors are kept appreciably below 10%. Some essential conditions for achieving this are reviewed.

1. INTRODUCTION

Determining absolute dimensions of main sequence stars from spectroscopic and photometric observations of double-lined eclipsing binaries has been a standard technique for several decades. Hundreds of determinations have been published and are summarized in standard compilations of, e.g. mass and radius vs. spectral type.

It is therefore necessary to ask ourselves whether it is still worthwhile, or even reasonable, to continue such "routine" work. Are we just beating a dead horse and piling up determinations of something that has already long been known to everybody's satisfaction? In other words, aren't we wasting valuable telescope time and journal space?

A devastating answer to this question is closer to the truth than generally recognized. Further work can in fact only be justified on the following two conditions:

1 - More accurate data really <u>are</u> needed, and
2 - The new data really <u>have</u> the required precision.

As just one example of the need for better data, one of the popular uses of such empirical determinations in recent years has been to compare with theoretical computations of various degrees of refinement of the evolution of single or double stars. Our own experience in determinations of the highest accuracy indicates that these "empirical data",

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whether taken from simple literature surveys or from standard compilations of M and R vs. spectral type, may be in error by as much as 10-40% in M and a factor 2 in R. This is quite inadequate for any critical test of the theoretical models: Little meaningful information can be extracted on chemical composition, age, or the importance of any processes of mass loss. What is worse, previous mass determinations for early-type stars are found to have serious systematic errors (see 2.3). In fact, use of the older data would lead one to derive a helium abundance Y = 0.33-0.40 for the (young) B stars as compared to Y = 0.20 for the (older) F and G stars (Popper et al., 1970), a degree of helium enrichment difficult to explain theoretically--and entirely spurious.

We conclude that a real accuracy in M and R of 1-2% or at least appreciably less than 10% is required. Only very few systems have yet been analyzed to this precision, but it is essential for future work to result in new information. New determinations should also be accompanied by photometric indices on a system providing quantitative and sensitive reddening-free parameters related to effective temperature and gravity. The parameters supplied by even a good MK class are simply too coarse to resolve moderate evolutionary effects easily discerned in the binaries. Stars of a given MK class may differ by as much as 30% in mass and a factor 2 in radius.

Experience from more than a dozen high-precision determinations has taught us that the precision limit set above will not be reached in practice without careful attention to a number of questions of method. These are reviewed below, hopefully for the benefit of colleagues interested in using and/or producing data of this kind.

2. NECESSARY CONDITIONS FOR ACHIEVING HIGH ACCURACY

2.1 Choice of System

Not all double-lined eclipsing systems are suitable for precision determination of stellar dimensions. They must have well-defined eclipses of appreciable and comparable depth and well-resolved spectral lines of both components. In too strongly interacting systems, the dimensions cannot be very accurately determined, and in addition their validity for single stars becomes doubtful.

Obviously, the system must be bright enough to yield observations of good quality with the available instrumentation (see 2.2). If a third component contributes appreciably to the total light, it must be sufficiently well separated from the main pair to allow an accurate determination of its contribution (area scanner, electrography).

2.2 Choice of Observational Material

The spectra used for radial velocity determination must be of sufficiently high resolution to produce no appreciable degradation of the line profiles, so that remaining line blending problems are inherent in the stellar spectrum and not caused by the instrument. Particularly for early-type stars, the signal-to-noise ratio of the spectra must be high enough to allow measurement of those, mostly relatively weak lines that yield velocities free of systematic error (see 2.3). The usual precautions in radial velocity work must be taken, including observations of standard stars.

The orbit should of course be well covered, but avoid phases when the lines of the two components are not clearly separated. In our view, judgment of such line blending can only be done reliably when the actual line profiles can be inspected during measurement, e.g. on an oscilloscope screen.

The light curves should be obtained in two or more colours in a homogeneous well-defined and well-calibrated system (i.e. intermediate or narrow-band). Avoiding wide-band systems eliminates troublesome bandwidth effects in extinction corrections and transformations, apart from the difficulty of interpreting wide-band observations with the modern, essentially monochromatic light curve simulation models. The photometric indices needed for both components were specified above (see 1).

The light curves should be well covered with observations of sufficiently long integration time (on both the variable <u>and</u> the two carefully selected comparison stars) to ensure good accuracy of each magnitude difference--about $0^m\!.005$ or less. In order to detect any non-orbital light variations, all phase intervals should be observed on at least two different nights.

2.3 Choice of Spectral Lines

Methods for selecting spectral lines for the determination of spectroscopic orbits have been described by Popper (1967, 1970) and Andersen (1975a). They will not be repeated here, but we stress the importance of an objective method to test the consistency of the velocity measures, both for each line by itself and from line to line (Andersen 1975a). Without a description of such tests--or even a list of the lines used--one cannot judge the quality of a published analysis.

