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STELLAR MASSES

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INTRODUCTION

In an earlier review (Popper 1967), the problems of determining masses from data for eclipsing binaries were discussed and some of the available results tabulated. The present review may be considered a sequel, although the most definitive visual binaries are also included. The same viewpoint is adopted, namely that only individual masses of considerable accuracy, determined directly from the observational data, are treated. In the first section of the earlier review, methods of mass determination based on various hypotheses (moving groups, photometric parallaxes, assumptions about the mass of one component of a binary, etc.) were discussed briefly and will not be referred to. The principal justification for this review lies in the very considerable increase in available data. Two classes of binary systems are not treated, contact binaries of the W UMa class and close binaries with a degenerate component (X-ray binaries, binary pulsars, dwarf novae, novae). The observational status of W UMa systems has been summarized by Binnendijk (1970), while Bahcall (1978) has discussed the masses of collapsed objects in X-ray binaries.

A list of the properties of the components of eclipsing binaries was prepared some years ago by Wood (1963). My commentary on this list (Popper 1966) was directed primarily to the question of the suitability of the observational data for providing reliable properties. More recent tables of the properties of binary star components, in addition to the brief list in my review (Popper 1967), have been published by Cester (1965a, eclipsing binaries; 1965b, visual binaries), Popov (1969a,b), Kříž (1969), McCluskey & Kondo (1972), Giannone & Giannuzzi (1974), Heintz (1978), and Lacy (1977b, 1979). Svechnikov (1969) assumes mass ratios for many systems. Popov, in particular, attempted to assess the uncertainties in the resulting parameters. McCluskey & Kondo, Heintz, and Lacy, as well as Cester, included visual binaries in their discussions. The data on eclipsing binaries included in these lists were taken from a large variety of published sources.

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Many of the results are based on spectrographic material obtained with prismatic spectrographs of relatively low dispersion, on photographic or visual light curves, or on studies in which details of the observational material are lacking. Lacy's lists are the most selective.

For most of the eclipsing binaries listed in the following sections, the analyses are based on spectrographic observations obtained with grating spectrographs giving 20 Å mm^{-1} or higher dispersion. In each case I have either examined spectrograms or have satisfied myself from published or unpublished material that the spectrographic material is of adequate quality and free of appreciable systematic errors. Justification for this approach to spectrographic material is contained in a series of papers, "Rediscussion of Eclipsing Binaries," appearing in the *Astrophysical Journal* and is also discussed in the earlier review (Popper 1967). Thus, the present review has more personal and perhaps more consistent standards than discussions in which published results are accepted at face value.

The quality of photometric observations can usually be judged from available light curves. Only photoelectric data are accepted. The form of a light curve is much less clearly dependent on the values of the system parameters than in the case of a velocity curve. Hence, the reliability of a photometric solution is more difficult to judge than that of a spectrographic solution. These matters are discussed in more detail in subsequent sections, as are the criteria for including visual binaries. The comments of Andersen, Clausen & Nordström (1979) on criteria for absolute dimensions should be read in the present context.

Emphasis is placed on the determination of mass because it is the quantity upon which the other properties, such as luminosity and rate of evolution, depend most sensitively. Masses are of little interest, however, without knowledge of other fundamental properties of the stars, which are usually determinable if the masses are. For visual and resolved spectroscopic binaries the masses and absolute visual magnitudes are obtained directly from the observations of a particular system. Evaluation of bolometric luminosities, effective temperatures, and radii, on the other hand, requires the use of scales of temperature, bolometric correction, and absolute radiative flux, calibrated in terms of color index or some other correlate of radiative flux. For eclipsing binaries it is the masses and radii that are obtained directly for individual stars, while effective temperatures, bolometric luminosities, and absolute visual magnitudes require calibrated scales. The scales adopted for these radiative quantities are based primarily on the scales of effective temperature and bolometric correction given by Hayes (1978), which is essentially that of Code et al. (1976) for the hotter stars, and on the scale of absolute visual fluxes compiled by Barnes, Evans & Moffett (1978). While Barnes, Evans & Moffett (BEM) have preferred to employ the color index V–R as the observable parameter correlated with surface flux, their study shows that, except for the coolest stars, the color index B–V serves as well. For a given binary, the color index that is known with greater accuracy, usually B–V, is used. The intermediate-band index, b–y, correlates closely with B–V, so that b–y observations are also employed. In some cases it is helpful to make use of the relationship between spectral type and color index. The list of Hayes (1978), which is in essential agreement with the compilation by FitzGerald (1970), is adopted.

Several considerations have led me to modify slightly the relations between visual absolute flux and color indices published by BEM. First, BEM have adopted linear relations between $F_V \propto$ log of flux and color index over some ranges of temperature. Examination of their data, particularly for the B and A stars, where the angular diameter results for main-sequence stars are most numerous, shows that systematic departures from linear relations are significant. Second, the scatter in the relation between flux and color index is reduced somewhat by considering b–y as well as B–V or V–R for the calibration stars with measured angular diameters. Third, the adopted scales of T_e, F_V, and bolometric correction (B.C.) must be consistent with each other:

$$F'_V(B\text{–}V) = \log\, T_e(B\text{–}V) + 0.1\,\text{B.C.}\,(B\text{–}V). \tag{1}$$

The symbol F'_V is used here rather than the F_V of BEM since the flux scale is established in a manner slightly different from that in BEM. The slight difference of a few hundredths of a magnitude in the two flux scales is caused by the use of stellar absolute fluxes rather than the sun's alone and by the adoption of Hayes' (1978) scale of bolometric corrections, which gives -0.14 mag for stars of solar color rather than -0.07. The reason for abandoning the time-honored value -0.07 for the sun as the zero point for bolometric corrections is, in addition to consistency with Hayes' scale, Hayes' (1979) argument that the colors and spectral energy distribution are not so well known now for the sun as they are for spectrophotometric standard stars. In employing Equation (1), Hayes' (1978) scale of bolometric corrections is adopted.

The form of the $F'_V\,(B$–$V)$ relation is best defined from angular diameters of main-sequence stars in the range $-0.15 < (B\text{–}V) < +0.06$. The zero point of the F'_V scale is then adjusted according to Equation (1) by employing Hayes' T_e's over this color range. Then the form of the T_e-(B–V) relation is modified slightly by requiring that (1) be satisfied at each value of B–V. Over the range of temperatures less than about 8000 K, the only main-sequence angular diameters available for temperature and flux calibration are of α CMi and the sun and, for M dwarfs, of YY Gem and CM Dra.

Table 1 Radiative parameters

Spectrum	B–V	b–y	V–R	B.C.	F'_V[a]	log T_e[a]
Main sequence						
O7	−0.31	—	—	−3.6	4.225	4.585
O8	−0.305	—	—	−3.4	4.211	4.551
O9	−0.30	—	—	−3.2	4.201	4.521
O9.5	−0.295	—	—	−3.1	4.187	4.497
B0	−0.285	—	—	−2.96	4.179	4.475
B0.5	−0.28	—	—	−2.83	4.172	4.455
B1	−0.26	—	—	−2.59	4.159	4.418
B2	−0.24	−0.115	—	−2.36	4.128	4.364
B3	−0.20	−0.090	—	−1.94	4.086	4.280
B5	−0.16	−0.072	—	−1.44	4.046	4.190
B6	−0.14	−0.063	—	−1.17	4.032	4.149
B7	−0.12	−0.052	—	−0.94	4.018	4.112
B8	−0.09	−0.035	—	−0.61	4.002	4.063
B9	−0.06	−0.024	—	−0.31	3.984	4.015
A0	0.00	+0.002	—	−0.15	3.959	3.974
A2	+0.06	+0.031	—	−0.08	3.935	3.943
A5	+0.14	+0.075	—	−0.02	3.909	3.911
A7	+0.19	+0.105	—	−0.01	3.889	3.890
F0	+0.31	+0.195	—	−0.01	3.843	3.844
F2	+0.36	+0.238	—	−0.02	3.824	3.826
F5	+0.43	+0.282	—	−0.03	3.807	3.810
F8	+0.54	+0.350	+0.47	−0.08	3.777	3.785
G0	+0.59	+0.382	+0.50	−0.10	3.762	3.772
G2	+0.63	+0.400	+0.53	−0.13	3.755	3.768
G5	+0.66	+0.417	+0.54	−0.14	3.748	3.762
G8	+0.74	+0.455	+0.58	−0.18	3.720	3.738
K0	+0.82	+0.485	+0.64	−0.24	3.691	3.715
K2	+0.92	+0.525	+0.74	−0.35	3.655	3.690
K5	+1.15	—	+0.99	−0.66	3.567	3.633
K7	+1.30	—	+1.15	−0.93	3.511	3.604
M0	+1.41	—	+1.28	−1.21	3.468	3.589
M1	+1.48	—	+1.40	−1.49	3.422	3.571
M2	—	—	+1.50	−1.75	3.381	3.556
M3	—	—	+1.60	−1.96	3.346	3.542
M4	—	—	+1.70	−2.28	3.300	3.528
M5	—	—	+1.80	−2.59	3.254	3.513
M6	—	—	+1.93	−2.93	3.204	3.497
M7	—	—	+2.20	−3.46	3.113	3.459
M8	—	—	+2.50	−4.0	3.018	3.418
Red giants						
G0	+0.64	—	+0.53	−0.13	3.750	3.763
G5	+0.90	+0.555	+0.685	−0.34	3.642	3.676
G8	+0.95	+0.584	+0.72	−0.38	3.624	3.662

Table 1 (*continued*)

Spectrum	B–V	b–y	V–R	B.C.	F'_V[a]	log T_e[a]
K0	+1.01	+0.617	+0.77	−0.42	3.594	3.636
K1	+1.09	+0.660	+0.81	−0.48	3.581	3.629
K2	+1.16	+0.710	+0.84	−0.53	3.571	3.624
K3	+1.26	—	+0.96	−0.60	3.533	3.593
K4	+1.43	—	+1.06	−0.90	3.501	3.591
K5	+1.51	—	+1.20	−1.19	3.456	3.575
M0	+1.57	—	+1.23	−1.28	3.446	3.574
M1	—	—	+1.28	−1.36	3.430	3.566
M2	—	—	+1.34	−1.52	3.411	3.563

[a] Primary determinants of F'_V and T_e
O7–B1: spectral type
B2–K7, main sequence: B–V
M0–M8, main sequence: V–R
G0–K2, red giants: B–V
K3–M2, red giants: V–R

Furthermore, α CMi appears somewhat anomalous in its color-color relationships. The F'_V and T_e scales have been adjusted over the range $+0.2 < B\text{–}V < +0.8$ by fitting F'_V to the solar values of T_e and B.C. at $B\text{–}V = +0.66$ (Barry, Cromwell & Schoolman 1978, Hayes 1979). Although Hayes' discussion is very comprehensive, a recent determination by Clements & Neff (1979), $(B\text{–}V)_\odot = +0.63$, reminds us that the determination of this fundamental quantity is still not completely satisfactory.

The scales for cooler main-sequence stars are even less well established. Hayes' (1978) scales of T_e and B.C. are adopted since they fit the flux for YY Gem better than the BEM flux scale, which is based primarily on angular diameters of giants over this range. For giant stars, the BEM flux scale is adopted since it is based on a considerably greater number of angular diameters than is Hayes'. Throughout the whole range of spectral types, Hayes' list of bolometric corrections has been employed in conjunction with Equation (1). The scales used in the following sections of this review are given in Table 1. For types B1 and earlier, spectral type is taken as the observable quantity with which F'_V, T_e, and B.C. are correlated rather than B–V, while for stars with $B\text{–}V > 1.2$, V–R is a much better discriminant, although Kunkel & Rydgren (1979) note difficulties with V–R for M dwarfs, as does Lacy (1979) for the redder stars.

The principal uses to be made of the values in Table 1 are, in addition to supplying effective temperatures, to determine the absolute visual magnitudes of eclipsing binaries:

$$M_V = -5 \log R - 10F'_V + C_1, \tag{2}$$

where R is the stellar radius in solar units and C_1 is a constant to be adjusted. The tabular values are also required to evaluate the radii of visual binaries:

$$\log R = -0.2M_V - 2F'_V + 0.2C_1. \tag{3}$$

The value of C_1 employed, 42.255, is 0.11 mag less than obtained from the BEM flux scale. The difference arises from my use of the best-determined angular diameters of 11 stars on the main sequence later than B5 in addition to the sun, which is the sole basis for the BEM value. Higher weight is given to the sun and the four other stars with largest diameters (α CMa, α CMi, α Lyr, and α Aql). Hayes (1979) has stressed the uncertainties introduced by relying too heavily on the sun alone. In computing the luminosities in solar units, solar values must be employed, for which $T_e = 5780$ K, $M_V = +4.83$, and B.C. $= -0.14$ are adopted in connection with the temperatures in Table 1 (eclipsing binaries) and the bolometric corrections (visual binaries).

There remain the effects on the radiative scales of differing surface gravity and chemical composition. There is a considerable range of metallicity, at least among A-type eclipsing binaries (Popper 1971b, Kitamura & Kondo 1978). Because of effects of differing wavelength-dependent line absorption, the relations between color index, absolute visual flux, and effective temperature are likely to be gravity and composition dependent. The data for the calibrating stars with angular diameters are quite inadequate to establish these differences, and recourse must be had to atmospheric models. Models available for this purpose are those of Bell (1971) for temperatures in the range 5000 K to 7400 K and metal abundances equal to solar, 1/4, and 4 times solar, with $\log g = 4.4$, 4.0, and 3.6; of Bell & Gustaffson (1978) for temperatures 5500 K and 6000 K, metal abundances equal to 1/2 and 1/10 solar, $\log g = 3.0$ and smaller; and of Kurucz (1979a) for temperatures 5500 K to 50,000 K, abundances equal to solar and 1/10 solar, and $\log g = 4.5$ and smaller. Results from the more complete grid, including heavy element abundances greater than solar (Kurucz 1979b), are not as yet available. These models, although not completely consistent with each other and stressing lower heavy element abundances rather than the higher abundances encountered in A-type eclipsing binaries, imply that, for a given value of the index $B–V$, stars with greater heavy element abundance have higher values of T_e and larger radiative fluxes in the V band. For most of the stars included in this review, good measures of heavy element abundance are not available. Higher surface gravities lead to small effects in the same direction as higher metal abundance. For the range of abundances likely to be encountered in population I and disk stars and for the range of surface gravities of main-sequence and subgiant stars, the effects appear to correspond to differences up to about 0.1 mag in luminosity for a given value of $B-V$. Uncertainties in the calibrations of the temperature and flux scales are of the same order. Since the emphasis of this review is on stellar masses rather than on radiative properties, further discussion of the rather complex details involved is not warranted. As Lacy (1979) has surmised, the models show that the predicted flux versus color index relations are considerably less sensitive to composition when $V-R$ is used as an index rather than $B-V$. But at the 0.1 mag level, the difference is relatively unimportant in view of uncertainties in the flux and temperature calibrations and in the radii, parallaxes, and, in some cases, color indices of the components of the binary stars. The temperature and flux scales of Table 1 are adopted without adjustment for the small effects discussed here.

