RESOLVING INFORMATION ON ALGOL SYSTEMS

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ABSTRACT. Our awareness of the facts on Algol systems, arising from both statistical evidence and examination of particular examples, is presented. The statistical information derives from the author's recent catalogue of Algol-type candidate stars. The particular cases of R Ara and W Cru are considered. The presence of undiscerned background factors in these systems exemplify persistent threats to the confidence we place on parameter sets characterising any models we may form of such objects.

1. GENERAL PROPERTIES OF ALGOLS

1.1 The standard picture

A fuller version of this paper will be given elsewhere, but the standard picture can be briefly summarized here thus: Algols are generally taken to be close, usually eclipsing, semi-detached binary systems consisting of an early type (A or late B, sometimes F) primary, which seems quite similar to a Main Sequence star in its broad characteristics, accompanied by a peculiar low mass star, which fills, or tends to overflow, its surrounding "Roche" surface of limiting dynamical stability. Photometrically they usually show deep primary and shallow secondary eclipses; spectroscopically they are usually single line binaries, often showing emission effects in the Balmer lines, or other indications of the presence of high temperature low density plasma.

1.2 Catalogued information on Algols

A candidate list of some 414 classical Algol binaries was catalogued a few years ago in order to provide more general background information of this class of star (Budding, 1984a). It was arranged into groups as follows:

75 systems of class 0.9 (well known classical Algols)
169 systems of class 0.7 (apparently similar to the 0.9 cases, but just generally less well known)

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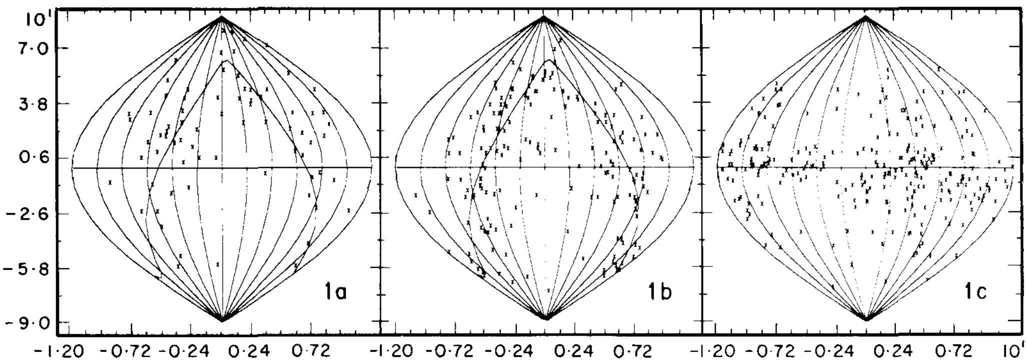
114 systems of class 0.5 (roughly even chance of being a classical Algol, or something else)
43 systems of class 0.3 (still possible to be a classical Algol, but rather more likely to be something else)
13 systems of class 0.1 (definitely unlikely to be an Algol, though sometimes apparently regarded as such in some reference).

The majority of candidates (244) thus belong to the "definite" or "quite likely" groups, and subsequent statistical discussion may concentrate on these stars. If we interpret the foregoing classification parameters as crude indicators of genuine Algol status we arrive at a conservative estimate of 257 definite Algols, implying that of the order of one in a thousand stars brighter than a given magnitude is an Algol system.

1.2.1 The sky distribution of Algols



In Figure 1a is shown the distribution on the celestial sphere of the 75 class 0.9 Algols, with equatorial declination corresponding to a uniform vertical scale, and separations in right ascension proportional to the horizontal spacing. The galactic equator is also marked as a continuous curve on this projection. Although some clustering towards the galactic equator seems evident, there is some other non-uniformity, for example, in that only 25% of the systems are located in the southern hemisphere.

The situation is much more normalized in this latter respect on moving to the class 0.7 systems (Figure 1b), of which almost half are now in the southern hemisphere; this is presumably just telling us something about the distribution of astronomers on the Earth, rather than anything intrinsic to Algols. Figure 1c shows the superposition of the two groups, where the eye seems to notice even more the clustering of the distribution toward the galactic plane; which is perhaps clearer with the transfer of the projections from equatorial to galactic coordinates.

