NEW WAYS TO ROTATION RATES

R. E. Wilson
Department of Astronomy and Space Astronomy Laboratory
211 SSRB
University of Florida
Gainesville, FL 32611

(Received 20 October, 1988)

ABSTRACT. Progress in determining rotation rates of Algol primary stars from light curves is assessed. Included are elementary ideas on why the new method works, how to carry out solutions, and how and when to apply the constraint on rotational lobe filling. Some comments are made on desirable improvements for measuring rotation from line broadening. A few remarks are made about the problem of identifying likely fast rotating Algols.

1. INTRODUCTION

The statistics of Algol primary star rotation rates potentially provide information on the mass transfer process, and therefore on close binary evolution. Until recently, virtually the only means to measure that rotation has been spectral line broadening, as with single stars. The only advantage over single stars is that the inclination of the rotation axis is (presumed to be) known for Algols. In principle, the rotational eclipse disturbance in velocity curves also can be used, but that requires many spectra, rather than one, and the velocity shifts in which we are interested suffer from subjective effects, at least in the traditional method of measurement. The overall situation has therefore been that only a few tens of measured rotation rates existed for Algols, and nearly all of these are by observations of line broadening (e.g. Koch, Olson, and Yoss, 1965; Levato, 1974; Olson, 1984). Now a new way to measure rotation has appeared -- one that exploits the eclipsing binary nature of certain Algols, and which can make use of a reservoir of observations which already exist. The idea is that fast rotation must produce both polar flattening and an altered distribution of surface brightness (through the gravity effect), so that light curves are necessarily affected. Inclusion of a rotation parameter in a general light curve model (Wilson, 1979) made it possible in principle to determine Algol rotations, but that does not prove that it can be done in practice. It could be that the effects of rotation are too small or too subtle (correlated with other parameters) to allow proper determinations. However now considerable apparent success at finding rotation has been demonstrated (e.g. Wilson, Van Hamme, and Pettera, 1985; Van Hamme and Wilson, 1986; Wilson and Mukherjee, 1988; Wilson and Plavec, 1988), and the prospect seems good for further addition to Algol rotation statistics.

Intuitively, we expect a light curve to be affected in several ways by rotation

Space Science Reviews **50** (1989), 235–243.

of the primary star. Most obvious is in the character of primary eclipse (shape, depth, duration), although how such effects are correlated with the ordinary eclipsing binary parameters is difficult to say — many things are tangled together. The same could be said for the secondary eclipse, although one would expect the effects to be small just because that eclipse is so shallow. The amplitude of ellipsoidal variation should be increased by fast primary rotation because the lenticular hot star appears relatively dim to observers who are near the orbit plane, thus rendering the tidally distorted cooler star relatively bright. Also, the irradiation of the secondary will be reduced, because of the smaller equator-on brightness of the primary, so the reflection effect should be smaller than in a normal Algol.

To find the rotation of Algol primaries from their light curves, one needs a physical model in which brightness is a function of a suitable rotation parameter in addition to the usual parameters. Reliable results require application of the least squares criterion in a suitable adjustment algorithm. The rotation parameter used so far (Wilson, 1979) is F, the ratio of the angular rotation rate to the synchronous (orbital) rate, under the assumption of uniform angular rotation. There is no presumption that the real rotation must be uniform, only that it would be overly ambitious to attempt to find more than one rotation parameter.

A concept which enters the picture along with non-synchronous rotation is that of an effective limiting lobe. Of course the classical Roche lobe has direct application only for synchronous rotation, but there will still be a lobe which sets a limit to the size of the star and is quite analogous to the Roche lobe. As before we need to ask, for given mass ratio and rotation, what size star has its effective gravity go to zero along the line of centers. That is, the "rotational" limiting lobe is the largest closed equipotential surrounding the star. To find it, we apply the same logic as for a Roche lobe, except that we operate with the rotationally generalized equations (1) and (3) of Wilson (1979) originally derived by Plavec (1958) and Limber (1963) . For faster than synchronous rotation, the lobe will be smaller than the Roche lobe, and for very fast rotation will have only small departures from axial symmetry. The small difference is important, however, because effective gravity will go exactly to zero only on the line of centers, rather than everywhere on the equator. Notice that a large value of F does not necessarily imply ultra-fast rotation, since a very small star can spin rapidly without approaching the centrifugal limit.