A particularly common--and disastrous--mistake is to ignore the effects of blending of the Stark broadened wings of the double Balmer and diffuse He I lines in early-type spectra, unfortunately the strongest lines in these spectra. Figure 1 (based in part on unpublished data) illustrates the systematic underestimate of the masses resulting from this, found for luminosity ratios ranging from one (Andersen 1975a, b) to about 0.05 (Hill et al. 1976). The empirical mass scale for B stars requires significant revision.

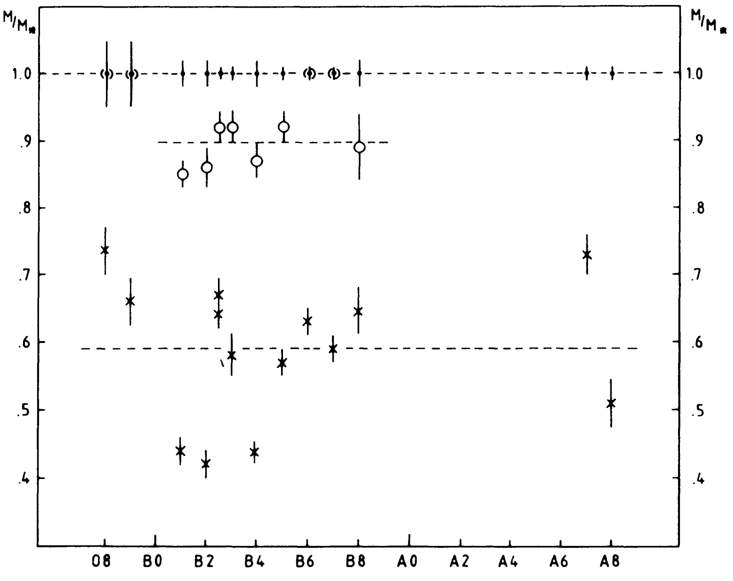

Fig. 1. The ratio between the masses derived from Balmer lines (crosses) or diffuse He I lines (circles), and the true masses derived from sharp lines (dots), plotted against spectral type. Mean errors are shown for each point. The average systematic error is 10% for He I and 40% for Balmer lines.

2.4 Choice of Photometric Model

The analysis of the light curves must be done with a physically realistic model. A few systems with circular orbits and very small fractional radii yield consistent results with almost all methods, including those involving rectification, etc. For most carefully observed systems, however, a physically realistic model is the way to accurate results - as distinct from small formal errors.

The computation of tidal and rotational deformation should take into account both circular and eccentric orbits, and non-synchronous as well as synchronous rotation. Reflection, gravity brightening, and limb darkening should be included in a realistic manner. Further, it must be possible to fix certain parameters like mass ratio or axial rotation, if they are better known from the spectroscopic analysis.

It is not advisable to attempt to solve simultaneously for all parameters defining the light curve. Some fundamental parameters (e.g. limb darkening or gravity brightening coefficients) should be fixed at values known to be applicable for the stars under study. One should then solve for the parameters peculiar to the system (i, k, r_A, T_B/T_A, e, ω). Subsequently, the effect upon the derived elements of likely errors in the fixed parameters should be investigated and taken into account in the discussion of the probable overall errors of the results.

2.5 Consistency Between Photometric and Spectroscopic Data

Traditionally the determination, if not the discussion, of photometric elements has proceeded without consideration of the spectroscopic data, or vice versa, usually because they were simply not available. In our program, photometric and spectroscopic observation and analysis normally proceed hand in hand, and we have become convinced that this is indeed essential to satisfy ourselves that our results are really correct.

First of all, the mass ratio cannot be used as a free parameter in fitting the computed light curve to the observations, when an accurate spectroscopic value is known. Next, not only should the photometric elements derived from light curves in different colours agree among themselves, but the computed luminosity ratio must be consistent with the observed line ratios. This condition sometimes offers the only possibility of fixing k in partially eclipsing systems of closely similar stars (see Fig. 2). A particular combination of assumed initial parameters and distribution of the observations may therefore lead even a good program completely astray on even the best observations, if no independent check is possible.

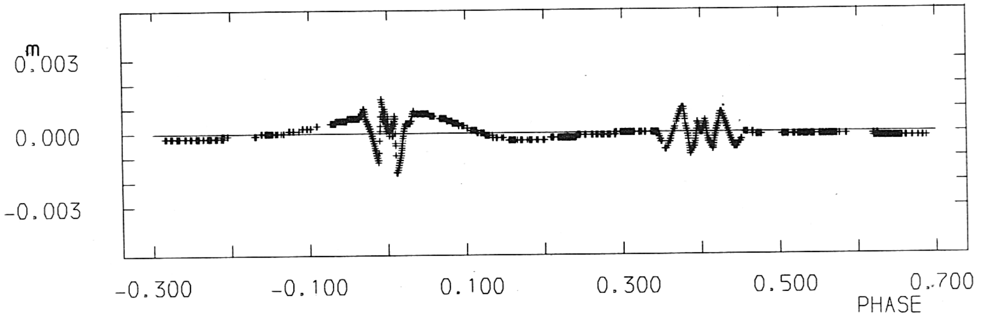

Fig. 2. The difference between two simulated light curves for QX Car, the first with k as a free parameter, with second with fixed k = 0.94, reproducing the spectroscopic line ratios. The curves are photometrically indistinguishable, yet the luminosity ratios differ by 40%.