Figure 2a presents a histogram of the distribution in 10 degree intervals of modulus of the galactic latitude for the 75 0.9 class Algols; Figure 2b shows the same arrangement for the 169 systems of class 0.7, and the two groups are added together in Figure 2c. These

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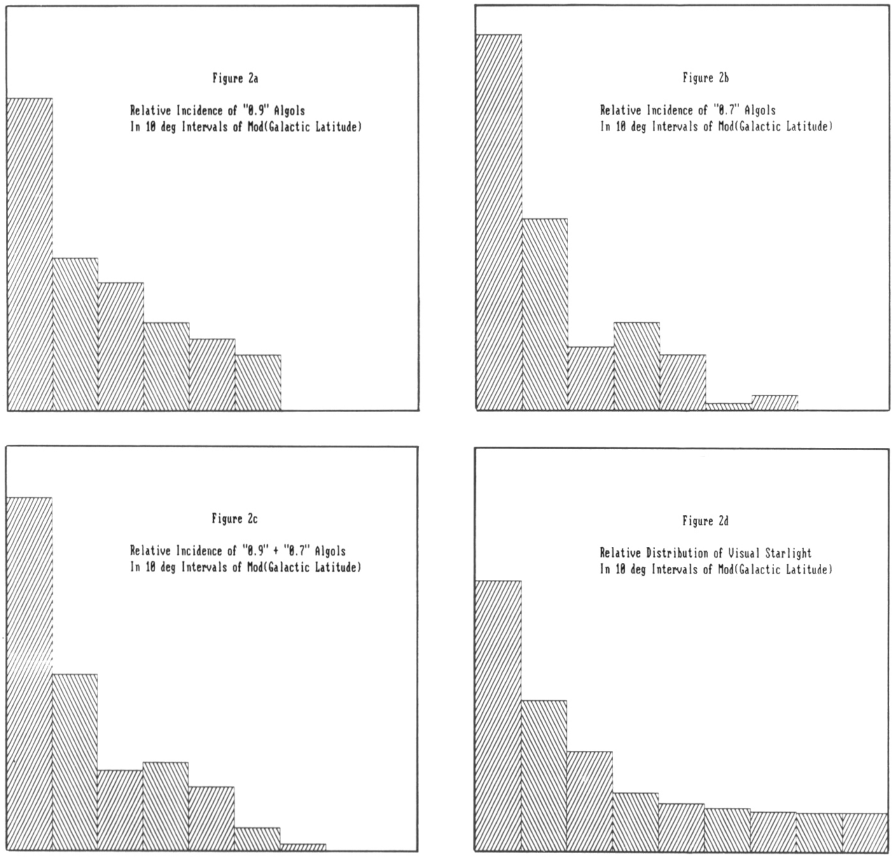

distributions may be compared with the general starlight distribution of Figure 2d (Allen, 1973). Clearly, more detailed analysis of such distributions could be made; for now we just make the point that Algols represent a somewhat more flattened distribution of stars in the Galaxy than average - which may be in keeping with our expectations of the masses of the component stars, and the consequences concerning age and evolutionary status.

1.2.2 Distribution in (primary) spectral type and period

A three-dimensional distribution of 311 Algol candidate stars, with frequency plotted against period and primary spectral type, was given previously (Budding, 1981a). The main features of that presentation are not likely to be changed much by the updated candidate list, or the group subdivisions. Thus the maximum of the distribution occurs at spectral type A0, and period around 2.5d. At rather short periods (around 1 d) there is some tendency for a proportional increase in the numbers of primaries of somewhat later type (i.e. the proportion of late A or F-type primaries increases). The numbers of Algol systems with

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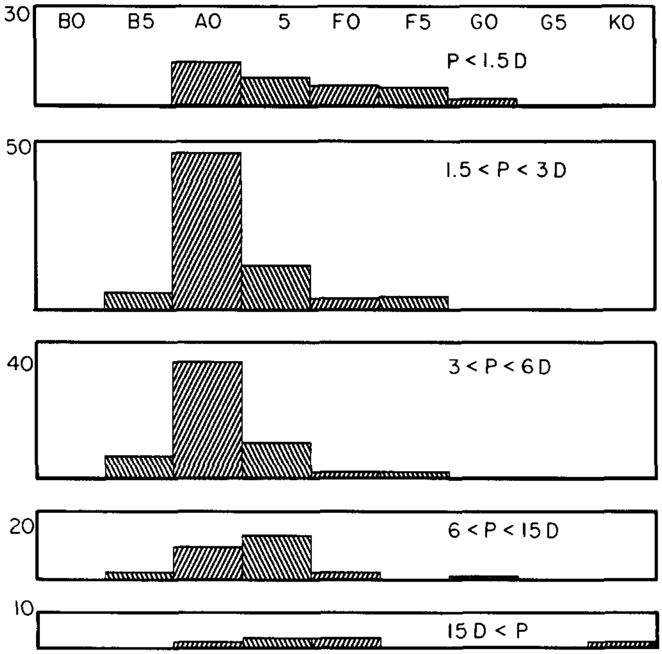