Consideration of the above leads inevitably to the idea of rotational lobe filling, and to that of a star being in contact with its limiting lobe without being in contact with its companion star. Since accreting matter, which is the natural cause of fast rotation, originates in overflow from the other star (which in a normal Algol system will be in contact with an ordinary Roche lobe), we are led directly to the idea of double contact (Wilson, 1979). Both stars are then in accurate contact with their limiting lobes — one by overflow (star expands to meet the lobe) and one by spin-up (lobe contracts to meet the star). This prospect cannot be escaped if one considers a sequence of Algol-type models with increasingly fast primary rotation, and realizes (Packet, 1981) that mass transfer spins the star up very efficiently, especially since rotation of only the outer envelope is relevant to the lobe-filling situation. An interesting aspect of double contact is that it adds a fourth type to the morphology of close binaries, augmenting the detached, semi-detached, and overcontact types recognized long ago by G. P. Kuiper.

2. STRATEGIES FOR IMPROVING STATISTICS

A major goal of the new measurements is to establish the statistical distribution of Algol rotations, including how many systems are close to, or in, double contact. An early objective is to test photometric F's against those from line broadening, for which there has already been a certain amount of success (Wilson, 1988a). Since there are only a few dozen Algol primaries for which F has been measured by line broadening, and many of those lack suitably observed light curves, a second stage is now being entered in which F is determined from light curves without a line broadening check (e.g. Wilson and Plavec, 1988; Wilson and Mukherjee, 1988). Sometimes a rough check can be made from the Rossiter effect, but often there may be no check at all. In those cases our confidence in the results will hinge strongly on the success of the few cases in which checks were available. How are candidates for fast-rotation to be uncovered, among the much greater number of slowly rotating Algols? Here, again, Rossiter effects can help, but a more promising diagnostic aid for dealing with large numbers of systems is the presence of emission line activity in and near a total primary eclipse. A list by Kaitchuck, Honeycutt, and Schlegel (1985) already has proved helpful for this purpose, in that all examples with such emission lines (except RW Tau) have turned out to have large F's. This makes good sense, because rapid rotation is induced by mass transfer, and is efficiently damped by tides when there is little transfer. Therefore only systems with fairly large-scale mass transfer (and thus emission lines) should be rapid rotators. Achieving the statistical base needed to establish the frequency distribution of F values will require going to faint systems, so observing time on large telescopes can be put to very good use both for detecting emission lines (and thus interesting systems) and for obtaining good light curves of those systems. It might seem that an eventual third stage would be to find photometric rotation rates for Algols of all F's — high, low, or intermediate (thus dispensing with intentional selection criteria and eliminating the more obvious selection effects). However, as brought out in the next section, that possibility appears to be impractical, and help will be needed from line broadening work.

To do the large number of light curve solutions needed for proper rotation statistics, work by more than one or two groups will be needed. It is easy to say that all suitable existing light curves should be analysed, but in practice it is an enormous amount of work to analyse even one conscientiously. One is not always sure which parameters should be adjusted, so a great deal of person-machine interaction is involved. While there have always been many persons ready and willing to carry out light curve analyses for various kinds of binaries, that enthusiasm has not yet spilled over into the area of rapidly rotating Algols (RRA's) and their rotations. Having a given light curve re-done by another person should not be so redundant for RRA's as for, say, ordinary Algols, because it is not yet clear how much the results depend on weighting and other procedural decisions. The required computer program (Wilson, 1979) has already been made generally available, so perhaps such work will soon begin appearing. Even more important is to fit several independent light curves for given RRA's to learn whether results on F and q (mass ratio) are reproducible. That effort cannot be expected to eliminate systematic effects (difficulties with circumstellar matter, etc.) but it may help if such problems do not occur at all epochs.