For each star with mass and other properties contained in most of the tables of this review, an effort is made to estimate realistic values of the uncertainties of the parameters. Considerable personal judgment is involved in these estimates. In some cases, it is permissible to accept the formal mean errors of published values, for example, for the masses of eclipsing binaries with orbital inclinations, *i*, close to 90° and with well-separated unblended lines of both components measured on spectrograms of adequate dispersion (greater than that corresponding to 20 Å mm^{-1} in most cases). But for most parameters the formal mean errors cannot be accepted literally. Examples are parallaxes of visual binaries and relative radii of eclipsing binaries, for both of which differences between values from independent investigations are often many times larger than the internal mean errors. In such cases only estimated uncertainties, rather than formal mean errors, can be assigned. I have tried to be conservative in the sense that the adopted uncertainty should not be smaller than a "true" mean error based on all sources of inaccuracy, internal and external. Such estimates should be taken as indications of the ranges within which, in the sense of a mean error, the parameters are thought to lie.

For the sake of convenience, the binary systems considered in this review are grouped into five categories: 1. detached main-sequence eclipsing binaries of types B6 to M; 2. OB eclipsing systems; 3. detached evolved eclipsing systems; 4. resolved spectroscopic binaries; 5. visual binaries; and 6. semidetached eclipsing systems.

DETACHED MAIN-SEQUENCE ECLIPSING SYSTEMS, B6 to M

General Considerations

Among all classes of binary systems, detached main-sequence eclipsing systems, with the spectrum lines of the two components well separated relative to their widths and with light curves showing two well-defined minima, provide the greatest number of reliable masses and radii. With few exceptions, systems earlier than B6 do not have such favorable properties. Problems of adequate dispersion and the selection of lines to measure in order to avoid systematic effects in the velocities were discussed in some detail in the earlier review, as well as elsewhere (Popper 1971a). With good homogeneous spectrographic material, the details of the method of orbit computation are relatively unimportant. In these cases the statistical mean errors of the minimum masses and orbital radii should be realistic approximations to their actual uncertainties.

In systems with these properties, effects of tidal distortion and of reflection on the light curves are usually quite small, as are irregularities associated with gas streams or intrinsic variability, encountered in other classes of close binaries. Then, if both minima are well observed with homogeneous photoelectric observations obtained under good conditions (scatter of points less than 0.01 mag), the values of the relative radii, r_h and r_c (h = hotter component, c = cooler) and of the light ratio L_h/L_c should be derivable with uncertainties of a few percent or less and the inclination i to within a degree or less. Here also the method of solution should be relatively unimportant, provided that all parts of the light curve are represented by the adopted elements without systematic trends in the residuals.

Many papers have been published in recent years describing computer programs and techniques for the analysis of eclipsing binary light curves, and it is not appropriate to review them here. The program of Wood (1972 and subsequent status reports) appears to have had the widest application for relatively undistorted systems. Etzel (1975) has shown that the method of Nelson & Davis (1972), modified by him to provide simultaneous, rather than sequential, adjustment of the elements by the method of least squares, gives results identical to those of Wood's program for spherical stars and is much more efficient of computer time. Numerous applications of Wood's and other computing programs to available observations have appeared in the literature. Cester and his co-workers (Cester et al. 1978c and references therein), in particular, have applied Wood's program to quite a few systems. Judicious use of the Russell model (Russell & Merrill 1952) may provide adequate representation of simple systems.

As mentioned in the introduction, the uncertainties of the parameters derived from a light curve (r_h, r_c, i, L_c/L_h) are much more difficult to evaluate than in the case of a radial velocity curve. Formal mean errors of the parameters in a least-squares adjustment based on several hundred photoelectric observations may be small fractions of a percent. On the other hand, representation of the observations with parameters differing from the "best" set by many times their formal mean errors may be indistinguishable from representation by the "best" set. Moreover, differences between the values of the parameters based on independent observations are usually much larger than the mean errors of either set. The probable reason for this situation is that the values of some of the parameters are very sensitive to small changes in the observations in critical parts of the minima. Even with several hundred observations (the usual number), each section of each minimum will usually be covered by observations on a very small number of nights. It is well known that small unexplained differences are often present between observations on different nights with identical equipment. The existence of such effects invalidates somewhat the use of the method of least squares, which requires that observational errors, particularly in critical parts of a light curve, be randomly distributed. Hence, the fitting of a particular set of observations by least-squares adjustment, while giving the "best fit" to that set in a formal sense, does not necessarily give a realistic evaluation of the uncertainties of the parameters. A better estimate of the real uncertainties of the parameters in a photometric solution may be obtained from the differences in the elements derived for different wavelength bands or, even better, from differences between the results from completely independent sets of equally good observations.

In the solution of a light curve observed in two or more wavelength regions, it is customary to evaluate the color indices of the two components from their light ratios in the two regions, obtained in the photometric solutions. But these light ratios contain uncertainties that are related to uncertainties in the geometric parameters. In the case of an eclipse of appreciable depth, the color of a star being eclipsed is best derived directly from the color index of the light lost during eclipse, without reference to the geometric elements or the corresponding light ratios. The difference in limb darkening at the two wavelengths should be taken into account. Failure to use this procedure may introduce another source of inaccuracy in the fluxes if the two components differ appreciably in color index, and hence an inaccuracy in the luminosities.

An additional source of uncertainty in the photometric parameters is the real indeterminacy in the ratio of the radii of the components in the case of partial eclipses of nearly equal depth. Clausen & Grønbech (1977 and references therein) show that even with excellent observations and use of a computer program this indeterminacy may remain. The ability of a computer to "converge" on a particular solution has, on occasion, led investigators to ignore this basic indeterminacy. Determinations of light ratios from spectrograms (e.g. Petrie 1950) have been employed to remove the indeterminacy, a procedure of limited validity in most cases. Qualitative results on the light ratio from spectrograms may be useful to detect incorrect photometric solutions (e.g. Popper 1976b). But the assumption that the light ratio is given by the ratio of line intensities, when the components are not identical, may not be valid because of the usually unknown dependence of line strength on temperature and gravity, which must be different for the two components if the stars are not identical. Hence, in systems with approximately but not exactly equal partially eclipsed components, neither photometric nor spectrographic analysis may lead to satisfactory light ratios or ratios of the radii. In such systems, differences in mass and in surface brightness (depths of minima) may be well determined; but not differences in radius or luminosity.

It is clear from this discussion that evaluation of meaningful uncertainties of the parameters in a photometric solution is subject to considerable difficulty, particularly when all details of the observations and solution are not provided. Thus, for favorable detached systems, the uncertainties in the masses will be well established, those in the radii less so. The procedures employed for evaluating surface temperatures and luminosities from observed quantities correlated with surface flux is discussed in the introduction. If the photometric observations, precise as they may be, are not accurately tied to one of the standard systems, good estimates or surface fluxes will not be available. The inability to evaluate surface fluxes well is an important cause of uncertainties in the stellar luminosities for a number of systems.

The Available Data

Table 2 contains masses, radii, and color indices for those detached systems with spectral types later than B5 for which the masses and radii are, in my judgment, known to an accuracy of 15% or better. The values in Table 2 are based on my own assessment of published and unpublished material. Table 2 contains a reference list showing where the material may be found from which the values of mass, radius, and color are derived. The list of references is not intended to be complete, but rather gives the sources considered most useful. The catalogues of Koch, Plavec & Wood (1970) and of Batten, Fletcher & Mann (1978) are cited wherever they contain references to material that is used. The Notes to the latter catalogues have proven exceptionally helpful. My apologies are extended to those whose work has not been adequately cited.

In Table 2 the systems are listed in order of decreasing mass of the more massive component of the system. The spectral types are listed for convenience. Except for the primaries in systems with appreciable color excess, the types are not actual evaluations, but are derived from the tabulated values of $(B{-}V)_0$ by use of the listing in Table 1. For AS Cam, χ^2 Hya, V451 Oph, RX Her, SZ Cen, MY Cyg, and DM Vir, the color excess is derived from multicolor indices. For V805 Aql and CM Lac, the excess is obtained from the observed colors and estimated spectral types of the primary components.

The estimated uncertainties in the masses listed are, for the most part, derived directly from the mean errors of the spectroscopic elements, K_1 and K_2, since these systems are considered to be without important sources of systematic error in the velocities. The estimated uncertainties in the radii are based on an assessment of several factors, and represent a judgment rather than an evaluation. In nearly every system, problems with the photometric solution dominate. For reasons given above, the published mean errors of the photometric elements obtained from a least-squares fit are not adopted. While the sum of the relative radii, $r_1 + r_2$, may be known to an accuracy of 1% or better in the more favorable cases, the individual radii usually are not. I have adopted uncertainties in the range 1–10% for the individual radii, depending on the quality of the observations, the depths of minima, the agreement between different investigations, and the quality of the evidence from spectrograms. In some cases, the components differ clearly in surface brightness, as shown by the different depths of the minima (and indicated by the difference in the listed values of $[B-V]_0$). These components probably differ in radius as well, but the observations are often inadequate to determine the ratio of the radii, a well-known indeterminacy in light-curve analysis, and a ratio of unity has been adopted. These systems are indicated by the footnote symbol c in Table 2. If the reader is interested in the accuracy of the *mean* radius of the components of a system, an uncertainty of about one-half to one-third that given in Table 2 for the individual components may be adopted.

For most of the systems, two or more independent measures of color index are available. Indices on the Strömgren system have been converted to $(B-V)_0$. The tabulation by Crawford & Barnes (1970) establishes a very tight relationship between $(b-y)_0$ and $(B-V)_0$. The dependence on metallicity in this relationship amounts to less than 0.01 mag in $B-V$ and is not clearly established. For reasons discussed in the introduction, the adopted values of $B-V$ have not been "adjusted" for ultraviolet excess or metallicity. Only rarely is the difference between the color indices of the two components well established from the photometry. On the other hand, the ratio of the surface fluxes *is* well determined directly from the depths of the minima for systems with circular orbits and spherical stars, as most of the systems in Table 2 are. In numerous recently published analyses of light curves, this ratio is, unfortunately, not given. The individual color indices listed in Table 2 are, in most cases, derived from the combined color index and from the relation between difference in color index and flux ratio, obtained from Table 1. For some systems (Popper 1968, 1970, 1971b), the differences in color indices derived from the depth ratios are not in good agreement with those given by the colors of the individual components, obtained from the differences in depths in the two colors. Such disagreements are reflected in the uncertainties listed for $(B-V)_0$.

Table 2 Detached main-sequence systems, B6 to M

Binary	Sp[b]	$(B-V)_0$	E_{B-V}	m	R	References[f] Vel	l.c.	CI Sp	Scale dependent[a] log T_e	log L	M_V
ζ Phe	B6	−0.145	0.00	3.92	2.85	3	4	4	4.160	2.50	−0.37
HD6882	—	±0.02	±0.01	±0.05	±0.05			5	±0.03	±0.12	±0.15
$P = 1^d.67$	B9	−0.05	—	2.54	1.85				4.005	1.51	1.13
	—	0.02	—	0.03	0.04				0.015	0.08	0.10
χ^2 Hya	B9	−0.09	0.02	3.61	4.39	1	6	6	4.063	2.49	−0.98
HD96314	—	0.02	0.01	0.08	0.04				0.035	0.14	0.10
$P = 2.27$	A0	−0.05	—	2.64	2.16				4.005	1.64	0.79
	—	0.02	—	0.05	0.04				0.02	0.08	0.10
AS Cam	B8	−0.105	0.09	3.31	2.70	1	1	7	4.088	2.17	0.00
HD35311	—	0.02	0.02	0.07	0.20		7	8	0.03	0.14	0.20
$P = 3.43$	B9	−0.045	—	2.51	2.00				4.001	1.56	0.98
	—	0.02	—	0.05	0.15				0.015	0.09	0.20
V451 Oph	B9	−0.06	0.05	2.78	2.65	1	2	9	4.015	1.86	0.30
HD170470	—	0.02	0.02	0.06	0.20			10	0.02	0.10	0.20
$P = 2.20$	A0	−0.02	—	2.36	2.12			11	3.985	1.54	0.95
	—	0.02	—	0.05	0.20				0.012	0.09	0.20
RX Her	B9	−0.06	0.07	2.75	2.44	1	2	9	4.015	1.79	0.48
HD170757	—	0.03	0.03	0.06	0.10			10	0.03	0.12	0.20
$P = 1.78$	A0	−0.02	—	2.33	1.96			12	3.985	1.48	1.12
	—	0.03	—	0.05	0.10				0.02	0.09	0.15
AR Aur[c]	B8	−0.08	0.00	2.48	1.83	1	2	2	4.048	1.67	0.99
HD34364	—	0.02	0.02	0.10	0.05		13	9	0.035	0.14	0.15
$P = 4.13$	B9	−0.04	—	2.29	1.83			10	3.997	1.46	1.19
	—	0.02	—	0.10	0.05			12	0.015	0.06	0.10