Figure 3

primary type earlier than A0 may increase somewhat at periods a little beyond 2-3 days, but, in any case, there is a swift decline with earlier type, and very few primaries are known with type earlier than B5. At long periods, say a week or greater, the proportion of later type primaries does not decline - it may indeed increase again.

These properties, discernible in the reference mentioned, can be seen again in Figure 3, which presents the information from the 244 quite probable candidates. The appearance of a few late type primaries at long periods reflects the inclusion of stars like RZ Cnc: systems believed to be essentially similar to classical Algols in their basic facts, except that their presently more massive components already left the Main Sequence and moved over to the Giant Branch (Popper, 1976). The mean period of the 244 systems, incidentally, stands at 7.4982 days.

1.2.3 Distribution of primary mass

The well studied Algols have values of primary mass which are known with some reasonable confidence; their distribution reflects what could be expected from the foregoing spectral type distribution, if the primaries are Main Sequence like stars.

The frequencies in uniform intervals of primary mass, and log mass, for the 244 probable Algols, are shown in Figure 4. The maximum occurs at about 2.5 $M_\odot$, in fair agreement with the A0V type in recent versions of the Main Sequence (Budding, 1981a). The mean mass of the sample is $3.32 M_\odot$; the corresponding radius is about $2.3 R_\odot$. No primary mass is

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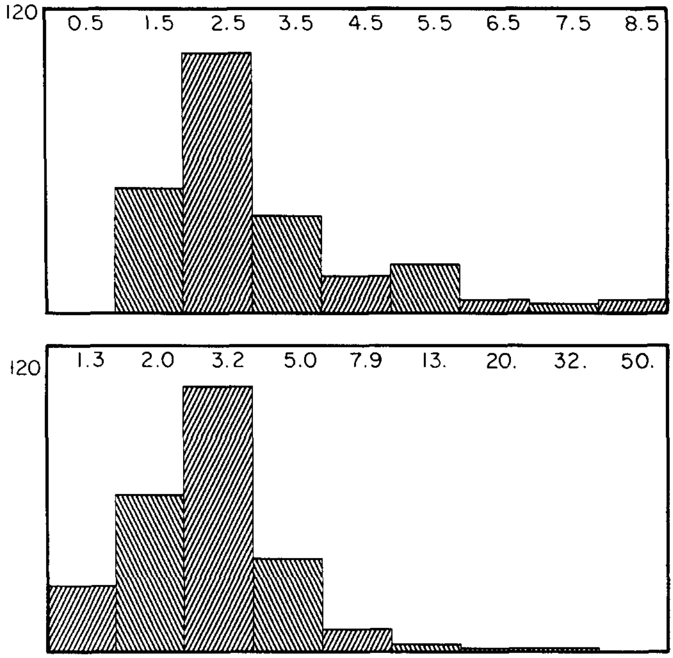

Figure 4

known less than $1.2M_\odot$. The lowest total mass in an Algol system is conspicuously that of R CMa, which most sources put at less than $1.5M_\odot$. About 10% of the 0.9 and 0.7 groups have a total mass less than $2M_\odot$ - some of these, like Z Dra and RT Per, appear to be in short period configurations like R CMa, and may have somewhat odd evolutionary histories. At the larger mass end, however, the spread out seems a bit protracted. RZ Sct, with its B3 type primary, must undoubtedly be massive, but Giuricin et al.'s (1983) value of $18M_\odot$ is appreciably higher than Brancewicz and Dworak's (1980) $13.5M_\odot$. If the giant system BL Tel is essentially similar to an evolved Algol, then a primary mass of around $20M_\odot$ can be reasonably expected.