3. PROCEDURES AND PROSPECTS

The general idea of carrying out light curve solutions with one or more applied parameter constraints is intrinsic to the Wilson-Devinney (WD; 1971) or Wilson (1979) model, where it is expressed in terms of the various solution modes. Each mode corresponds to a particular set of constraints (viz. Wilson, 1988b), such as exact filling of one limiting lobe or the other, or both. For RRA's one would normally assume the secondary star to fill its lobe, while the primary may or may not do so. Of course, the secondary's lobe is an ordinary Roche lobe (synchronous rotation) while the primary's is the smaller one associated with fast rotation. The solution mode should be 5 if (only) the secondary fills its lobe (semi-detached) and 6 if the primary also does. The usual way to begin is in mode 5, with the (model) primary star rotating slowly. Experience shows that for known fast rotators, F quickly jumps to large values, although many iterations may be needed to settle on a final value. Sometimes there is an interesting rejection of prejudice as, for example, with RW Tauri. There, W. Van Hamme and the author had a feeling — based on the star's well-known emission line activity — that the rotation had been underestimated from line broadening work, and that the photometric F would turn out to be large. We were wrong, as F_{ptm} showed no tendency at all to run to large values, but stayed nicely in the vicinity of the spectroscopic F. A similar experience was earlier reported for U Sge (Van Hamme and Wilson, 1986). However, when binaries have been selected for having spectroscopically demonstrated fast rotation, the consistent experience has been for F_{ptm} to climb quickly, usually arriving at something close to F_{sp}. For a few binaries, corrections have been found which place the primary slightly (a few percent in radius) beyond the limiting rotational lobe, and there seem to be particularly unusual and active systems, such as RZ Sct (Wilson, Van Hamme, and Pettera, 1985), SW Cyg, and AQ Peg (Wilson and Mukherjee, 1988). Surprisingly, perhaps the most bizarre RRA of all, U Cephei, was found by Rafert and Markworth (1983) to be a little below double contact, and it will be interesting to analyse other U Cep light curves to see if that result persists. Of course, light curves of U Cep usually are so disturbed by circumstellar gas that it is difficult to find an epoch of reasonable photometric behavior. Naturally, one should require consistent lobe overflow throughout several iterations of the fitting process, or at least an approach to lobe filling within about a standard deviation, before seriously proposing double contact for a given binary.

The possibility of determining F_{ptm} in principle does not mean that it can be done in practice. What can really be done depends on how large are the effects of rotation on the light curve, and on how serious are correlations between F_{ptm} and other parameters. The latter subject is difficult to discuss, but some useful remarks can be made about the former. Since the essential effects are rotational polar flattening and equator-on dimming, some insight can be gained by plotting those effects vs. F/F(critical), as in Figures 1 and 2. Notice that departures from the synchronous case grow slowly at first, reaching only about 18 percent of the full effect when F/F(critical) is 0.5. Accordingly, we can expect photometric rotation rates to be strongly determined only for rather fast rotation, and experience shows this to be the case. Therefore overall rotation statistics will need to rely on both line broadening and photometric determinations, with most information on slow rotators coming from line broadening, and from fast rotators from the new photometric method.