Next, the computed rotations should reproduce the observed line widths when compared with spectra of rotation standards (Clausen et al. 1977). Finally, the observed colour changes in eclipse should be consistent with the temperature difference found in the analysis, and the colour indices themselves should be consistent with the spectral types. The latter constraint is a rather weak one, since spectral types are difficult to determine accurately in double-lined spectra, particularly from the high-dispersion spectrograms needed to determine accurate radial velocities.

3. CONCLUSIONS

The basic result of our work is a set of accurate values of mass, radius, and colour indices for the components of the binary systems studied. There are good reasons to believe that they are valid also for single stars. Interesting comparisons with stellar structure models have already been possible, leading to determinations of helium abundance also in later-type stars without observable spectral lines of helium. Some improvement in the determination of the basic parameters may still result from better treatment of, e.g. limb darkening and reflection. However, although eventually a purely empirical calibration of colour indices in terms of mass and radius is possible, the greatest uncertainty in the comparison with theory, and thus in the derivation of age and chemical abundance, stems from the calibration of colour indices into effective temperature and other intrinsic parameters.

We conclude that it is still useful to continue our work, provided we take it quite seriously and produce results of the quality needed: "Routine" work all too easily results in useless numbers.

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DISCUSSION FOLLOWING ANDERSEN, CLAUSEN AND NORDSTRÖM

Popper: I endorse the comments of Dr. Andersen. There are five additional points I would like to make briefly about the treatment of photometric data of close binaries. Three of them are pleas to those discussing light curves of relatively simple systems with one or the other of the available computer programs. The output of these programs tends not to give some of the important quantities derivable most directly from the photometric observations. First is the ratio of the surface fluxes of the two stars. This basic result is obtainable directly from the ratio of the depths of the minima, without reference to the ratio of the radii or to the ratio of light, which may be poorly determined in systems with partial eclipses that are not very deep. Second, the color index of a component undergoing eclipse is obtainable directly from the color index of the light lost, again without reference to the photometric solution. Third: important information about the system is contained in the light variation between eclipses. In the bad old days one used this variation to "rectify" the light curve within minima. While rectification is rarely carried out now, the coefficients of the variation between minima, a_0, a_1, and a_2, are very useful in understanding properties of the system. My fourth point concerns use of the spectrographic luminosity ratio, as discussed by Dr. Andersen, to rescue an otherwise indeterminate photometric solution, or at least to improve the solution. It is not safe to assume that the luminosity ratio is the same as the ratio of like intensities if the two components differ in temperature or gravity. Lastly, it is not valid, in my opinion, to derive "mean errors" of photometric elements by the usual least squares treatment of the observations. The conditions required for this treatment to be valid are not generally satisfied.

Andersen: It is very much our own philosophy to give the fundamental data obtained directly from the observations, so that anyone may rediscuss the interpretation with improved temperature scales, etc., but without having to reanalyze the observations themselves. We will be glad to discuss directly with you how to best do this in practice. With regard to your fourth point, the line ratio is always determined from several unblended lines varying differently with spectral type (the gravity differences are always quite small in the cases when the photometric indeterminancy requires additional spectroscopic data). We quite agree with your final point and base our own estimates more on interagreement between solutions in different colours, with different assumptions on limb darkening, gravity brightening, reflection, agreement with spectroscopic data, etc.

Smak: Did you try to use a profile-synthesis technique to extract information from blended hydrogen lines?

Andersen: Not yet. We are planning to do it, but at the moment we concentrate on getting a number of reliable orbits from the sharp lines, so we can check the results of such a correction procedure.

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Wilson: You imply that parameters are more easily determined for well-detached binaries than for those with larger components. However, I would say that the reverse is often the case, especially in regard to the mass ratio, because light curves of very close binaries provide information from the proximity effects as well as from the eclipses.

Andersen: That's right, of course, but it puts you into the hands of your model, and we have seen "determinations" of mass ratio with less refined models than yours, which we found to be completely up in the air when we got the radial velocities. So I must confess a preference for getting the mass ratio from spectra, and to the precision we are aiming at, that is best done in detached systems.

Van Paradijs: It would be interesting to compare your accurate gravity values with spectroscopic gravities as obtained from the ionization equilibrium or the profiles of spectral lines. Have such comparisons been made?

Andersen: No. This paper is on methods, not on results, but it is certainly one of our hopes in doing this work that it would interest some of the spectrum-synthesis groups to have a number of stars for which log g is known to 0.01 or even better.