But this raises the issue of defining the boundary wherein the classical Algol systems lie. Systems larger than a certain mass might evolve in a somewhat different way. For example, for the precursor systems having secondary (MS) components of type earlier than B5, the role of radiation pressure in the Roche Lobe overflow mechanism might produce some significantly different outcome (WR stars? - Budding, 1981b). The initial total mass of such a binary would have to be greater than about $12M_\odot$. The existence of RZ Sct would seem to argue against such a hypothesis, but then RZ Sct is the most massive classical Algol. More massive systems could be expected to spend a proportionally much smaller time in the Algol configuration, it is true, but, countering that selection effect, such stars could more easily be seen out to a much greater distance.

The absence of any current primary with mass less than $1.2M_\odot$ is in

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keeping with the general tenets of the Roche Lobe overflow theory of the Algols; a complete theory should be able to explain, though, not just the main features of a typical Algol configuration, but also the observed form of such distributions in mass and spectral type and period as have been given.

1.2.4 The mass ratio versus period diagram

Potentially significant implications on the mass loss/transfer theory of Algols also come from the form of the mass ratio (q) versus period (P) distribution, as has been noted in various previous compilations (cf. Giuricin et al., 1983). The general trend of low q at long period can be easily noticed, and fits in with the broad expectation of mass being transferred from the secondary to the primary during the course of the Algol phase of binary life.

By studying a sample of 147 stars from the same catalogue already used, but in a relatively narrow mass range, the likelihood of a mass transfer process in which a relatively small fraction of the overall mass was lost from the system, but carrying a relatively high proportion of the system's angular momentum, was indicated (Budding, 1984b). One odd feature of this work was that there tended to remain a small subgroup of Algols, typified by R CMa, whose location in the P:q diagram is difficult to explain by the basic mass transfer process, even including non-conservative effects in a formula which gives a reasonable account of the overall form of the P:q distribution. For such cases, corresponding to about 10% of the entire set, something other than the standard picture must apply: perhaps "third bodies" play a part, or perhaps there is some more drastic angular momentum loss mechanism which might be associated with a "contact" phase in Algol evolution.

A few of the "0.7" type candidates in the list of 244 fairly likely Algols have rather suspect parameter sets. The mean mass ratio of 238 of the candidates, for which there are reasonably reliable values turns out to be 0.276. Taken together with the previously mentioned average mass ($3.32M_\odot$), this value underlines a key element of the Algol paradox - i.e. that the average subgiant component mass is only about the same as, or even less than, that of the Sun.

1.2.5 Primary radius against mass ratio

The plot of primary relative radius against mass ratio has provided a setting for comparative studies of Algol properties since the time of Otto Struve, and has appeared in various places with various discussions and related to various particular stars. The 238 likely Algols are shown in Figure 5, which is an updating of a previously presented version (Budding, 1980).

Apart from the observed values of primary radius r_1 and mass ratio, also shown are the "r_{disk}" and "r_{min}" values, which come from formulae for accretion structure parameters given by Lubow and Shu (1975). The outer radius represents a value at which quasi-circular particle orbits in the restricted three body problem attain long term stability. Real disks of low density may well reflect this mathematical feature in their

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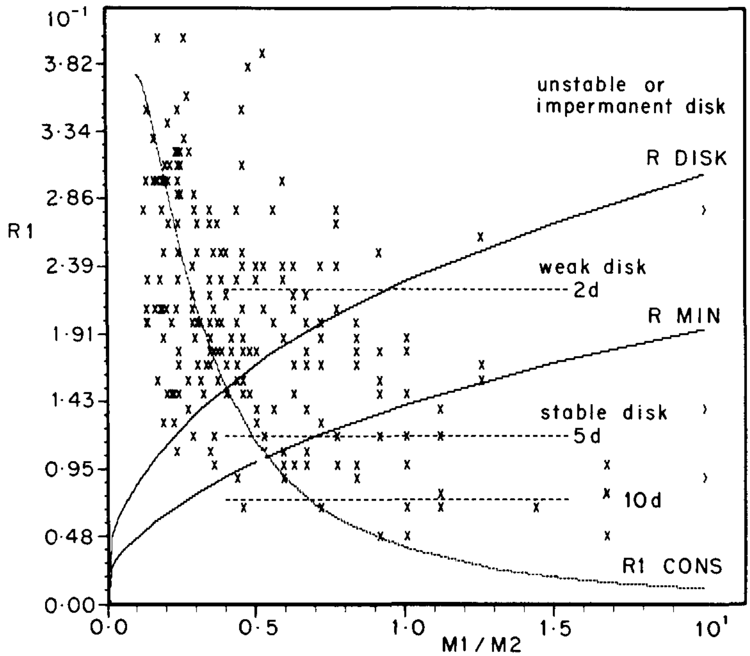

Figure 5

structure - expansion of a disk beyond this radius could be regarded as entailing some likely structural break-up, at least on the basis of a simple physical representation. The inner radius is a similar extraction from a particle behaviour approximation. An infalling particle moving with the velocity and direction of the 'stream' of the Lubow and Shu calculations would not approach the attracting mass centre to within closer than this radius. These radii may well guide our expectations concerning accretion structures in semi-detached binary stars.