Are we facing a major new opportunity to improve on the rotation statistics

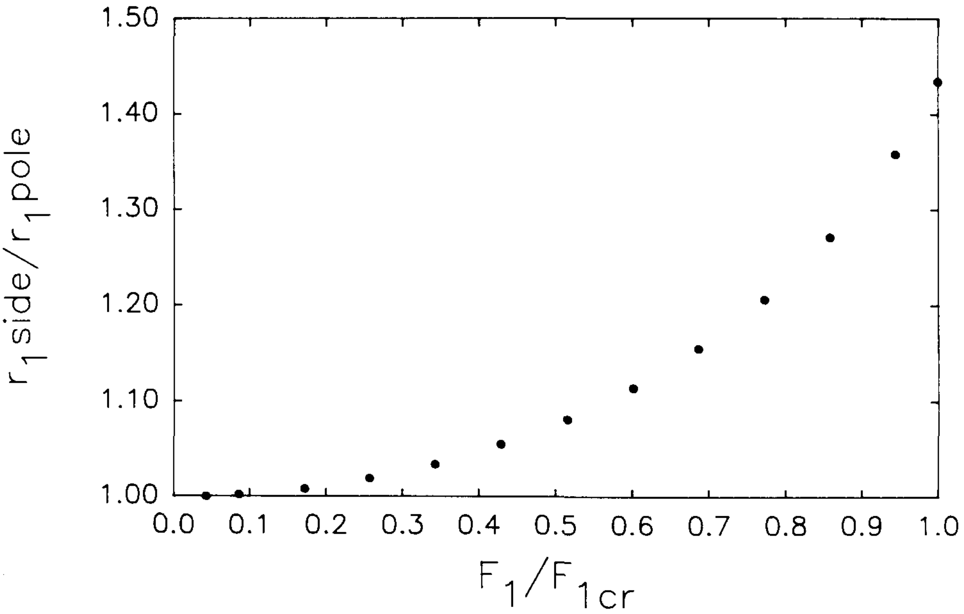

Figure 1. Ratio of side to polar radius for a rotating star as a function of the rotation parameter F. Notice that most of the variation occurs for large F.

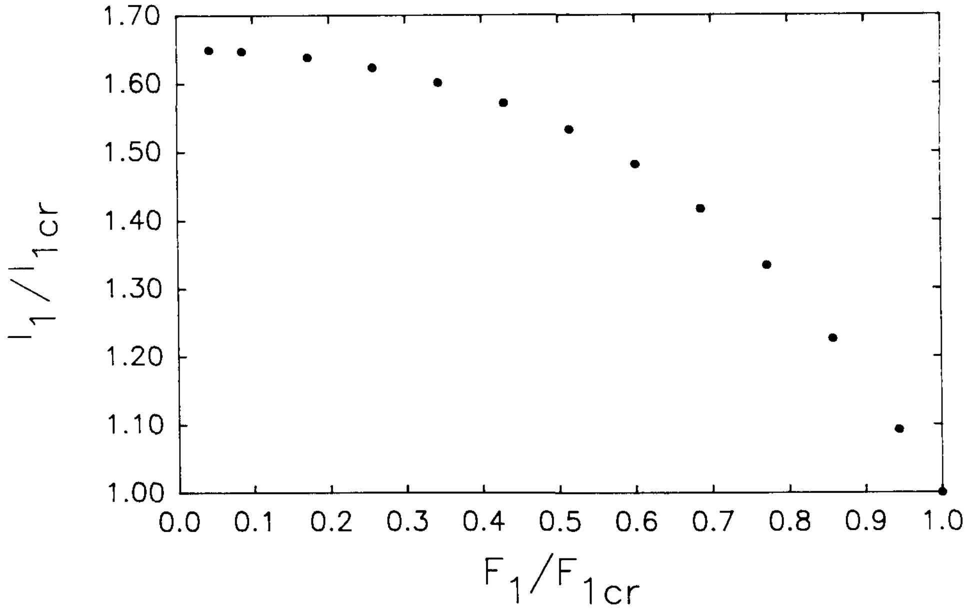

Figure 2. Relative flux from a rotating star as a function of the rotation parameter F. The observer is in the equatorial plane.

of Algols? On the one hand, we have a large reservoir of observed Algol light curves waiting to be analysed for rotation. On the other hand, only a few of these have F/F(critical) greater than 0.5, so perhaps not so much will be learned, at least until much fainter limiting magnitudes are routinely reached photometrically. It will be interesting, however, to exploit present resources to the extent that they exist.