β Aur[c]	A1	+0.035	0.00	2.35	2.49	1	1	9	3.955	1.56	0.82
HD40183	—	0.03	0.00	0.03	0.15			11	0.02	0.10	0.20
$P = 3.96$	A1	+0.035	—	2.27	2.49			12	3.955	1.56	0.82
	—	0.03	—	0.03	0.15			15	0.02	0.10	0.20
SZ Cen	A7	+0.20	0.08	2.28	3.62	1	16	16	3.885	1.60	0.61
HD120359	—	0.04	0.03	0.02	0.10				0.05	0.06	0.20
$P = 4.11$	A7	+0.22	—	2.32	4.55				3.878	1.79	0.17
	—	0.04	—	0.03	0.10				0.015	0.06	0.20
EE Peg[d]	A3	+0.10	0.00	2.08	2.05	1	17	8	3.927	1.28	1.48
HD206155	—	0.02	0.02	0.16	0.10	11		9	0.01	0.06	0.15
$P = 2.63$	F5	+0.45	—	1.32	1.29			10	3.806	0.40	3.68
	—	0.04	—	0.04	0.06				0.01	0.04	0.15
V624 Her[d]	Am	+0.19	0.00	2.1	3.0	1	1	10	3.890	1.47	0.98
HD161321A	—	0.03	0.02	0.3	0.3			11	0.012	0.10	0.25
$P = 3.90$	Am	+0.21	—	1.8	2.2			18	3.882	1.16	1.73
	—	0.03	—	0.2	0.25				0.012	0.10	0.25
V805 Aql[d]	A5	+0.13	0.13	2.06	2.10	1	2	11	3.915	1.26	1.52
HD177708	—	0.04	0.03	0.07	0.12	11	11		0.015	0.08	0.20
$P = 2.41$	F0	+0.28	—	1.60	1.75		13		3.855	0.86	2.50
	—	0.05	—	0.04	0.12				0.02	0.10	0.25
RR Lyn	Am	+0.22	0.00	2.00	2.50	1	20	10	3.880	1.26	1.49
HD44691	—	0.02	0.01	0.05	0.15	19		12	0.01	0.06	0.15
$P = 9.95$	F0	+0.29	—	1.55	1.93			21	3.850	0.93	2.32
	—	0.02	—	0.03	0.15				0.01	0.08	0.20
WW Aur[c]	Am	+0.14	0.00	1.98	1.89	1	1	1	3.910	1.15	1.78
HD46052	—	0.04	0.02	0.05	0.04		22	10	0.015	0.06	0.15
$P = 2.52$	Am	+0.19	—	1.82	1.89			12	3.890	1.065	1.98
	—	0.04	—	0.05	0.04			22	0.015	0.06	0.15
CM Lac	A2	+0.08	0.03	1.88	1.59	1	2	1	3.935	1.095	1.97
HD209147	—	0.04	0.02	0.09	0.06			9	0.015	0.07	0.15
$P = 1.60$	F0	+0.28	—	1.47	1.42			14	3.855	0.68	2.95
	—	0.06	—	0.04	0.06				0.02	0.09	0.25

Table 2 (*continued*)

Binary	Sp[b]	$(B-V)_0$	E_{B-V}	m	R	References[f] Vel	l.c.	CI Sp	Scale dependent[a] log T_e	log L	M_V
RS Cha[c]	A8	+0.20	0.00	1.86	2.28	1	1	11	3.885	1.21	1.61
HD75747	—	0.03	0.01	0.02	0.15			23	0.01	0.07	0.20
$P = 1.67$	A8	+0.26	—	1.82	2.28				3.863	1.12	1.85
	—	0.03	—	0.02	0.15				0.01	0.07	0.20
MY Cyg	Am	+0.30	0.04	1.81	2.20	1	11	11	3.848	1.03	2.07
HD193637	—	0.03	0.03	0.04	0.04		25	12	0.01	0.04	0.13
$P = 4.00$	Am	+0.31	—	1.78	2.20		26		3.845	1.02	2.11
	—	0.03	—	0.04	0.04				0.01	0.04	0.13
V477 Cyg	A2	+0.07	0.00	1.78	1.52	1	1	9	3.940	1.08	2.03
HD190786	—	0.04	0.02	0.12	0.06		2	10	0.015	0.07	0.15
$P = 2.35$	F2	+0.38	—	1.34	1.20		24	11	3.820	0.41	3.66
	—	0.06	—	0.07	0.05				0.020	0.09	0.20
EI Cep	F0	+0.32	0.00	1.68	2.54	1	13	8	3.840	1.12	1.84
HD205234	—	0.03	0.02	0.03	0.25		27	27	0.01	0.09	0.25
$P = 8.44$	F2	+0.36	—	1.78	2.80			28	3.827	1.15	1.77
	—	0.03	—	0.03	0.25				0.01	0.09	0.20
XY Cet[c]	Am	+0.23	0.00	1.76	1.88	1	27	8	3.875	1.00	2.15
HD18597	—	0.03	0.02	0.02	0.07		29	10	0.01	0.05	0.15
$P = 2.78$	Am	+0.27	—	1.63	1.88			29	3.860	0.94	2.30
	—	0.03	—	0.02	0.07				0.01	0.05	0.15
ZZ Boo[d]	F2	+0.37	0.00	1.72	2.22	1	1	8	3.824	0.94	2.29
HD121648	—	0.02	0.01	0.08	0.10		13	10	0.007	0.05	0.10
$P = 4.99$	F2	+0.37	—	1.72	2.22			30	3.824	0.94	2.29
	—	0.02	—	0.08	0.10				0.007	0.05	0.10

TX Her	A8	+0.26	0.00	1.62	1.58	1	1	1	3.863	0.80	2.64
HD156965	—	0.03	0.02	0.04	0.05		13	10	0.01	0.05	0.15
$P = 2.06$	F2	+0.36	—	1.45	1.48			12	3.827	0.60	3.15
	—	0.03	—	0.03	0.05				0.01	0.05	0.13
CW Eri	F2	+0.35	0.00	1.52	2.11	11	31	11	3.830	0.92	2.35
HD19115	—	0.03	0.01	0.015	0.15		32		0.01	0.07	0.20
$P = 2.73$	F2	+0.39	—	1.28	1.48				3.820	0.57	3.23
	—	0.03	—	0.01	0.10				0.01	0.07	0.20
RZ Cha	F5	+0.47	0.00	1.51	2.26	1	33	11	3.800	0.86	2.51
HD93486	—	0.02	0.00	0.04	0.06			33	0.005	0.03	0.08
$P = 2.83$	F5	+0.47	—	1.51	2.26			34	3.800	0.86	2.51
	—	0.02	—	0.04	0.06				0.005	0.03	0.08
BK Peg[d]	F8	+0.54	0.00	1.27	1.48	11	11	8	3.785	0.43	3.63
+25°5003	—	0.02	0.01	0.01	0.15				0.005	0.09	0.20
$P = 5.49$	F8	+0.56	—	1.43	2.03				3.780	0.69	3.01
	—	0.02	—	0.02	0.20				0.005	0.09	0.20
DM Vir	F7	+0.47	0.02	1.46	1.76	1	3	3	3.800	0.64	3.06
HD123423	—	0.02	0.02	0.03	0.08			11	0.005	0.04	0.10
$P = 4.67$	F7	+0.47	—	1.46	1.76			34	3.800	0.64	3.06
	—	0.02	—	0.03	0.08				0.005	0.04	0.10
CD Tau	F7	+0.48	0.00	1.40	1.74	1	1	8	3.798	0.625	3.11
HD34335	—	0.02	0.01	0.05	0.07		35	14	0.004	0.04	0.10
$P = 3.44$	F7	+0.48	—	1.31	1.61			36	3.798	0.56	3.28
	—	0.02	—	0.04	0.07			37	0.004	0.04	0.10
TV Cet	F2	+0.39	0.00	1.39	1.50	1	11	8	3.820	0.58	3.20
HD20173	—	0.03	0.01	0.05	0.05		38	10	0.01	0.05	0.10
$P = 9.10$	F5	+0.46	—	1.27	1.26			38	3.803	0.365	3.75
	—	0.03	—	0.04	0.05				0.007	0.04	0.10
BS Dra	F5	+0.44	0.00	1.37	1.44	1	11	8	3.808	0.50	3.41
HD190020	—	0.01	0.01	0.03	0.05		39	10	0.002	0.03	0.12
$P = 3.36$	F5	+0.44	—	1.37	1.44				3.808	0.50	3.41
	—	0.01	—	0.03	0.05				0.002	0.03	0.12

Table 2 (*continued*)

Binary	Sp[b]	$(B-V)_0$	E_{B-V}	m	R	References[f] Vel	l.c.	CI Sp	Scale dependent[a] log T_e	log L	M_V
HS Hya	F5	+0.43	0.00	1.34	1.36	1	40	8	3.810	0.46	3.52
HD90242	—	0.02	0.01	0.05	0.14			40	0.005	0.09	0.25
$P = 1.57$	F5	+0.46	—	1.28	1.22				3.803	0.34	3.82
	—	0.02	—	0.05	0.14				0.005	0.10	0.25
V1143 Cyg[c]	F5	+0.45	0.00	1.33	1.31	1	2	1	3.806	0.41	3.64
HD185912	—	0.02	0.01	0.03	0.10			12	0.005	0.07	0.20
$P = 7.64$	F5	+0.45	—	1.29	1.31				3.806	0.41	3.64
	—	0.02	—	0.03	0.10				0.005	0.07	0.20
VZ Hya	F5	+0.42	0.00	1.23	1.35	1	13	11	3.812	0.46	3.51
HD72257	—	0.03	0.01	0.03	0.04		41	41	0.007	0.04	0.10
$P = 2.90$	F6	+0.48	—	1.12	1.12		42	43	3.798	0.24	4.07
	—	0.03	—	0.03	0.03		43		0.007	0.04	0.10
UX Men[c]	F8	+0.54	0.00	1.17	1.28	1	44	44	3.785	0.31	3.95
HD37513	—	0.02	0.01	0.05	0.05				0.005	0.04	0.10
$P = 4.18$	F8	+0.55	—	1.11	1.28				3.782	0.29	3.98
	—	0.02	—	0.05	0.05				0.005	0.04	0.10
WZ Oph	F8	+0.54	0.00	1.12	1.34	1	2	1	3.785	0.35	3.85
HD154676	—	0.02	0.01	0.04	0.03		13	10	0.005	0.03	0.08
$P = 4.18$	F8	+0.54	—	1.12	1.34				3.785	0.35	3.85
	—	0.02	—	0.04	0.03				0.005	0.03	0.08
UV Leo[c]	G2	+0.62	0.00	0.99	1.08	1	2	1	3.768	0.09	4.52
HD92109	—	0.02	0.00	0.04	0.04		13	10	0.005	0.04	0.10
$P = 0.60$	G2	+0.62	—	0.92	1.08				3.768	0.09	4.52
	—	0.02	—	0.04	0.04				0.005	0.04	0.10

YY Gem[e]	M1	+1.37	0.00	0.59	0.62	1	45	46	3.576	−1.13	8.90
+32°1582	—	0.02	0.00	0.015	0.01			47	0.003	0.10	0.10
$P = 0.81$	M1	+1.37	—	0.59	0.62				3.576	−1.13	8.90
	—	0.02	—	0.015	0.01				0.003	0.10	0.10
CM Dra[e]	M4	+1.83	0.00	0.24	0.25	48	48	48	3.500	−2.16	12.77
GL630.1	—	0.02	0.00	0.015	0.01				0.01	0.10	0.10
$P = 1.27$	M4	+1.83	—	0.21	0.235				3.500	−2.16	12.92
	—	0.02	—	0.015	0.01				0.01	0.10	0.10

[a] Uncertainties of scale-dependent quantities do not include effects of uncertainties in T_e and flux scales.
[b] Spectral types are derived primarily from color indices.
[c] Photometry is inadequate to establish ratio of the radii, which are assumed equal, even though colors and/or masses differ significantly.
[d] Unpublished spectrographic material may lead to improved masses and radii.
[e] Absolute magnitudes are derived from parallaxes, and hence are not scale dependent. Colors are V–R rather than B–V.

[f] References

1. Cited in BFM tables and notes
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31. Mauder & Ammann 1976
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33. Jørgensen & Gyldenkerne 1975
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36. Eggen 1963
37. Wood 1976
38. Jørgensen 1979
39. Güdür et al. 1979
40. Gyldenkerne, Jørgensen & Carstensen 1975
41. Walker 1970
42. Wood 1971
43. Padalia & Srivastava 1975a
44. Clausen & Grønbech 1976
45. Leung & Schneider 1978
46. Lacy 1979
47. Veeder 1974
48. Lacy 1977a

For comparisons of observed properties of the components of close binaries with those of single stars or with those predicted by theory, it is desirable to give values of effective temperatures, luminosities, and absolute magnitudes. The values of these quantities listed in Table 2 are obtained from the observed values of the color indices and radii by using the scales of effective temperatures and radiative fluxes given in Table 1. Since there is not complete agreement among astronomers on these scales, and since they are subject to alteration as more information becomes available, the derived temperatures and luminosities are listed in Table 2 as "scale-dependent" quantities. The uncertainties given for them depend only on those adopted for the color indices and radii, and not on uncertainties in the scales of Table 1 themselves.

To illustrate some of the points discussed here, it may be instructive to treat one system in some detail. Consider RX Her (HD170757), for example. The masses given in Table 2 are adopted directly from the spectrographic analysis (Popper 1959). Table 3 gives solutions by F. B. Wood (1948) and Magalashvili (1953) of their unfiltered photometric observations, obtained with Russell's method. A reanalysis of F. B. Wood's observations by Cester et al. (1978c) using D. B. Wood's (1972) computer program is also listed. In the table, k is the ratio of the radii, r_h and r_c the relative radii of the hotter and cooler component, respectively, i the orbital inclination, L the light of each component, J the surface flux, and $1-l$ the depth of minimum. We may adopt $r_h = 0.230 \pm 0.005$, $r_c = 0.185 \pm 0.005$, $i = 86° \pm 0.4$. The flux ratio should be better determined from the light curve than is the light ratio or the ratio of the radii. The listed values of J_h/J_c are derived from L_h/L_c and k. They should equal the ratio of the observed depths, given in the last column of the table. That they do not is a measure of the inconsistency in the solutions. Petrie's (1950) rather uncertain value of the spectroscopic light ratio is $L_h/L_c = 1.44$. The large disagreement between this value and the value 2.44 given by Cester et al. (1978c), as well as the significant difference between the flux ratios obtained in the Cester et al. solution and that obtained from the depth of minima, are examples of the

Table 3 Photometric solutions of RX Her

Author	k	r_h	r_c	i	L_h/L_c	J_h/J_c	$\frac{(1-l)_{pri}}{(1-l)_{sec}}$
Wood	0.81	0.228	0.186	85.°6	1.75	1.15	1.22
Magalashvili	0.85	0.223	0.190	86.2	1.60	1.16	1.14
Cester et al.	0.76	0.231	0.174	86.3	2.44	1.38	1.22
	±0.02	±0.002	±0.005	±0.3			

misleading results that can be obtained by allowing a computer program to "converge" to a solution. A more nearly definitive light curve of RX Her is required to establish the luminosity and flux ratios with precision. We may adopt a flux ratio in the V band of 1.15 ± 0.05, a small correction having been made to correct for the shorter effective wavelength of the unfiltered observations. A flux ratio of 1.15 ± 0.05 corresponds to a color difference between the components, $\Delta(B-V) = 0.04 \pm 0.015$ (Table 1).