Thus, points in the $M_1/M_2:r_1$ plane above the r_{disk} curve have gainer radii which are actually bigger than the circular orbit stability limit. They should not form large and stable accretion disks: there simply is not the room to get the structure started. On the other hand, any points near the bottom right corner of the diagram have plenty of space about the primary, relative to the orbit dimensions, in which to accumulate infalling material. The stars which lie between the two curves may exhibit intermediate properties between these two conceptualized extremes.

From the distribution of the stars in relation to the r_{disk} and r_{min} curves we may deduce that a majority of the Algols are unlikely to have formed substantial accretion structures, but a sizeable minority do have a sufficiently large separation between the components to allow disk accumulation.

The horizontal dashed lines shown in Figure 5 are meant to indicate typical periods associated with the corresponding r_1 values, where the

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primary is a Main Sequence star of the average mass of the sample, and at that mass it is accompanied by a star of average secondary mass. Individual stars need not conform to these indications exactly, but the lines do suggest that Algols having reasonably stable disk-like structures might be more expected among those with periods greater than about 5 days.

Also of interest is the curve labelled "r_{1cons}". This represents a track taken by a primary of a given constant size, when in an Algol system which is conserving its total mass and angular momentum. In this case its relative radius r_1 will vary like

$$r_1 = 16r_{1o}(Q^2/(1+Q)^4)$$

where r_{1o} is its maximum relative radius (~0.38 in a "contact" configuration with equal mass components), and Q is the mass ratio expressed as M_1/M_2. As a whole, the Algols seem to trend roughly parallel with this track, suggesting some relevance to mass transfer theories of Algols evolution under conditions which may be comparable to the conservative case. It is notable, however, that at long periods and low r_1 values, all the Algols lie above the curve - suggesting that angular momentum loss occurs during the course of Algol evolution, (though expansion of the primary star itself may have a part to play in this trend). But again, the existence of some points with both largish r_1 values (>0.15, say) and large Q values, supports the point made earlier about the P:q diagram. The location of these stars in the Q:r_1 plane is curious.

2. PARTICULAR CASES

2.1 Parameter resolution

An important general point underlying much of the specification of parameter sets, which are estimated to characterize data sets coming from observations of individual systems, concerns the deterioration of the resolution of particular parameters as their set size is increased. To be more definite, we can say that it can be shown that the probable error Δa, appertaining to a parameter a, in a given set $\underline{A}$ of m such parameters, which are determined from a set of equations involving a symmetric square "normal" matrix, or curvature Hessian, whose elements derive from a given set of N (N>m) observations, will, at best, stay constant, and, in general, increase as the number m increases, up to some maximum value m_{max} (<N), beyond which it becomes indeterminable.

This is an important point in any information inversion problem, where we set out with a data set to apply to a fitting procedure to derive a corresponding parameter set. The parameter values appear as constants in the "fitting function", whose form may reflect some underlying theoretical model. Ideally, such theory should minimize its preconceptions, in order to maximize the role of real experiment in furnishing valid information. But now a basic dilemma becomes apparent - the more particular facts we ask our data to deliver, the less