Recently there has been renewed interest in the old fitting technique of iterative minimization, as an alternative to differential corrections. Although that approach does not provide standard error estimates, it has the advantage of being relatively immune to convergence problems caused by parameter correlations, so it becomes interesting where there are serious correlations, as in determinations of F. However, some of its practitioners advocate completely automatic computations, with no human intervention at all, and one should realize that this practice often has the undesirable effect of locking one into one definite parameter set. The subjective examination of intermediate results not only provides insight into the fitting process, but permits dynamic development of good sets of adjustable parameters. Otherwise, enormous amounts of machine time can be wasted. Some recent contributions also make the mistake of ignoring proper weighting of the curve-dependent or level-dependent types, or both. In each case, that has the disastrous effect of having the worst observations control the solution (they have the largest residuals). One cannot neglect weighting and claim to have a solution in accord with error and adjustment theory, since it is the sum of the squares of the weighted residuals which is to be minimized.

4. ROTATION FROM LINE BROADENING

As brought out in Section 3, for small or modest degrees of rotation (say F/F(critical) not larger than 0.5), the line broadening method will decidedly outperform the photometric method, so it is necessary to make progress in that area also. Both improved analyses and improved data bases (quality and quantity) are needed. At present we owe our observed F_{sp} values for Algols to a remarkably small number of publications, and there seems not to be an acceleration in the rate of appearance of those contributions. A curious problem, generally characteristic of this type of observational work, is that no one publishes the observed line profiles, but only the derived rotation rates. It is as if all papers on observation and fitting of light curves were to give only solution parameters, and not the light curves themselves. Such a situation would stifle interest in developing improved light curve models (there would be no data to try them on), and would make it impossible to check on published parameters. That is exactly the situation we now have in regard to line profiles, where the most important observational data (residual flux vs. wavelength) always has been omitted from publications — a strange situation which needs to change. Of course, judgment is required (estimating the effective continuum level), but that problem could easily be bypassed by presenting both residual flux and the original relative flux itself, so that in new analyses the effective continuum could be changed. There are indeed other problems concerning how the data would be presented in a standard way, but they are relatively minor and could be worked out with a modest amount of thought.

Overall, the following advances are needed:

1. Improved observational material (actually published). This means high

resolution (say CCD) spectrometry.

2. Direct modeling and fitting of the profiles, with the aid of a profile generator which incorporates the main local broadening mechanisms, and includes binary star effects (tidal and rotational distortion, reflection effect).
3. Work on primary star velocity curves, whose amplitudes are often seriously uncertain. That amplitude is important in setting the scale for F_{sp}.
4. Observations of the velocity amplitudes of secondary components (as in, for example, Tomkin 1979, 1981). That amplitude, plus a photometric mass ratio, yields absolute masses and dimensions.

With regard to modeling line profiles, the mechanisms of damping, thermal Doppler broadening, etc. have often been assumed negligible relative to rotational broadening, or they may be treated, but in a cursory manner. It is not clear that one can ignore proper treatment of these effects when the full accuracy of the observations is to be exploited. There certainly are other kinds of adjustment problems in which seemingly secondary parameters are found to wield a substantial influence when properly taken into account. One should always ask if the proper theory is being neglected because its consequences are truly negligible, or because a proper treatment is too much trouble.

5. CONFIDENCE IN MEASURED ROTATION RATES

The building of confidence in Algol rotation rates and their statistics is not an easy task, considering that selection effects are rampant, the numbers of well-conditioned systems is (at present) small, and independent checks on the procedure are minimal. The faster rotators preferentially attract attention, but some of the very fastest ones have light curves and line profiles which are very difficult to analyse. For RZ Sct and RY Per (viz. Wilson, 1989) there seems to be good agreement between line broadening and light curve results, but for now those two comprise the entire list of favorable checks. Achieving confidence is partly a matter of doing enough binaries and, while the number of interesting (fast rotating) systems in present catalogs may be limited, their number can be increased by going to fainter limiting magnitudes. This would mean pushing the photographic surveys which discover Algols to fainter limits, and looking for emission line activity in totality (e.g Kaitchuck, Honeycutt, and Schlegel, 1985) to disclose the fast rotators.