Strömgren photometry of RX Her by Cameron (1966), Hilditch & Hill (1975), and Olson (1975) leads to values of $(B-V)_0 = -0.035$ and color excess $E_{B-V} = 0.06$, whereas Olson's (1975) photometry of lines in the spectrum leads to $(B-V)_0 = -0.05$. My *UBV* photometry (Popper 1959) leads to $(B-V)_0 = -0.025$ and $E_{B-V} = 0.07$. $(B-V)_0 = -0.04$ and $E_{B-V} = 0.07$ are adopted as are individual color indices of -0.06 and -0.02, with estimated uncertainties of 0.03 mags. The corresponding spectral types are B9 and A0. The estimate by Hill et al. (1975) outside eclipse is B9.5V. The values of log T_e, log L, and M_V follow. The difference in the values of M_V between the two components, 0.65, corresponds to a light ratio $L_h/L_c = 1.8$, a value not seriously violating the results in Table 3, particularly in view of all the intervening steps and their uncertainties. The values of M_V in Table 2 for RX Her are approximately 0.3 mag less positive than the values given by Lacy (1979). The most important reason for the difference is that Lacy's value of $(V-R)_0$, based on only two observations, corresponds more nearly to $(B-V)_0 = 0.00$ than to our adopted value, -0.04, leading to lower surface fluxes. A similar analysis was undertaken for each of the systems of Table 2.

Double-lined detached systems for which my spectrographic material is not yet complete are PV Cas (B9), EG Ser (A0), WX Cep (A2), GZ CMa (Am), AI Hya (F2), VZ CVn (F2), EW Ori (F8), and HS Aur (K0). In addition, new material is on hand for V624 Her (Am) and ZZ Boo (F2). Of these systems, only for WX Cep, GZ CMa, ZZ Boo, and AI Hya is the photometry reasonably satisfactory, while it is almost completely lacking for EG Ser, EW Ori, and HS Aur. HS Aur could be the important long-sought main-sequence eclipsing binary lying in its properties between the sun and YY Gem. The secondary of UV Psc, a binary with H and K emission (Table 6), may have similar properties (Sadik 1979).

OB ECLIPSING SYSTEMS

General Considerations

As seen in the preceding section, a considerable number of detached main-sequence systems in the spectral range B6–G0 is available for reasonably definitive spectroscopic and photometric analysis. The most important considerations for systems with approximately equal components are 1. that the fractional radii of the stars, $r = R/a$, be sufficiently small so that (*a*) the spectral lines of the two components are well resolved, and (*b*) the proximity effects on the light curve are small, and 2. that lines are present in the spectrum that are strong enough for reliable measurement and yet do not have damping wings causing the profiles of the component lines to overlap significantly. Of the 72 stars listed in Table 2, only nine have values of $r > 0.2$, and, with the possible exception of UV Leo, lines are available in all of them that are free of overlapping.

Nature has been less kind in designing its supply of hotter binaries. Only three systems are known to me with reasonably good spectrographic and photometric coverage having $r < 0.2$ for both components, namely, QX Car, CV Vel, and DI Her. When $r > 0.2$, the rotational velocities are so large that the central intensities of all but the strongest lines are low. But the stronger lines, primarily those of H and He, are just those with broad damping wings (e.g. Leckrone 1971), which tend to overlap in the two components. In a very careful study, Andersen (1975) has shown that even in the case of CV Vel ($r = 0.13$), in which the lines are separated by several times their rotational widths, only lines without appreciable damping wings give velocities not subject to systematic effects. In particular, the strong diffuse triplet lines of He I, which in a considerable fraction of the systems may otherwise be the best lines available to measure, give velocity separations that are systematically too small. The profiles of the hydrogen lines in all these systems are, of course, hopelessly blended. An additional irony is that MgII 4481, which in CV Vel and other systems is the most favorable line, without appreciable wings, may have its shortward displaced component blend with the wing of the longward displaced component of HeI 4471 in systems with large orbital velocities.

Comparison of Andersen's (1975) profile of HeI 4471 in CV Vel with my profile of HeI 4026 in the spectrum of U Oph (Popper 1978), $r \approx 0.25$, shows that systematic effects in the velocities, and hence in the radii and masses, can be expected to be appreciable even in such a relatively favorable system as U Oph. My stated belief (Popper 1974) that, for the best B-type systems, "there are no important sources of systematic error" in the masses and radii, now appears too optimistic. The magnitude of the systematic effects in published results depends not only on the nature of the spectrum and quality of the spectrograms, but also on the method of measurement. Under some circumstances, visual measurement of spectrograms has been shown to result fortuitously in smaller underestimates of line separations than oscilloscopic measurement (Petrie, Andrews & Scarfe 1967, Batten & Fletcher 1971). Andersen (1975 and unpublished) has shown how it is possible to obtain velocities free of the systematic effects of overlapping wings by a careful selection of lines. Modern recording devices or plates with high signal-to-noise ratio, such as the IIIaJ emulsion, and dispersions corresponding to 20 Å mm^{-1} or higher may be required. This latter technique has been applied successfully by Andersen (unpublished) to the additional systems QX Car ($r = 0.14$) and V539 Ara ($r = 0.20$). The orbit of DI Her ($r = 0.06$) is so eccentric that the lines of the components were not well resolved on older material at one nodal passage (Petrie, Andrews & Scarfe 1967). New material with higher dispersion on IIIaJ plates (Popper, unpublished) appears to remove the difficulty. Improvements in the masses and radii of other relatively favorable OB systems listed in Table 4 will require careful re-examination of existing spectrographic material or the acquisition of improved material. In some cases, spectrophotometric modeling of the line profiles may be required. Confidence in results obtained in this way cannot be as great as in results obtained from clearly separated lines.

We are led to the conclusion that only for V539 Ara, QX Car, CV Vel, and probably DI Her, can we be confident that masses of stars earlier than about B6 are currently available with an accuracy (better than 15%) comparable to that achieved for many cooler systems. The published masses of the other systems in Table 4 are likely to be smaller than their true values by unknown amounts up to possibly 20%. The fractional systematic effects in the radii from the same cause are one-third those in the masses. An additional uncertainty in the radii is introduced in a number of systems because of proximity effects on the light curves for $r \gtrsim 0.2$. Sophisticated computer models (e.g. Hill & Hutchings 1970, Wilson & Devinney 1971, Leung & Wilson 1977) have been applied to the light curves of a number of OB systems. The resulting photometric parameters have greater validity than those obtained with less satisfactory models, but inherent uncertainties remain in the solutions, the degree of uncertainty depending on the nature of the light curve and quality of the observations. An added advantage of the computer models is that they provide improved discrimination between detached, semidetached, and contact systems.

The principal criteria employed for including an OB system in Tables 4 and 5 are that the lines of both components be clearly visible in the spectrum and appear at least as well resolved as those of V382 Cyg or U Oph (Popper 1978), and that a photoelectric light curve showing two well-defined minima be available. These criteria will not necessarily exclude contact and semidetached systems.

The radiative properties (fluxes, T_e's, B.C.'s) of B stars may also be less well determined than for cooler stars because of interstellar reddening and the relative insensitivity of color index to radiative flux. For stars of type B1 and earlier, spectral type is taken as the primary determinant of radiative

Table 4 Detached OB systems

Binary	Sp[b]	$(B-V)_0$	E_{B-V}	m	R	References[e] Vel	l.c.	$B-V$ Sp	Scale dependent[a] log T_e	log L	M_V
Y Cyg	O9.8	−0.30	0.23	16.7	6.0	1	1	3	4.485	4.45	−3.45
HD198846	±0.5	±0.02	±0.03	±0.5	±0.3		2		±0.025	±0.11	±0.15
$P = 3\overset{d}{.}00$	O9.8	−0.30	—	16.7	6.0				4.485	4.45	−3.45
	0.5	0.02	—	0.5	0.3				0.025	0.11	0.15
V478 Cyg[c]	O9.8	−0.29	0.84	15.6	7.3	1	4	5	4.485	4.62	−3.90
HD193611	0.3	0.02	0.03	0.7	0.2			6	0.015	0.07	0.10
$P = 2.88$	O9.8	−0.29	—	15.6	7.3				4.485	4.62	−3.90
	0.3	0.02	—	0.7	0.2				0.015	0.07	0.10
V453 Cyg[c]	B0.4	−0.27	0.46	14.5	8.6	1	1	1	4.47	4.69	−4.15
HD227696	0.3	0.02	0.03	1.2	0.3	7	8	6	0.015	0.07	0.10
$P = 2.88$	B0.7	−0.26	—	11.3	5.4			9	4.445	4.20	−3.10
	0.5	0.02	—	1.0	0.2				0.025	0.10	0.15
CW Cep	B0.4	−0.28	0.67	11.8	5.4	1	1	1	4.47	4.28	−3.15
HD218066	0.5	0.02	0.03	0.2	0.3		8		0.025	0.10	0.15
$P = 2.73$	B0.7	−0.28	—	11.1	5.0		10		4.445	4.13	−2.90
	0.5	0.02	—	0.2	0.3				0.025	0.10	0.15
α Vir[d]	B1.5	−0.25	0.00	10.8	8.1	1		12	4.39	4.33	−3.5
HD116658	—	0.02	0.01	1.3	0.5	11		13	0.04	0.10	0.1
$P = 4.01$	B4	−0.18	—	6.8	4.4				4.23	3.16	−1.5
	—	0.03	—	0.9	0.7				0.06	0.17	0.2
QX Car	B2	−0.23	0.04	9.2	4.3	14	14	14	4.34	3.59	−2.10
HD86118	—	0.01	0.01	0.15	0.1				0.02	0.08	0.10
$P = 4.48$	B2	−0.225	—	8.5	4.0				4.33	3.48	−1.90
	—	0.01	—	0.15	0.1				0.02	0.08	0.10
V539 Ara	B4	−0.19	0.07	6.13	4.4	14	15	15	4.255	3.26	−1.70
HD161783	—	0.015	0.02	0.07	0.1			16	0.03	0.12	0.15
$P = 3.17$	B4	−0.18	—	5.25	3.7				4.23	3.02	−1.25
	—	0.015	—	0.06	0.2				0.03	0.12	0.15

CV Vel	B3	−0.19	0.03	6.10	4.05	1	17	17	4.255	3.19	−1.55
HD77464	—	0.02	0.02	0.04	0.1			18	0.04	0.16	0.15
$P = 6.89$	B3	−0.19	—	6.00	4.05			19	4.255	3.19	−1.55
	—	0.02	—	0.04	0.1				0.04	0.16	0.15
BM Ori	B3	−0.21	0.30	5.90	2.90	1	1	1	4.30	3.08	−1.05
HD37021	—	0.02	0.03	0.08	0.4				0.04	0.20	0.20
DI Her[c]	B5	−0.175	0.19	5.2	2.55	7	20	6	4.22	2.65	−0.40
HD175227	—	0.02	0.02	0.3	0.2		21	22	0.04	0.17	0.25
$P = 10.55$	B5	−0.16	—	4.6	2.55			23	4.19	2.52	−0.25
	—	0.02	—	0.3	0.2				0.04	0.17	0.25
U Oph	B5	−0.175	0.22	5.16	3.43	1	1	4	4.22	2.90	−1.00
HD156247	—	0.01	0.02	0.10	0.07		2	12	0.02	0.08	0.10
$P = 1.68$	B5	−0.165	—	4.60	3.11		8	22	4.20	2.74	−0.70
	—	0.01	—	0.06	0.06		24	23	0.02	0.08	0.10
V760 Sco[c]	B5	−0.165	0.34	5.00	3.00	7	25	25	4.20	2.71	−0.65
HD147683	—	0.01	0.02	0.12	0.15	25			0.02	0.09	0.15
$P = 1.73$	B5	−0.155	—	4.65	2.70				4.18	2.53	−0.30
	—	0.01	—	0.09	0.15				0.02	0.09	0.15
AG Per	B4	−0.185	0.19	4.53	3.00	1	1	6	4.245	2.89	−0.85
HD25833	—	0.015	0.02	0.07	0.15		2	22	0.03	0.13	0.15
$P = 2.03$	B5	−0.17	—	4.12	2.60		26	23	4.21	2.62	−0.35
	—	0.015	—	0.06	0.15				0.03	0.13	0.20

[a] Uncertainties of scale-dependent quantities do not include effects of uncertainties in the T_e and flux scales.
[b] Spectral types later than B1 are derived from color indices as well as from appearance of the spectra.
[c] Additional radial velocities are becoming available. Masses and radii provisional.
[d] M_V's are independent of flux scale. Radius of secondary is scale dependent.
[e] References

1. Cited in BFM tables and notes
2. Cited in KPW notes
3. Olson 1968
4. D. M. Popper and P. B. Etzel, unpublished
5. Roman 1956
6. Popper & Dumont 1977
7. D. M. Popper, unpublished
8. Cester et al. 1978c
9. Morgan, Whitford & Code 1953
10. Söderhjelm 1976
11. Dukes 1974
12. Olson 1975
13. Johnson & Morgan 1953
14. Andersen & Clausen 1980
15. Clausen 1979
16. Crawford, Barnes & Golson 1971a
17. Clausen & Grønbech 1977
18. Cousins & Stoy 1963
19. Feast 1954
20. Martynov & Khaliullin 1978
21. S. Catalano and M. Rodonó, private communication and P. B. Etzel, unpublished
22. Hilditch & Hill 1975
23. McNamara 1966
24. Koch & Koegler 1977
25. J. Andersen, J. V. Clausen and B. Nordström, private communication
26. Güdür 1978

properties (Table 1), while for later types the color index, $B-V$, corrected for reddening, is utilized. The difference in spectral type or color index between the components of a system is obtained in most cases from the ratio of the surface fluxes (see Table 1) derived from the light curve. The correction of Strömgren intermediate-band indices for reddening and their conversion to $(B-V)_0$ follow the precepts given by Crawford (1978).