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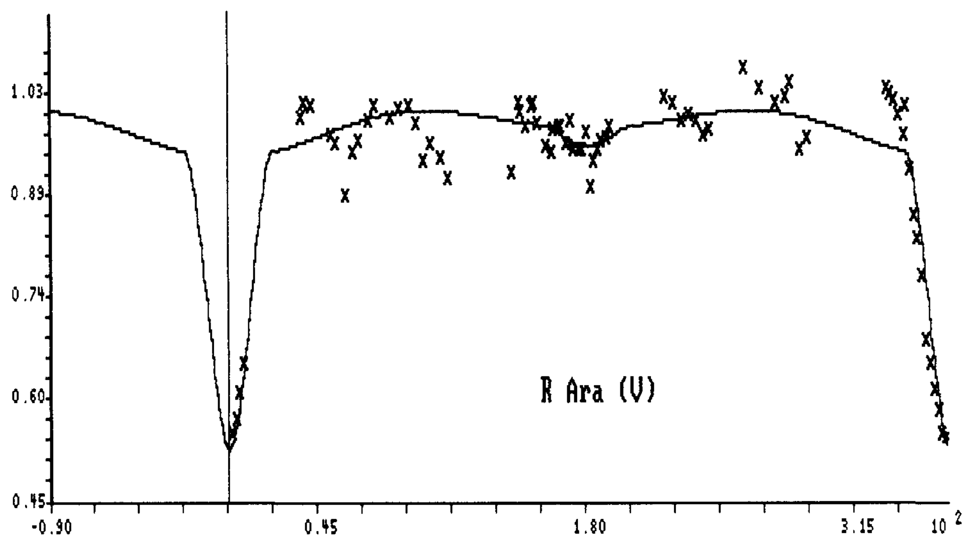
they can reliably tell us. The problem seldom confronts us strongly, because observations are usually directed to situations where we can clearly separate what we want to know from what we think we know already; but concealed or undiscerned background factors can affect observations of Algol systems. In what follows we will consider two particular cases, but the problems raised by undiscerned background factors in these cases may have quite general implications.

2.2 R Arae

Recent UBV photometry of this system has been reported by Nield et al. (1986), and is given more completely by Nield (1987), who also includes a review, analysis and discussion. John Herschel, in 1833, noted that the star appears as a close visual pair, with a separation of about 4", but the role of the companion, which would surely have been included in subsequent photometry of the variable brighter component of the pair, seems to have been glossed over, and no good determination of its relative light has been published, though the New Zealand group have estimated a contribution of about 1/3 to the combined light in V.

Sahade (1952) presented a thorough spectroscopic discussion of R Arae, noting abnormal radial velocities, apparent doubling of Balmer features and other irregularities, which we would now tend to associate with typical indications of "interactive" Algol type effects. That R Arae may be a "good actor", in this respect, is also borne out by more recent satellite borne studies, both in the ultraviolet and X-ray domains (Kondo et al., 1984).

Nield (1987) showed that the third light can make a critical difference to the question of whether the photometry of the system indicates semi-detached (sd) status or not. She demonstrated that



inclusion of third light as a free parameter will tend to increase the derived ratio of radii r_2/r_1. Since too low a secondary radius for a sd arrangement is found when L_3 is neglected (using Sahade's mass ratio (0.35), and the known relationship between secondary relative radius and mass ratio (Kopal, 1959)), inclusion of the third light may bring up the secondary's proportions to allow for the sd configuration, as might be anticipated from the interactive accompanying phenomena.

The situation is complicated, however, by the inherent irregularities of the system. Both Nield and, more recently, Forbes (1988), showed that the broad band light curve has fluctuations, of order 0.1 mag, varying from day to day, or sometimes in one night. These irregularities are consistent with the other activity of the system. From our present point of view, however, they represent an embarrassment to confident parameter specification. Though they have been clearly shown to be real discrepancies, from careful check star comparisons, they play the same role as accidental errors, or large amplitude noise, and would be reflected in correspondingly large solution errors. For example, in an independent repeat of Nield's curve fitting experiment, starting from the same raw data sample and a similar initial trial parameter set, where the third light contribution was neglected, the present author derived relative radii r_1 and r_2 of 0.20 and 0.16 respectively, as distinct from Nield's (1987) 0.22 and 0.20. The scale of error in these five parameter determinations is, however, sufficiently large to allow both these answers to be consistent with each other.

With a relaxation to three light contributions, and a constrained r_2, Nield found sd configurations were possible, and these have been confirmed in subsequent experiments: an example is shown in Figure 6. We do not present this curve-fit as definitive, but rather stress the importance of undiscerned factors in influencing analysis of the photometry, and consequent interpretations. In the present case, these factors concern (a) the third light contribution, which is present, though at an uncertain level, and (b) the fluctuations of background light, whose range is quite accurately determinable, but whose physical explanation is not clear, and completely omitted in the underlying model. Apart from these effects, which are known about even if not properly accounted for, we could also countenance some role for completely undistinguished agencies which could render the model to be inadequate. On this ground any quoted error estimates can therefore be seen as lower limits to real errors of the parameters.