At first sight it seems curious that there are not more checks between line broadening and photometric F values. The discussion of Section 3 makes it clear why photometric F's are missing at the low end, near synchronism, but why are line broadening F's rare at the high end, near the centrifugal limit? Several reasons can be suggested, although it is not obvious which of these is most important. For example, lines can be rotationally broadened beyond the point of observability. Perhaps CCD techniques can help on that problem. It may be that lines due to gas orbiting the primary star are falsely assumed to be photospheric, while the actual photospheric lines are too broadened for ready detection. In regard to light curves, there have been several instances in which the photometric effects of lenticular shape have been attributed to an optically thick circumstellar disk, so that the underlying cause (rapid rotation) has gone unrecognized.

In summary, it seems too early to have a great deal of confidence in the statistics of measured rotation rates for Algols for several reasons, but we can anticipate growth toward confidence over, say, the next decade. We are seeing the first attempts at an intrinsically difficult problem, and the main excitement is in the chase.

ACKNOWLEDGMENT

The author is pleased to acknowledge support of this work under National Science Foundation Grant AST 8412610.

REFERENCES

Kaitchuck, R.H., Honeycutt, R.K., and Schlegel, E.M. 1985, Publ. Astron. Soc. Pacific **97**, 1178.

Koch, R.H., Olson, E.C., and Yoss, K.M. 1965, Ap. J. **141**, 955.

Levato, H. 1974, Astron. and Ap. **35**, 259.

Limber, D.N. 1963, Ap. J. **138**, 1112.

Olson, E.C. 1984, Publ. Astron. Soc. Pacific **96**, 376.

Packet, W. 1981, Astron. and Ap. **102**, 17.

Plavec, M. 1958, Mem. Soc. Roy. Sci. Liege **20**, 411.

Rafert, J.B. and Markworth, N.L. 1983, Bull. Am. Astron. Soc. **15**, 926.

Tomkin, J. 1979, Ap. J. **231**, 495.

Tomkin, J. 1981, Ap. J. **244**, 546.

Van Hamme, W. and Wilson, R.E. 1986, Astron. J. **92**, 1168.

Wilson, R.E. 1979, Ap. J. **234**, 1054.

Wilson, R.E. 1988a, in Proceedings I.A.U. Symp. 107, ed. K.C. Leung (Gordon and Breach), p. 455.

Wilson, R.E. 1988b, in Proceedings I.A.U. Symp. 107, ed. K.C. Leung (Gordon and Breach), p. 193.

Wilson, R.E. 1989, "The Relation of Algol and W Serpentis Stars" (this volume).

Wilson, R.E. and Devinney, E.J. 1971, Ap.J. **166**, 605.

Wilson, R.E. and Mukherjee, J.D. 1988, Astron. J. **96**, 747.

Wilson, R.E. and Plavec, M.J. 1988, Astron. J. **95**, 1828.

Wilson, R.E., Van Hamme, W. and Pettera, L.E. 1985, Ap. J. **289**, 748.

DISCUSSION

Holmgren reported on his analysis of the light-curves and velocity-curve of Z Vul, in which the two methods of determining rotational velocities gave concordant results, even though the rotation rates were not very high. The spectrum of the primary gave a rate of 1.5 times synchronous rotation for that star, while the line of MgII 4481 in the spectrum of the secondary shows that star to be rotating synchronously. The light-curve was best satisfied when these figures were used. Smak inquired about the models Wilson had used for rotating stars. Wilson replied that his equipotentials included the point-mass gravitation of the two stars and the centrifugal effects of rotation.

Hill remarked that it is now possible to determine the rotational rates of secondaries in Algol systems by measuring the FWHM of the cross-correlation function of spectrograms of the blue region, even if individual lines of the secondary component are not visible.