The Available Data

In Table 4 are listed results for the eleven detached systems in which systematic effects on the masses from line blending are considered to be no worse than in the case of U Oph (Popper 1978). Only for QX Car, V539 Ara, CV Vel, and DI Her are these effects probably absent. The systems are listed in order of decreasing mass. The components of α Vir are listed from Table 7, while the hotter component of BM Ori (Popper & Plavec 1976) is also listed. The results for α Vir probably suffer from the effects of line blending similar to those in other systems (Struve et al. 1958). The absolute magnitudes of the components of α Vir are not "scale dependent," since they are obtained directly from interferometric data (Herbison-Evans et al. 1971). The radius of the smaller component is obtained from its absolute magnitude and adopted color index. The B star of known mass in ζ Aur (Popper 1961) is not listed because its radius and absolute magnitude are poorly known.

Three more massive, hotter main-sequence systems with masses as well determined as some of those in Table 4 are listed in Table 5. These systems are all probably contact systems. In contrast to the systems in Table 4, these O-type binaries have mass ratios differing much more from unity than expected from the small differences in their luminosities. Two apparently similar systems are LZ Cep (HD209481; O9; minimum masses 6.2 and 2.9; noneclipsing) and NY Cep (HD217312; O9; minimum masses 27 and 13; possibly eclipsing). See BFM for references. Although NY Cep has been classified as BO, the HeII lines are pronounced on my plates. It is possible that this rather large group of O-type systems contains high-mass counterparts of the W UMa systems.

There is good evidence for stars with higher masses than those discussed here (e.g. Conti & Walborn 1976, Hutchings & Cowley 1976). Hutchings' (1975) discussion contains material on masses of OB stars considerably less well established than is appropriate in this review.

B-type systems for which analyses have been published but with lines even less well resolved than those of V382 Cyg and U Oph (Popper 1978) include SX Aur, TT Aur, BF Aur, and IU Aur. It is not clear whether any of these systems are detached (e.g. Chambliss & Leung 1979, Mammano, Margoni & Stagni 1974). The lines in the spectra of EO Aur (Popper 1978)

Table 5 O-type systems[a]

Binary	Sp	$(B-V)_0$	E_{B-V}	m	R	References[c] Vel	l.c.	$B-V$ Sp	Scale dependent[b] $\log T_e$	$\log L$	M_V
V382 Cyg	O7.3	−0.30	1.00	26.9	9.2	3	2	3	4.575	5.17	−4.75
HD228854	±0.5	±0.02	±0.06	±2.7	±0.7		4	6	±0.015	±0.09	±0.20
$P = 1^{d}.89$	O7.7	−0.30	—	19.0	7.5		5		4.565	4.95	−4.25
	0.5	0.02	—	1.9	0.5				0.015	0.08	0.15
TU Mus	O7.8	−0.30	0.37	23.8	7.3	1	1	1	4.555	4.90	−4.20
HD100213	0.5	0.02	0.04	2.5	0.4		7	6	0.015	0.08	0.15
$P = 1.39$	O8.2	−0.30	—	15.8	6.2		8		4.545	4.72	−3.80
	0.5	0.02	—	1.5	0.3				0.015	0.07	0.15
LY Aur	O9.2	−0.30	0.50	21.7	13.0	1	1	6	4.512	5.23	−5.30
HD35921	0.5	0.02	0.03	1.7	0.8	9	10	11	0.025	0.11	0.20
$P = 4.00$	O9.4	−0.30	—	8.4	10.0			12	4.502	4.96	−4.65
	0.5	0.02	—	0.9	0.8				0.025	0.12	0.20

[a] These are all probably contact systems.
[b] Uncertainties of scale-dependent quantities do not include effects of uncertainties in the T_e and flux scales.
[c] References
1. Cited in BFM tables and notes
2. Cited in KPW notes
3. Popper 1978
4. Bloomer, Burke & Millis 1979
5. Devinney & Twigg 1974
6. Popper & Dumont 1977
7. Eggen 1978
8. Wilson & Rafert 1980
9. D. M. Popper, unpublished
10. Cester et al. 1978a
11. Morgan, Whitford & Code 1953
12. Hill et al. 1975

and VV Ori (Popper, unpublished) are completely unresolved, while V380 Cyg is a system in which I have been unable to find on high-contrast plates the lines of the secondary reported by Batten (1962). The better-studied semidetached systems are listed in a later section.

The references given in Tables 4 and 5 contain sources of the data employed in evaluating the results in the preceding columns. As in Table 2, works that are referred to in the Notes in the *Seventh Catalogue of Spectroscopic Binary Orbits* (BFM) are cited by reference to that catalogue (reference 1 in the tables) rather than to the original papers. The determination of the "scale dependent" parameters for the stars follows the same procedures discussed earlier for detached cooler systems (Table 2). The difference in the derived values of M_V of the components of a system may differ by as much as 0.1 mag from the difference obtained in the photometric solution because of uncertainties in the intervening steps. The tabulated uncertainties in the individual values of M_V are generally less than 2.5 times the uncertainties in log L, since log T_e is more sensitive to color or spectral type than is the surface flux because of the rapidly varying bolometric correction.

DETACHED BINARIES WITH COOL EVOLVED COMPONENTS

Systems Containing Subgiants

Most G-type eclipsing binaries with periods greater than one day, as well as a few F-type systems, contain detached subgiant components. The cooler components, at least, have emission at the H and K lines of Ca II strong enough to be seen outside eclipse on spectrograms of moderate resolution. These are the classical "RS CVn" systems, although the term is currently employed in a much broader sense. Most of the material on which the masses of the components in systems of this type, listed in Table 6, are based is as yet provisional. Even though the systems are totally eclipsing in many cases, the relative radii are generally quite uncertain, both because of limited photometric observations and because of instabilities in most of the light curves. For these reasons estimated uncertainties are not given in Table 6, where the systems are listed in order of decreasing total mass. The radii followed by colons (:) are rough determinations based on the durations of partial and total phases of primary eclipses with the assumption that the orbital inclinations i are 90°. This assumption minimizes the radius of the larger star and maximizes that of the smaller. Unpublished as well as published radial velocities are employed for the masses and radii except for Z Her, AR Lac, and TY Pyx, which are listed in

Table 6 Detached subgiant eclipsing systems

Binary	P	Sp:	$B–V$	$m \sin^3 i$	R	$\log L$	M_V
CQ Aur	$10^{d}.62$	G2	+0.87	1.6	—	—	—
+31°1179		K0		2.0	—	—	—
RZ Eri	39.28	Am	+0.43	1.7	—	—	—
HD30050		K0	+0.91	1.7	—	—	—
RU Cnc	10.18	F5	+0.46	1.5	1.9:	0.7	2.9
+24°1959		K1	+1.01	1.5	5.0:	1.0	2.6
PW Her	2.88	G2	+0.91	1.4	—	—	—
—		K0		1.6	—	—	—
SZ Psc	3.97	F8	+0.83	1.33	1.6:	0.5	3.5
HD219113		K1		1.65	4.0:	0.8	3.0
RW UMa	7.33	F8	+0.50	1.5	2.0:	0.7	2.9
+52°1579		K1	+1.08	1.45	3.8:	0.7	3.4
VV Mon	6.05	G2	+0.81	1.45	1.8	0.5	3.4
−5°1935		K0		1.35	6.0:	1.3	1.8
RS CVn	4.80	F5	+0.42	1.35	1.7:	0.7	3.0
HD114519		K0	+0.91	1.40	4.0:	0.9	2.7
WW Dra	4.63	G2	+0.60	1.4	2.3:	0.8	2.8
HD150708		K0	+0.97	1.4	3.9:	0.8	2.9
AW Her	8.81	G0	—	1.4	—	—	—
+18°3678		K1	—	1.4	—	—	—
RT CrB	5.12	G0	+0.70	1.3	—	—	—
HD139588		G8		1.3	—	—	—
AR Lac	1.98	G2	—	1.30	1.8	0.5	3.5
HD210334		K0	+0.93	1.30	3.1	0.7	3.3
LX Per	8.04	G0	+0.55	1.23	1.6:	0.5	3.5
+47°781		K0	+0.95	1.32	2.8:	0.6	3.6
GK Hya	3.59	F8	+0.52	1.2:	1.4:	0.4	3.7
+2°1993		G8	+0.81	1.3:	3.0:	0.8	2.9
MM Her	7.96	G2	+0.85	1.2	1.5:	0.4	3.9
+22°3245		G8		1.25	3:	0.8	3.0
TY Pyx	3.20	G5	+0.69	1.21	1.6	0.4	3.9
HD77137		G5	+0.69	1.21	1.7	0.4	3.8
Z Her	3.99	F5	+0.47	1.22	1.6	0.6	3.3
HD163930		K0	+0.91	1.10	2.6	0.6	3.6
UV Psc	0.86	G2	+0.65	1.2	1.2:	0.2	4.4
HD7700		K0	+0.91	0.9	0.9:	−0.4	5.9
UX Com	3.64	G2	+0.61	0.95	—	—	—
+29°2355		K1	+1.05	1.12	—	—	—
SS Boo	7.61	G0	+0.59	1.00	—	—	—
+39°2849		K1	+1.01	1.00	—	—	—

BFM. Changes and additions to the list published earlier (Popper & Ulrich 1977) are based on additional material. The color indices given are based on published sources listed in BFM and KPW, as well as on my own material (Popper & Dumont 1977). They are generally less well established than for the detached systems of Table 2 because photometric analyses are made uncertain by the nature of the light curves. The spectral types listed are generally only rough estimates based on color indices as well as the appearance of the spectrograms. Thus, uncertainties in the absolute magnitudes are relatively large and are not estimated. For the best-studied and most stable systems, such as TY Pyx and Z Her, they may be as small as 0.1 mag, but more typically they are considerably larger. Masses given to one decimal place and to two decimal places may be considered uncertain by about 0.15 $m_{\odot}$ and 0.05 $m_{\odot}$, respectively. UV Psc appears to be the only system in Table 6 in which the cooler component also has the smaller radius (Sadik 1979). The radii are from Sadik's solution. The systems RV Lib and RT Lac, resembling other members of the group spectroscopically but with mass ratios differing greatly from unity, are probably not detached (see Milone 1977).

Many of the properties of this and related groups of binaries have been discussed by Hall (1976). Their evolutionary status has been reviewed by Popper & Ulrich (1977) and by Morgan & Eggleton (1979). The conjecture of the latter authors, that mass ratios in the systems listed in Table 6 differing substantially from 0.96 do so because of observational uncertainties, is without foundation.

The subgiant component of the visual binary ζ Her (Table 8) has properties similar to those of some of the hotter components of the systems in Table 6, although its radius is larger than most.

Systems With Giant or Supergiant Components

The paucity of data on the masses of giants and supergiants is understandable in terms of selection effects. The nearest giants are too distant for good parallaxes. If a potential giant or supergiant is in a small enough binary system to have a good chance of becoming eclipsing as it expands, the star is likely to fill its Roche lobe before reaching the giant stage. Alpha Aur is still the only system containing giants of luminosity class III with the masses obtained directly (G0III, $m = 2.6$; G5III, $m = 2.7$; see Table 7). After α Aur, ϕ Cyg (G8III–IV, minimum masses 2.3 for each component) appears to be the most favorable double-lined giant spectroscopic binary for optical resolution. But according to H. A. McAlister (private communication) ϕ Cyg is not well resolved by the speckle technique. TW Cnc and AL Vel are totally eclipsing systems containing apparently normal red giants near KO. But in neither system has a velocity curve of the hotter (B or A) component been successfully obtained. Uncertain estimates of about 3 $m_\odot$ have been made for each of the giants. DL Vir and probably V635 Mon are eclipsing systems containing red giants, but they are triple systems in which the giant is distant from the eclipsing pair. The minimum mass of the K0II–III star in the triple system β Cap is 3.6 $m_\odot$ (Evans & Fekel 1979). Fekel's (1979) value of 2.9 $m_\odot$ for the minimum mass of the G5III component in the visual-spectroscopic triple system ψ Sgr requires a definitive visual orbit to combine with the spectrographic observations. McLaughlin has given values of 3.6 and 4.7 as minimum masses for the G-type giants in HD 15798/9 and γ Per, respectively, but the individual observations have not been published. References are in BFM. Of the five additional double-lined binaries in BFM containing cool giants, only one has minimum masses less than one solar mass. The weight of all this evidence is that, despite selection effects favoring larger masses, the masses of cool giants in binaries are appreciably greater than the value 1 $m_\odot$ obtained from indirect arguments by Scalo, Dominy & Pumphrey (1978). HD 20301, a double-lined eclipsing system probably consisting of early G giants, may lead to definitive masses (Andersen & Nordström 1977, Olsen 1977).

To the masses of the supergiants in the systems ζ Aur (K4Ib, $m = 8\ m_\odot$, $R_{\min} = 130\ R_\odot$) and 31 Cyg (K4Ib, $m = 10\ m_\odot$, $R_{\min} = 135\ R_\odot$) (Wright 1970), listed in the earlier review (Popper 1967), we may now add the M supergiant in VV Cep (M1Ia, $m = 18\ m_\odot$, $R = 1600\ R_\odot$) (Wright 1977). The velocity curve of the hot companion is poorly determined from Hα emission, and the published mean error of only 4% in its amplitude is probably too optimistic.

RESOLVED SPECTROSCOPIC BINARIES

In the case of a double-lined spectroscopic binary with good orbits of both components, only the value of the inclination, i, is needed in addition for mass determination. Values of i are known for a large number of visual binaries, and in principle all binaries except those with $i = 0$ are spectroscopic binaries. But only in particularly favorable circumstances can one resolve optically the components of binaries so close together as to have orbital velocities large enough for our purposes. Resolution may be attempted by a variety of techniques: (*a*) visual measurement; (*b*) visual Michelson interferometry; (*c*) intensity interferometry; (*d*) speckle interferometry; (*e*) amplitude (or electronic Michelson) interferometry; (*f*) lunar occultation. A discussion of interferometric techniques was the subject of IAU Colloquium No. 50 (In press). Method (*f*) is quite limited in its application to the binary problem (see Evans & Fekel 1979 for its application to β Cap), and results from various approaches to method (*e*) are yet to appear. Programs of speckle interferometry of spectroscopic binaries are being undertaken by McAlister (1976) and by Morgan et al. (1978). Method (*a*) has led to satisfactory results for δ Equ and ADS10598, while each of methods (*b*), (*c*), and (*d*) has borne fruit for one system, namely α Aur, α Vir, and 12 Per, respectively. Comments on these systems follow. Results are listed in Table 7.