2.3 W Cru

Photoelectric UBV photometry of this long period eclipsing binary system was gathered over an 18-month period in 1984-85 at the Auckland Observatory. A more detailed account of W Cru has been recently presented elsewhere (Walker et al., 1988).

The light curve is characterised by continuous "Beta Lyrae" like variation: unexpected in such a long period (198.5 d) system; together with peculiar irregularities, of the order of 0.1 mag (or more in U) and timescales of a few days. These irregularities, together with some

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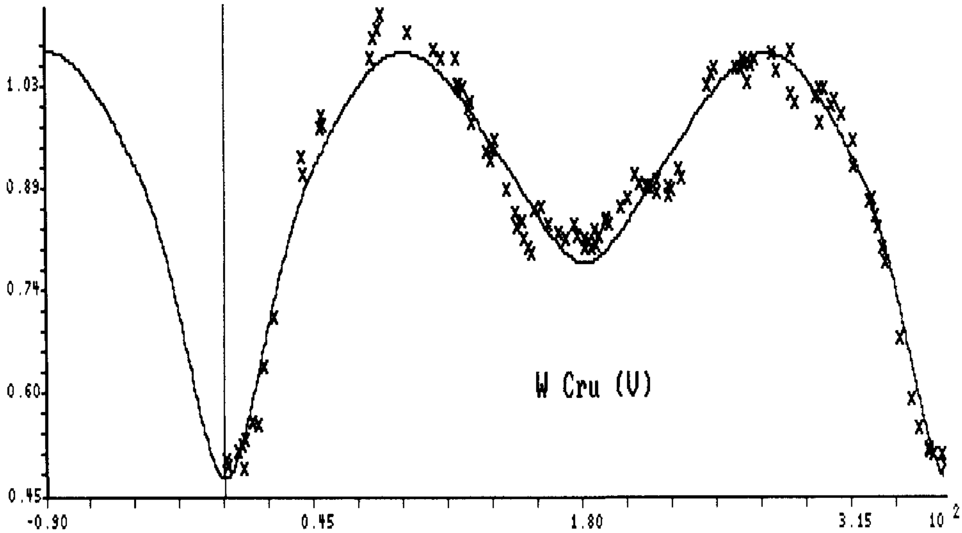

possibility for a third light contribution (although a visual pair is not seen), place the analysis of the system in a quite comparable situation to that of R Arae.

W Cru has been cited as being of particular interest in the context of the interactive evolution of binary stars, and yet one for which observational data have been regrettably low in quantity hitherto (Plavec, 1984). It may represent a rather extreme case of the "serpentid" type of large mass loss Algols (Plavec, 1980). The irregular features, particularly in the secondary minimum region, also seem suggestive of some thick accretion structure and/or quasi-unstable large scale mass transfer process.

Woolf's (1962) spectroscopic evidence and supergiant luminosity classification, combined with the undoubtedly large size of the more luminous star necessitated by the strong "ellipticity" effect in the light curve, make the hypothesis of the supergiant being close to or in contact with its surrounding Roche Lobe feasible. If this were the case it might allow a specification of the mass ratio, the mass ratio appropriate for any sized 'contact' component in a close binary being known from classical studies of the Roche configuration (cf. Kopal, 1959). The light curve might be expected to yield a value for the primary relative radius r_1.

Unfortunately, the photometry alone is unable to resolve all the required quantities in this case. Even with a "text-book" type of eclipsing binary light curve the total information content can seldom allow the specification of more than six independent derivable parameters (Budding and Najim, 1980), and five of these usually refer to the two radii, the two luminosities and the orbital inclination. The mass-ratio parameter has a strong correlation with the gravity-darkening or flux-redistribution parameter, and even for a complication-free

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system it would normally be necessary to have some good physical understanding of the stars involved so that certain quantities can be reasonably fixed allowing the determination to concentrate on others.

A mass ratio M_2/M_1 of 0.7 yielding masses of 42 $M_\odot$ and 29 $M_\odot$ to the two stars was studied, and shown to be able to match the observed data to within "reasonable" limits - but this is largely due to the uncertainties introduced by the extraneous irregularities. An alternative, lower mass configuration may also be possible if we take $M_2/M_1 > 1$. This now implies the "β Lyrae" paradox, however - i.e. the more massive component is not seen. This idea, arising in massive interacting binaries is thought to provide a generally more convincing account of the much discussed case of β Lyrae itself than the older, high mass picture (Plavec, 1983).