ADS10598 Although the lines of the two components of this 5th mag G-type binary are marginally resolved on the small number of available spectrograms (Batten, Fletcher & West 1971), the masses resulting from combining the velocity differences with the visual orbit are of acceptable accuracy. The uncertainties in the masses (Table 7) are increased over those given in Batten, Fletcher & West to allow for the effects of uncertainties in the visual elements, particularly in the phasing of the spectroscopic observations. Photometry is from Johnson et al. (1966). The properties of the components are nearly enough identical for us to neglect their

Table 7 Resolved spectroscopic binaries

					Scale dependent[a]		
Binary	Sp	B–V	m	M_V	log T_e	log L	log R
ADS10598	G8	+0.72	1.11	4.95	3.745	−0.03	0.01
HD158614	—	±0.02	±0.10	±0.07	±0.005	±0.03	±0.02
$P = 46^{y}1$	G8	+0.72	1.11	4.95	3.745	−0.03	0.01
		0.02	0.10	0.07	0.005	0.03	0.02
δ Equ	F7	+0.50	1.19	3.95	3.794	0.32	0.085
HD202275	—	0.01	0.02	0.05	0.003	0.02	0.01
$P = 2083^{d}5$	F7	+0.50	1.19	3.95	3.794	0.32	0.085
	—	0.01	0.02	0.05	0.003	0.02	0.01
α Aur	G0III	+0.66	2.55	0.25	3.765	1.84	0.91
HD33959	—	0.03	0.2	0.15	0.01	0.06	0.045
$P = 104.0$	G5III	+0.94	2.65	0.10	3.662	1.98	1.17
	—	0.04	0.5	0.15	0.015	0.06	0.04
α Vir	B1.5	−0.25	10.8	−3.5	4.390	4.33	0.91[b]
HD116658	—	0.02	1.3	0.1	0.04	0.10	0.025
$P = 4.0$	B4	−0.18	6.8	−1.5	4.235	3.16	0.62
	—	0.03	0.9	0.2	0.06	0.17	0.07
12 Per	F9	+0.55	1.19	3.8	3.782	0.38	0.14
HD16739	—	0.04	0.20	0.2	0.010	0.08	0.05
$P = 331.0$	F9	+0.62	1.04	4.1	3.770	0.23	0.09
	—	0.04	0.15	0.2	0.008	0.08	0.05

[a] Uncertainties of scale-dependent quantities do not include effects of uncertainties in the T_e and flux scales.

[b] Radius of primary not scale dependent.

differences. The parallax obtained, $0\rlap{.}''060 \pm 0\rlap{.}''002$, may be compared to the trigonometric value $0\rlap{.}''051$.

δ Equ The properties of the nearly identical components of δ Equ appear firmly established (Popper & Dworetsky 1978, Hans et al. 1979). The parallax derived by combining spectroscopic and visual observations, $0\rlap{.}''055$, agrees with the trigonometric value, $0\rlap{.}''053$.

α Aur Uncertainties in the masses are caused by the difficulty of measuring the lines of the hotter component and by the sensitivity to a small uncertainty in the inclination of 43°. The data are discussed in BFM. The colors of the composite system correspond more closely to types G8III and G0III and a magnitude difference, $\Delta V = 0.15$, than to Wright's (1954) types of G5III and G0III with $\Delta V = 0.25$. These uncertainties are reflected in those of the luminosities and radii. The angular diameters of the components given by Blazit et al. (1977) are of insufficient precision to aid in this problem.

α Vir The data for α Vir, resolved by intensity interferometry, are taken from Herbison-Evans et al. (1971) and Shobbrok, Lomb & Herbison-Evans (1972). The radius of the primary component is obtained from its angular diameter, rather than from the magnitude and color index, which are used for the other stars listed in Table 7. The spectral type of the secondary is uncertain (Struve et al. 1958), leading to the large uncertainty in its radius. A value of $B\text{–}V = -0.18$ is adopted for this component, corresponding to type B4. Difficulties with the radial velocities remain, particularly for the secondary component.

12 Per McAlister's (1978) analysis of his speckle observations of 12 Per give $i = 123° \pm 2°$. Reanalysis of Colacevich's (1941) spectroscopic observations gives $P = 331\rlap{.}^{d}2 \pm 0\rlap{.}^{d}15$, $K_1 = 21.8 \pm 0.8$, $K_2 = 24.8 \pm 1.4$, $e = 0.69 \pm 0.02$. The masses in Table 7 result from combining McAlister's inclination with these spectroscopic results. The parallax used in obtaining M_V, $0\rlap{.}''047 \pm 0\rlap{.}''003$, is obtained from McAlister's values of i and a'' and the spectroscopic value of $a \sin i$. The trigonometric parallax is $0\rlap{.}''040$. The magnitude difference between the components is poorly known. The color difference, which is unknown, was adopted to correspond to the difference in masses.

The bolometric corrections and surface fluxes, used in deriving the luminosities and radii of the stars listed in Table 7, are from Table 1, as are the effective temperatures.

χ Dra (Breakiron & Gatewood 1974), ADS11060 (Batten et al. 1979), and ψ Sgr (Fekel 1979) are examples of resolved spectroscopic binaries for which the masses are not as yet obtained with sufficient accuracy for our purposes. A more general discussion of combining available radial velocity and astrometric data is given by Halliwell (1980).

VISUAL BINARIES

General Considerations

Critical lists of the masses and other properties of visual binaries have been given by van de Kamp (1958) and by Lacy (1977b). Less restricted lists are those of Harris, Strand & Worley (1963) and Heintz (1978). Veeder (1974) has discussed M dwarfs. It is rather sad, in view of the very great amount of difficult observing for more than 150 years, that the number of visual binaries for which masses are known to an accuracy of about 20% is not more than a dozen or so. Lacy's list contains only three systems not listed by van de Kamp nearly 20 years earlier, and one of these is of doubtful quality. There are, of course, orbits of many more visual binaries that are adequate for determining the sum of the masses of the components. The compilation by Finsen & Worley (1970) contains nearly 200 systems considered by the authors to have definitive or reliable orbits. The parallax of a system must be known to an accuracy of 7% for 20% accuracy in the masses. It is true that individual parallax determinations, as well as the mean of the determinations from two or more observatories, may have formal mean errors considerably less than 0.″01. But random differences between the well-observed values for a given star from two observatories, as well as systematic differences between observatories (see, for example, Vasilevskis 1966, Gliese 1972, Upgren 1977) and somewhat uncertain corrections from relative to absolute parallaxes, make it appear unwise to assume at this time that the true uncertainty of a parallax is less than 0.″01.

The major axes of the better-determined orbits of eclipsing binaries have uncertainties considerably less than 10%. If results from visual binaries are to be of comparable accuracy, the ratio of angular major axis to parallax should have an uncertainty of less than 10%, as well. Hence, in the present context, parallaxes less than 0.″1 are of little use in mass determination. Examination of existing material on parallaxes shows that, for reliable values, in addition to the limiting size, there should be at least three reasonably accordant independent determinations. Van de Kamp & Worth (1971) discuss further this matter of the accuracy in parallaxes required for stellar masses in connection with η Cas. For purposes other than mass determination or for studies in which masses of high reliability are not required, less rigid standards would be appropriate.

Programs designed to obtain parallaxes of higher accuracy have been undertaken at the Lick (Vasilevskis 1969), Yerkes (van Altena 1971), and US Naval (Worley 1966) Observatories. But binary stars with good orbits do not appear to have priority in these programs. Greatly improved accuracy is predicted for parallaxes from space stations and with other improved techniques (Lacroute 1977, Høg & Fogh Olson 1977, Connes 1979, Høg 1979). In principle, means are at hand or may become available for deriving masses of many more of the visual binaries with good orbits than are presently available. It it not clear, however, that improved results for visual binary systems will be forthcoming soon.

The accuracy with which the masses are known in a visual binary system depends also on the reliability of the double star measures and on the uncertainty in the orbital solutions. The catalogue of Finsen & Worley (1970) classifies orbital solutions according to quality. Only systems with orbits corresponding to their classes 1 ("definitive") or 2 ("reliable") are considered as candidates. Even among these systems there are a few cases in which independent solutions lead to values of a^3P^{-2} differing by 20%, where a is the angular semimajor axis and P is the orbital period. One reason for such differences lies in the choice and weighting of observations. Eggen (1956) has emphasized this point. In six of the 29 systems listed by Eggen with orbits of quality 1 or 2, his value of a^3P^{-2} differs from that obtained from the data listed in Finsen & Worley by more than 15%. The average difference is 13%. The most extreme case is the bright system, ψ Vel, with nearly equal components (van den Bos 1945), for which values of a from observations of different experienced observers range from 0.″76 to 1.″11. The matter of systematic errors in visual double star observations was discussed in IAU Colloquium No. 10 (Heintz 1971), and is clearly a matter of personal opinion. The use of photoelectric scanning techniques (Rakos 1965, Franz 1970) does not appear to have led to published results as yet. The use of speckle interferometry was referred to in the previous section.

For orbits of high quality, uncertainties introduced by the method of orbital solution are of less importance than uncertainties in the parallaxes. In recent years, most orbital solutions have been carried out with modern digital computing systems. Their use for this purpose has been discussed by Wielen (1962), Eggen (1967), Heintz (1967), and Morbey (1975). Eichhorn & Clary (1974) point out that for very close systems the usual first-order least-squares treatment may not be adequate. Among the more active workers applying machine methods have been Heintz (e.g. 1976) and Starikova (e.g. 1978).

A final consideration concerning masses is the mass ratio, obtained photographically except for the wider pairs. The most recent compilation of mass ratios I am aware of is that of Harris, Strand & Worley (1963). The Sproul Observatory observers appear to have been the most active in this important enterprise in recent years, as they have been in obtaining additional parallaxes of visual binaries. The reliability of the mass ratio for a close system is difficult to estimate, being dependent on the effects of blending of images under different seeing conditions. Tests carried out by

Feierman (1971) imply that there are greater uncertainties in the correction from photocenter to barycenter in the blended stellar images than had been assumed.

In order to obtain luminosities and radii to correlate with the masses, we need, in addition to parallaxes, apparent magnitudes and color indices or spectral types on standardized systems. For binaries with separations closer than a few arcseconds, data for the individual components must often be based on estimates rather than on measures. For the nearby stars under consideration here, the relevant data have been compiled by Gliese (1969). Worley (1969) has shown that the better estimates of magnitude differences are usually reliable to within 0.1 mag. For the fainter components of close systems, the bolometric corrections and surfaces fluxes (and consequently their radii) may be quite uncertain.

The Available Data

According to the principles adopted in this review, we consider only visual binary systems with parallaxes greater than 0″.09, with at least three independent determinations of the parallax within 10% of their mean value, and with orbits of quality 1 or 2. There are 14 such systems, if we include L726-8 (Worley & Behall 1973) and o^2 Eri BC (Heintz 1974), for which discussions subsequent to the Finsen-Worley catalogue may provide sufficient improvement in the visual orbit to put them marginally into quality category 2. The properties of these 14 systems are listed in Table 8. Fourteen is really a pitifully small number in view of the great effort by many observers. The only systems in Table 8 not included in the list carefully selected 20 years ago by van de Kamp (1958) are L726-8, Wolf 630, and HR6426. The systems in the table not included in Lacy's (1977b) list are o^2 Eri BC, ξ Boo, HR6426, and ζ Her.

To illustrate the problems encountered in attempting to add visual binary systems to the list of objects with well-defined properties, we may consider the data for HR6426 and ζ Her.

HR6426 is GL 667 (Gliese 1969), and is often referred to as M1b 4. Finsen & Worley (1970) list two orbits, *both* of quality 1. The two values of a^3P^{-2} differ by 14%. The reasonably accordant parallaxes lead to $\pi = 0''.14 \pm 0''.01$. (The ± 0.01 is adopted from the discussion above.) In this case, the mass ratio, $m_B(m_A+m_B)^{-1} = 0.41 \pm 0.03$, is obtained from micrometer measures relative to nearby stars (Hirst 1947) rather than from the usual long-focus photographic astrometry, so the problems of blended images are avoided. The resulting masses (Table 8) have nearly acceptable uncertainties in the context of this review, but the spectral types and magnitude difference in HR6426 are poorly known. Composite types from K2 to K5 may be found in the literature and visual magnitude differences of 0.9 and 1.5 mag. Thus, the luminosities and radii are subject to more uncertainty than is desirable for a first-rate system. *UBV* photometry of the combined light (Johnson et al. 1966) shows $V = 5.91$, $B–V = +1.04$, $U–B = +0.82$. While these colors can be matched by combining those of main-sequence stars of types K2-3 and K5 with a V magnitude difference of 1.0 mag, the radii and luminosities obtained from these data can hardly be considered definitive determinations. That the radius of the less luminous component is found to be greater than that of the more luminous one is undoubtedly a consequence of incorrect differences in magnitude and color.

Zeta Her illustrates a somewhat different set of problems. There are four parallax determinations within a range of 0″.016. In this case, 0″.01 uncertainty in the parallax may be somewhat of an overestimate, and the uncertainty of the masses from this cause may be taken as 25%. The value of a given by Eggen (1956) is 3.5% less than the value adopted by Finsen & Worley (1970), and the values of the mass ratio found in the literature range from 0.34 to 0.42. Thus, the uncertainty in the masses depends principally, though not entirely, on that in the parallax. The visual magnitude difference between the components of ζ Her is well determined as 2.65 ± 0.1 (Worley 1969). But the deconvolution of the individual color indices requires an assumption as to the "normality" of the colors, as in the case of HR6426.

The apparent magnitudes and parallaxes in Table 8 are taken from Gliese (1969) and Veeder (1974) except for the parallaxes of L726-8 (Worley & Behall 1973) and 70 Oph (Worth & Heintz 1974). An uncertainty of $\pm 0''.01$ is adopted for each value of π except for L726-8 ($\pm 0''.02$) and ζ Her ($\pm 0''.008$). An uncertainty of $\pm 0''.01$ is assumed in a for orbits of quality 1, $\pm 0''.02$ for quality 2, and $\pm 0''.04$ for quality 2–3. The periods are assumed known without sensible error. The values of a and P are taken from Finsen & Worley (1970), except for L726–8 (Worley & Behall 1973) and o^2 Eri BC (Heintz 1974). The sources for the mass ratios are given in the table. An uncertainty of ± 0.02 is adopted for the ratios except for the wider pairs and systems with large values of the magnitude difference, for which ± 0.01 is adopted. In cases where the ratio is *assumed* to be unity, larger values are adopted (± 0.03 for ζ Her and ± 0.05 for Wolf 630 and Fu 46). In most cases, the uncertainty in the masses is dominated by that in the parallax. The masses in Table 8 differ but little from those given by Lacy (1977b), although his mean errors are usually smaller than those obtained here, since he has adopted published mean errors of the parallaxes. There is good evidence (e.g. Lippincott & Hershey 1972, Probst 1977, Hershey 1978) for stellar masses less than 0.1 $m_{\odot}$, but they are as yet not known with sufficient accuracy for inclusion here.

Table 8 Visual binaries

Binary	Sp	V	$(B-V)$ or $(V-R)$[b]	π''	a''	$m_B/\Sigma m$	m	M_V	Ref.[d] for $m_B/\Sigma m$	Scale dependent[a] log T_e	log L	log R
α CMa	A1V	−1.46	0.00	0.377	7.50	0.30	2.20	1.42	1	3.975	1.37	0.225[c]
HD48915	—	±0.02	±0.01	+0.010	±0.01	±0.02	±0.2	±0.06	2	±0.005	±0.025	±0.015
$P = 50^y.1$	wA	8.3	−0.12:	—	—	—	0.94	11.2		—	—	—
	—	0.1	—	—	—	—	0.1	0.1		—	—	—
α CMi	F51V-V	0.37	+0.42	0.287	4.55	0.27	1.77	2.66	1	3.816	0.82	0.314[c]
HD61421	—	0.02	0.01	0.010	0.01	0.01	0.2	0.08	2	0.002	0.03	0.020
$P = 40.6$	w	10.7:	—	—	—	—	0.65	13.0:		—	—	—
	—	—	—	—	—	—	0.1	—		—	—	—
ζ Her	G0IV	2.89	+0.64	0.104	1.37	0.35	1.25	3.00	2	3.765	0.74	0.35
HD150680	—	0.02	0.01	0.008	0.01	0.03	0.3	0.17	3	0.003	0.07	0.035
$P = 34.4$	K0V	5.49	+0.75	—	—	—	0.70	5.60	4	3.735	−0.28	−0.10
	—	0.03	0.05	—	—	—	0.2	0.17		0.015	0.07	0.05
α Cen	G2V	−0.01	+0.68	0.743	17.56	0.45	1.14	4.34	1	3.755	0.12	0.105
HD128620/1	—	0.02	0.03	0.01	0.01	0.01	0.05	0.03	2	0.010	0.01	0.02
$P = 79.9$	K0V	1.33	+0.88	—	—	—	0.93	5.68		3.700	−0.28	−0.025
	—	0.03	0.03	—	—	—	0.04	0.04		0.010	0.015	0.02
γ Vir	F0V	3.49	+0.36	0.094	3.75	0.50	1.08	3.36	1	3.826	0.52	0.13
HD110379/80	—	0.03	0.01	0.01	0.01	0.01	0.35	0.23	2	0.002	0.09	0.05
$P = 171.4$	F0V	3.49	+0.36	—	—	—	1.08	3.36		3.826	0.52	0.13
	—	0.03	0.01	—	—	—	0.35	0.23		0.002	0.09	0.05
η Cas	G0V	3.45	+0.57	0.172	11.99	0.38	0.91	4.63	1	3.777	0.06	−0.01
HD4614	—	0.02	0.02	0.01	0.02	0.01	0.15	0.15	5	0.005	0.06	0.03
$P = 480$	M0V	7.51	+1.40	—	—	—	0.56	8.69	6	3.590	−1.13	−0.23
	—	0.05	0.15	—	—	—	0.10	0.15		0.02	0.06	0.12
ξ Boo	G8V	4.68	+0.71	0.148	4.92	0.45	0.90	5.53	2	3.745	−0.27	−0.115
HD131156	—	0.03	0.02	0.01	0.01	0.02	0.20	0.15	7	0.005	0.06	0.03
$P = 152$	K4V	6.84	+1.10	—	—	—	0.72	7.69		3.645	−0.96	−0.26
	—	0.05	0.08	—	—	—	0.15	0.15		0.02	0.06	0.07

70 Oph	K0V	4.24	+0.80	0.203	4.55	0.42	0.84	5.78	1	3.721	−0.35	−0.10
HD165341	—	0.02	0.03	0.01	0.01	0.02	0.15	0.10	2	0.01	0.04	0.03
$P = 88.1$	K5V	5.94	+1.16	—	—	—	0.61	7.48	8	3.631	−0.84	−0.17
	—	0.06	0.10	—	—	—	0.10	0.12		0.03	0.05	0.08
HR6426	K3V	6.3	+0.94	0.137	1.82	0.41	0.78	7.0	9	3.685	−0.77	−0.24
HD156384	—	0.1	0.06	0.01	0.01	0.02	0.2	0.2		0.015	0.085	0.06
$P = 42.1$	K5V	7.2	+1.20	—	—	—	0.54	7.9		3.622	−0.98	−0.22
	—	0.4	0.12	—	—	—	0.1	0.4		0.025	0.2	0.12
Wolf 630	M4.5V	9.76	+1.63[b]	0.161	0.22	0.50	0.42	10.80	4	3.538	−1.62	−0.37
HD152751	—	0.05	0.1	0.01	0.01	0.05	0.10	0.15		0.015	0.15	0.10
$P = 144.5$	M4.5V	9.76	+1.63[b]	—	—	—	0.42	10.80		3.538	−1.62	−0.37
	—	0.05	0.1	—	—	—	0.10	0.15		0.015	0.15	0.10
Fu 46	M3V	9.96	+1.58[b]	0.153	0.71	0.50	0.30	10.90	1	3.546	−1.71	−0.43
HD155876	—	0.03	0.03	0.01	0.01	0.05	0.07	0.15	2	0.005	0.07	0.04
$P = 13.0$	M3.5V	10.39	+1.70[b]	—	—	—	0.30	11.30	4	3.528	−1.73	−0.41
	—	0.10	0.06	—	—	—	0.07	0.17		0.01	0.10	0.06
Kr 60	M3V	9.85	+1.76[b]	0.250	2.38	0.36	0.28	11.85	1	3.518	−1.86	−0.46
+56°2783	—	0.10	0.03	0.01	0.01	0.02	0.03	0.15	2	0.005	0.07	0.04
$P = 44.4$	M4.5V	11.30	+1.89[b]	—	—	—	0.16	13.30	10	3.503	−2.30	−0.64
	—	0.30	0.09	—	—	—	0.02	0.30	11	0.015	0.15	0.09
o^2Eri BC	wA	9.52	+0.03	0.207	6.94	0.27	0.43	11.1	2	—	—	—
HD26976 BC	—	0.02	0.02	0.01	0.04	0.03	0.07	0.1	12	—	—	—
$P = 252$	M4.5V	11.2	+1.75[b]	—	—	—	0.16	12.8		3.520	−2.25	−0.66
	—	0.15	0.15	—	—	—	0.03	0.15		0.025	0.20	0.14
L726-8	M5.5V	12.50	+2.32[b]	0.385	2.06	0.49	0.11	15.45	13	3.443	−2.83	−0.79
Star B = UVCet	—	0.1	0.05	0.02	0.04	0.02	0.02	0.15		0.007	0.07	0.04
$P = 26.5$	M5.5V	13.10	+2.45	—	—	—	0.11	16.00		3.425	−2.98	−0.82
	—	0.2	0.10	—	—	—	0.02	0.25		0.015	0.15	0.08

[a] Uncertainties in scale-dependent quantities do not include effects of uncertainties in T_e and flux scales.
[b] Color indices are $V-R$.
[c] These radii are not scale dependent.
[d] References for mass ratios

1. van de Kamp 1954
2. Strand & Hall 1954
3. Wyller 1955
4. Harris, Strand & Worley 1963
5. Strand 1969
6. van de Kamp & Worth 1971
7. Hershey 1977
8. Worth & Heintz 1974
9. Hirst 1947
10. Lippincott 1953
11. Wanner 1967
12. Heintz 1974
13. Worley & Behall 1973

The values of V and the color indices $B-V$ or $V-R$ are from Gliese (1969) and Veeder (1974) when available. The uncertainties of the color indices, upon which the fluxes required for the luminosities and radii depend, are quite large for most of the cooler stars, as shown in Table 8. The discussion above of HR6426 and ζ Her illustrates some of the problems encountered in separating the colors of the components. In some cases, the observations themselves are of low weight, and when values of both $V-R$ and $B-V$ are available, they may not be compatible. Kunkel & Rydgren (1979) noted difficulties in transforming observations to $V-R$ indices for M dwarfs. For the fainter members of the closer binaries, the apparent magnitudes may

Table 9 The nearest visual binaries with orbits of quality 1–4

Binary	A or GL[a]	Spectra[b]	Orbit[c] quality	Period	Par.	n[d]	Needed[e]
α Cen	GL559	G2, K0	1	80[y]	0.″75	4	—
L726-8	GL65	M5.5	2–3	27	0.38	3	(o), (p)
α CMa	A5423	A1, w	1	50	0.37	6	—
α CMi	A6251	F5, w	1	41	0.29	6	—
61 Cyg	A14636	K5, K7	4	650	0.29	6	o
+59°1915	A11632	M4, M5	4	450	0.28	6	o
Ross 614	GL234	M7, ?	3	16	0.25	6	r
Kr 60	A15972	M3, M4.5	1	44	0.25	4	—
Wolf 424	GL473	M5.5	4	16	0.23	5	r
o^2Eri BC	A3093	w, M4.5	2–3	250	0.20	5	(o)
70 Oph	A11046	K0, K5	1	88	0.20	4	—
η Cas	A671	G0, K5	2	480	0.17	4	(o)
Wolf 630	GL644	M4.5	1	1.7	0.16	5	—
Fu 46	GL661	M3	1	13	0.15	3	(p)
ξ Boo	A9413	G8, K4	1	150	0.15	3	(p)
HR486-7	GL66	K2, K5	4	480	0.15	2	o, p
HR6426	GL667	K3, K5	1	42	0.14	3	(o), (p)
ξ UMa	A8119	G0	1	60	0.13	1	p
−21°1051	GL185	M1, ?	3	48	0.13	1	o, p
μ Her BC	A10786	M4	1	43	0.12	2	p
HR6416	GL666	G8, M0	4	700	0.12	2	o, p
HD115953	A8862	M2, ?	2	49	0.11	1	(o), p
ζ Her	A10157	G0IV, K0	1	34	0.10	4	—
γ Vir	A8630	F0	1	170	0.09	3	(p)
HD99279	GL428	K7, M0	3	421	0.09	3	o, p

[a] A = Aitken Double Star Catalogue; GL = Gliese Catalogue of Nearby Stars, 1969 edition.
[b] All are main sequence unless otherwise indicated.
[c] As given in Finsen & Worley (1970).
[d] Number of independent parallax determinations within 10% of their mean [Jenkins (1963) and later determinations].
[e] o: orbit; p: parallax; r: resolution.

also not be well established. All these sources of uncertainty, in addition to those in the parallaxes, enter into the calculations of log L and log R. The values of T_e and F'_V are obtained from Table 1.

It should be clear from this brief discussion that determination of the radii of visual binaries, as well as their masses, is beset with more serious and a greater variety of difficulties than in the cases of the better eclipsing binaries. While most of the values of log R in Table 8 are in reasonable agreement with those of Lacy (1977b) for the stars in common, there are a few significant differences, and my m.e.'s are generally larger than Lacy's because of the considerations discussed above. The radii listed in Table 8 for α CMa and α CMi are taken directly from their angular diameters (Hanbury Brown, Davis & Allen 1974).

In Table 9 are listed, in order of increasing distance, 24 visual binaries with $\pi \geq 0''.09$ and with orbits of quality 4 or better. For the systems with inadequate data, notes specify the inadequacies that would have to be removed for the systems to be added to Table 8. Additional nearby systems of particular interest are the astrometric binaries $+20°2465$ = GL388 (M4, $\pi = 0''.21$, $P = 26^y$) and μ Cas (sdG5, $\pi = 0''.13$, $P = 18^y$), for which resolution of the components would provide masses of importance, and AC $+59°24610/1$ = GL169 (M5+w, $\pi = 0''.19$, $P = 350^y$) for which an improved parallax and orbit could give us an additional direct determination of the mass of a white dwarf.

The systems listed in Table 10 are those with parallaxes between $0''.05$ and $0''.09$ and orbits of quality 1 or 2. A new standard of accuracy for parallaxes, applied to some of these systems, would appreciably increase our knowledge of stellar masses, particularly among the G and K main-sequence stars, where the eclipsing binaries provide little information. A number of these systems of smaller parallax are included in the compilation of masses by Harris, Strand & Worley (1963).

As an alternative to improved parallax determination, a great increase in the precision of radial velocities (e.g. Campbell & Walker 1979), to the order of ± 50 m s^{-1}, would place many visual binaries in the category of "resolved spectroscopic binaries" discussed above. The velocity system would have to be stable and the velocities measured over time intervals comparable to the orbital periods. Hence, this improvement in technique, which may be forthcoming, would rescue good visual orbits less rapidly than could a program of more reliable parallaxes.

In addition to the systems listed in Tables 9 and 10, there are nearby binaries of relatively short period with orbits and parallaxes as yet inadequately known (e.g. Heintz 1979), as well as undiscovered binaries, that can be expected to provide significant mass determinations.