Adopting the contact restraint, we may determine solutions for the masses, primary size and separation of the two mass centres A for any given mass ratio. Thus at $q = 1.5$, we find $M_1 = 9.3$, $M_2 = 14$, $R_1 = 138$ and $A = 406$; all in solar units. The size of the obscured star is, of course, much harder to be clear about, but at least we can reasonably expect that $R_2 < 0.75\ A - R_1$, which would still allow plenty of room for a normal star to become effectively submerged in. Figure 7 shows a curvefit corresponding to such parameters. The fit looks alright, but an *ad hoc* third light contribution of 50% has been assumed to achieve this. While the aforementioned curve-fits suggest standard eclipsing binary models can go some way towards matching the observed light variations, there remain significant indications of additional confusing effects, possibly due to rapid mass loss and transfer.

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DISCUSSION

Rucinski raised the question of selection effects in catalogue data, particularly the preference of observers for particular objects. He felt that they could account for 50 per cent to 99.9 per cent of the results one obtained from such compilations and wondered if Budding could estimate more precisely the effects of selection on his own work. Budding agreed that these effects could be important but declined to quantify them. He felt that systems with a period of a week or two were often discriminated against by observers: the periods were too long for observations to be made by students, or by many professionals in their vacations, and too short to appeal to the kind of amateur who wanted to be able to make a few observations of a given star each night, over a long interval. While Budding recognized the probability that other such choices might affect what was included in a compilation, he was unconvinced that they had much effect on general deductions from the data.

Andersen raised the question of the reliability of some compilations. He had reservations about the catalogue of Giuricin *et al.* (*Astrophys. J. Supp.* **52**, 35, 1983) which several speakers had reported using. The photometric solutions in it were made with a program based on unrealistic geometry, often without the support of spectroscopic data (mass-ratio etc.). Masses were inferred from an ill-defined spectral-type-mass relation and, often, from poorly determined spectral types and from mass-ratios based on the assumption that the secondary fills the Roche lobe. It is well-known that, for small relative radii, the mass-ratio is *very* sensitive to errors in the radii. He felt that much of the data in the catalogue for *individual* systems were highly uncertain and that, therefore, mean properties derived from them could be *systematically* in error. For this reason, Andersen believed that the critical catalogue of Algol parameters, now being compiled in Madrid by Mario Garcia, would be very useful. Hilditch quoted the specific example of TV Mus, listed in the catalogue compiled by H.K. Brancewicz and T.Z. Dworak (*Acta Astr.* **30**, 501, 1980) as a pair of equal-mass F2 stars; his own observations showed it to be a deep-contact binary with a mass-ratio of 0.13. Budding conceded that these uncertainties did exist in individual data, but reiterated his conviction that they would not *seriously* affect the kind of general conclusions that he was attempting to draw. He saw his work as an example of the kind of study needed, if the complete problem of Algols was to be addressed.

Andersen had further comments on masses inferred from spectral

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types:

(i) the spectral type observed in systems containing circumstellar material refer not to the star but to the disk, which is always cooler (i.e later type);

(ii) even if the star itself is visible, it will appear to be of later type if it is rotating near its critical velocity (cf. discussion on V356 Sgr p.202).

Both these effects lead to systematic errors in mass estimates. Budding conceded the importance of these effects in W Serpentis stars or in β Lyr, but felt they were not significant in many Algols, for which the spectrum is determined by that of the early-type primary. In Algol itself, for example, the disk can be seen only with difficulty and this was true for the great majority of Algols. He believed that for the 75 or so "very likely and well-known" Algols the masses of primaries were known within, at worst, about 1 $m_\odot$, and any systematic error in the means derived for this group should be small.

Parthasarathy felt that existing catalogues did not give enough data. Only for very few systems were spectral types known for both components. He felt that there was need for a systematic study of a larger sample of binary systems, yielding a catalogue of spectral types for both components and uvby data during and outside eclipse. Budding replied that his own catalogue of Algol candidates quoted spectral types for all primary, and many secondary, components.

Scarfe pointed out that one kind of third-light problem could now be dealt with reliably. When an eclipsing binary has a close companion (within the photometer aperture) resolvable by the telescope in good seeing, a CCD frame of the field can be analyzed by DAOPHOT to remove the third light. This had recently been done by Tim Davidge for eclipsing binaries in crowded fields in the Magellanic Clouds.

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