Table 10 Visual binaries with parallaxes between 0″.05 and 0″.09 and orbits of quality 1 or 2

Binary	A or GL[a]	Spectrum[b]	Orbit[c] quality	Period	Par.[d]
	A490	F8	2	6ʸ.9	0″.063
	A520	G5	1	25	0.074
	GL60	K3	1	4.6	0.057
	A1865	M0	2	25	0.064
ε Cet	GL105.4	F8	2	2.7	0.069
	A6420	G1	1	23	0.069
	A6664	M0	2	59	0.057
	A7114	M1	2	40	0.066
10 UMa	GL332	F5	2	22	0.074
	A7284	K3	1	34	0.058
ψ Vel	GL351	F2	1	34	0.065
α Com	A8804	F5	1	26	0.053
	A9031	K2	2	155	0.086
η CrB	A9617	G2	1	42	0.060
	A9689	K5	2	54	0.09[e]
	A9716	K0	1	56	0.053
	A10075	K2	2	236	0.058
η Oph	A10374	A2	2	88	0.051
	A10585	M0	2	60	0.055
	A10598	G8IV-V	1	46	0.052
	A10660	G1	2	76	0.067
99 Her	A11077	F7	2	55	0.061
	A11871	G0	2	61	0.054
γ CrA	GL743.1	F8	1	120	0.054
τ Cyg	A14787	F0	1	50	0.050
85 Peg	A17175	G3	1	26	0.084

[a] A = Aitken Double Star Catalogue; GL = Gliese Catalogue of Nearby Stars, 1969 edition.
[b] All are main sequence except A10598.
[c] Finsen & Worley (1970).
[d] Jenkins (1963).
[e] Spectroscopic parallax.

SEMIDETACHED SYSTEMS

General Considerations

Semidetached systems are close binaries in which the less massive component, which is usually the cooler and larger one, fills the zero-velocity surface passing through the inner Lagrangian point. The more complex physical nature of these systems leads in most cases to difficulties in the analyses of observational data, so that the fundamental properties of the components cannot usually be determined as reliably as for many detached systems (Table 2). These difficulties include relative faintness of the cooler component so that its spectral lines are difficult to measure; ellipticity and reflection in the light curves, making analyses less definitive; gas streams giving rise to nonorbital displacements of spectrum lines associated with the hotter component as well as to nongeometrical effects in the light curves. Even the decision that a system is semidetached may not always be based on clear evidence, since both the mass ratio and radii of the components must be known in order to make the decision.

Systems to be included in this section are those in which the lines of both components are measured throughout the orbits. It is convenient to distinguish somewhat arbitrarily three groups of semidetached eclipsing systems. First are the more massive systems in which the hotter component is an early B-type star and the cooler of type B or early A (V Pup, V356 Sgr, u Her, Z Vul). The system μ_1 Sco is omitted because its low orbital inclination, near 60°, makes its properties even less well defined than in the other systems. Second are the more "typical" Algol systems of lower mass, in which the more massive component lies in the range from middle B to early F, and the other is of type F or later. Third are the later subgiant (RV Lib, RT Lac) and giant (RZ Cnc, AR Mon) semidetached systems.

While the first and third groups, with the two components not differing greatly in spectral type, have limited membership among observed eclipsing binaries, there are large numbers of typical Algol systems. In most of them the lines of the cooler components are difficult to measure, if indeed they are visible in spectrograms of the resolution available. Most success in obtaining velocity curves of the cooler components has resulted from use of the D lines, although these lines have their own difficulties including, in addition to their weakness in most cases, blending with interstellar or circumstellar lines, blending with water-vapor lines, and blending of the lines of the two components. Although lines of the hotter components in most typical Algol systems are strong and readily measurable, it has been realized ever since Struve's early work on U Cep that the measured velocities may not represent orbital motion because of the effects of material not moving with the photosphere of the star. Even when the lines appear reasonably sharp and symmetrical (e.g. RY Gem, McKellar 1949, or TT Hya, D. M. Popper and M. Plavec, unpublished), they may show considerable departures from orbital motion, whereas the D lines of the cooler components appear to represent true orbital motion. Because of the small amplitudes of velocity variation for the hotter components in a number of systems, these effects can make determination of the masses of the cooler components very uncertain.

Table 11 Hot semidetached systems

						References[b]			Scale dependent[a]		
Binary	Sp	$(B-V)_0$	E_{B-V}	m	R	Vel	l.c.	$B-V$ Sp	$\log T_e$	$\log L$	M_V
V Pup	B1	−0.26	0.03	17	6.3	1	2	5	4.42	4.20	−3.35
HD65818	—	±0.02	±0.02	±1	±0.3		3	6	±0.04	±0.16	±0.25
$P = 1^{\mathrm{d}}.45$	B2	−0.24	—	9	5.3		4	7	4.36	3.85	−2.65
	—	0.03	—	1	0.3				0.06	0.25	0.20
V356 Sgr	B4	−0.18	0.20	12.1	6.0	1	8	1	4.23	3.45	−2.30
HD173787	—	0.02	0.03	1.1	0.7				0.04	0.16	0.30
$\dot{P} = 8.90$	A2	+0.08	—	4.7	14.0				3.935	3.00	−2.75
	—	0.03	—	0.6	1.5				0.012	0.10	0.25
u Her	B2.5	−0.22	0.03	7.3	4.8	1	9	11	4.32	3.60	−2.20
HD156633	—	0.02	0.02	1.0	0.4		10	12	0.04	0.16	0.25
$P = 2.05$	B7	−0.12	—	2.7	4.3			13	4.11	2.65	−1.10
	—	0.03	—	0.3	0.2			14	0.04	0.16	0.20
Z Vul	B3	−0.19	0.23	5.4	4.7	1	1	1	4.255	3.30	−1.85
HD181987	—	0.02	0.03	0.3	0.2		15	16	0.04	0.16	0.20
$P = 2.455$	A2	+0.04	—	2.3	4.5			17	3.955	2.07	−0.45
	—	0.03	—	0.1	0.2				0.015	0.06	0.15

[a] Uncertainties of scale-dependent quantities do not include effects of uncertainties in the T_e and flux scales.

[b] References

1. Cited in BFM tables and notes
2. Cited in KPW notes
3. Schneider, Darland & Leung 1979
4. Eaton 1978a
5. Johnson et al. 1966
6. Crawford, Barnes & Golson 1970
7. Hiltner, Garrison & Schild 1969
8. Wilson & Caldwell 1978
9. Eaton 1978b
10. Söderhjelm 1978
11. Kopylov 1958
12. Olson 1968
13. Crawford, Barnes & Golson 1971b
14. McNamara 1966
15. Cester et al. 1977
16. Olson & Weiss 1974
17. Olson 1975

The Available Data

Observational results for the three groups of semidetached eclipsing binaries are presented in Tables 11, 12, and 13. For reasons discussed above, these results are generally less well established than for the detached eclipsing systems of Tables 2 and 4. For the more massive systems, listed in Table 11, an attempt is made to estimate the uncertainties of the results, although these estimates are less well grounded than for the detached system. For V Pup and u Her, in particular, the velocity curves are quite uncertain. The Roche-lobe–filling less-massive component in V Pup is the smaller one, in contrast to nearly all other semidetached systems.

Table 12 Algol systems

Binary	P	Sp[a]	m	R	$\log L$	M_V
RY Per[b]	$6^d.86$	B4	5:	3.4:	3.0	−1.1
HD17034	—	F5	0.8::	7	1.9	0.0
RS Vul	4.48	B5	4.5	4.1	2.9	−1.3
HD180939	—	G0:	1.4	5.6	1.5	0.9
U Sge	3.38	B8	5.7	4.1	2.6	−1.0
HD181182	—	G5	1.9	5.3	1.3	1.5
Algol	2.87	B8	3.7	3.1	2.2	−0.2
HD19356	—	G8	0.8	3.2	0.8	2.8
S Cnc	9.48	A0	2.4	2.1	1.5	1.1
HD74307	—	K2:	0.2::	5	1.0	2.6
RY Gem[b]	9.30	A2	2.6	3.3	1.8	0.2
HD58713	—	K2:	0.6:	6	1.1	2.3
TT Hya[b]	6.95	A2	2.6:	2:	1.3	1.4
HD97528	—	K1:	0.7::	5:	1.1	2.1
XY Pup[b]	13.78	A2	2.3:	—	—	—
HD67862	—	K	0.3::	—	—	—
AS Eri	2.66	A3	1.9	1.8	1.2	1.7
HD21985	—	K0:	0.2	2.2	0.4	3.9
TW Dra	2.81	A3	1.7	2.4	1.4	1.1
HD139319	—	K0:	0.8	3.4	0.8	2.9
AW Peg[b]	10.62	A5:	2.0:	—	—	—
HD207956	—	K1	0.3::	—	—	—
RY Aqr	1.97	A5	1.3	1.5:	0.9	2.3
HD203069	—	K1:	0.3:	1.7:	0.2	4.4
TW And	4.12	A8	1.8	2.2	1.1	1.9
+32°4756	—	K2:	0.4	3.4	0.7	3.4

[a] Types of cooler components based on colors and depths of minima of light curves as well as on appearance of the spectra.

[b] Strong double Hα emission.

Table 12 lists results for those "typical" Algol systems for which velocity curves of the cooler stars have been measured. Except for AS Eri (Popper 1973), AW Peg (Hilton & McNamara 1961), Algol (Tomkin & Lambert 1978), and U Sge (Tomkin 1979), the masses are based on unpublished velocities for the cooler components and published (BFM) and unpublished velocities for the hotter ones. Work is continuing on these systems. Photometric analyses, required for the radii, are obtained from KPW. These analyses are often uncertain because of shallow secondary minima, large reflection effects, effects of gas streams, unrealistic photometric models, etc. With a few exceptions, both the photometric observations of Algol systems and their interpretation require thorough investigation. For systems with partial eclipses, the spectral types of the cooler components are estimated from the photometry (depths of minima, color indices), in which cases corrections for reflected light may be large and uncertain. On the basis of available information, the cooler components have colors and types near K1 IV except for AW Peg, RY Per, RS Vul, and U Sge, for which types of F5:, F5:, GO:, and G5 are indicated. Instead of attempting to estimate uncertainties in the masses and radii, I employ single (:) or double (::) colons to indicate that the digit immediately preceding the colon is poorly or very poorly known. With few exceptions, the luminosities listed are quite uncertain because of poorly known radii and temperatures.

Table 13 Cool semidetached systems

					Scale dependent[a]		
Binary	Sp	B–V	m	R	log T_e	log L	M_V
RZ Cnc	K1	+1.08	3.20	10.2	3.630	1.50	1.35
HD73343	—	±0.03	±0.15	±0.5	±0.006	±0.05	±0.15
$P = 21^d.6$	K4	+1.40	0.54	12.2	3.585	1.45	1.90
	—	0.06	0.05	0.7	0.006	0.05	0.20
AR Mon	K0	+0.95	2.70	10.8	3.660	1.65	0.85
HD37364	—	0.04	0.10	1.0	0.012	0.10	0.25
$P = 21.2$	K3	+1.30	0.80	14.2	3.590	1.62	1.25
	—	0.06	0.05	1.5	0.010	0.10	0.30
RV Lib	G5:		2.2:	—	—	—	—
HD128171	—	+1.04	—	—	—	—	—
$P = 10.7$	K2:		0.4:	—	—	—	—
RT Lac	G8:	—	0.6	4.6	3.72:	1.15:	2.10:
HD209318	—	—	—	—	—	—	—
$P = 5.1$	K1:	—	1.5	4.3	3.66:	0.85:	2.90:

[a] Uncertainties given for scale-dependent quantities do not include effects introduced by uncertainties in the flux and T_e scales.

Results for the small group of cooler semidetached systems are in Table 13. The available material and analyses of the giants RZ Cnc and AR Mon are from Popper (1976a). No photometric solution is available for RV Lib, the semidetached nature of which is inferred from the considerable inequality of the masses. According to Milone's (1977) analysis, the hotter component of RT Lac fills its Roche lobe, although the nature of the components of this system is still in question. The velocity curves of both systems are based on unpublished material. See also Popper & Ulrich (1977). No evaluation of realistic uncertainties of the parameters of these two systems is possible at present.

CONCLUDING REMARKS

The attempt has been made in this review to gather together our current knowledge of the masses of the components of detached binary systems when they can be determined with reasonable accuracy. An effort to provide realistic estimates of uncertainties of the tabulated parameters has also been made. A great deal of work is in progress on various aspects of binary star observation that will add significantly to the store of fundamental properties. The present compilation constitutes a progress report, subject to continuous revision. I am aware that the selection of data and their treatment reflect a personal point of view, and that other reviewers would make different selections.

In the tabulations in this review, those parameters of the stars derived directly from observations are distinguished from those that depend, in addition, on adopted scales of radiative parameters. In order to evaluate radii of visual binaries and luminosities of all the stars, it has been necessary to adopt scales of surface flux, bolometric correction, and effective temperature. Since the emphasis here is on masses, an exhaustive study of these scales has not been attempted. Many readers will have their own views of the appropriateness of the entries in Table 1. Values of the "scale dependent" parameters in the other tables can be adjusted accordingly.

Difficulties restricting the reliability with which the masses and other properties can be determined are discussed for each group of systems. It is to be expected that improved techniques in observation and analysis will lessen the effects of some of these difficulties, enabling knowledge of fundamental stellar properties to be placed on an improved basis. Comparison of the number of detached main-sequence eclipsing systems and the uncertainties of their properties (Table 2) with the corresponding quantities for visual binaries (Table 8), which furnish most of our data for main-sequence stars cooler than G0, shows that lower main-sequence masses are much less well known than masses of hotter main-sequence stars. As discussed in the section on visual binaries, major improvements in the techniques of parallax determination, in particular, are required before stars of the later types are on equal footing with the late B, A, and F stars insofar as masses are concerned.

Except for the white dwarfs, none of the stars in detached systems listed in Tables 2, 4, 7, and 8, including the giants in α Aur, departs from a single smooth mass-luminosity relation by an amount significantly greater than the uncertainties in the parameters. As in earlier listings, apparent outstanding exceptions to this statement in BFM, such as EO Aur, WX Cep, and VV Ori, have been shown (Popper 1978 and unpublished; Andersen 1976) to be based on misinterpretation of spectroscopic data. An additional apparent exception, HD208095, is under investigation.

The results listed in Tables 2, 4–9, and 11–13 can be displayed in a variety of two-dimensional diagrams with a variety of scales, and compared with predictions of a variety of theories. Examples of such comparisons are in Popper et al. (1970; interior composition), Lacy (1977b; interior models), and Popper & Ulrich (1977; evolutionary status). An approach that has been little used is to require, for a system with components of appreciably different mass, that the models predict, with the same composition and age, the radii and luminosities of *both* components to within the accuracy of the results derived from observation.

While models for single stars, appropriate for comparisons with observed results for components of detached binaries, may be in a reasonably satisfactory state, both theory and observation are much less satisfactory for semidetached systems (Tables 11–13), as emphasized in several contributions to IAU Symposium No. 88 on close binary stars: observation and interpretation, held in Toronto, Ontario, Canada in August 1979 (in press).

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