Mon. Not. R. astr. Soc. (1991) **250**, 209–214

A re-discussion of four early-type eclipsing binary systems

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Accepted 1990 December 21. Received 1990 December 18; in original form 1990 October 30

SUMMARY

We have begun to analyse the published photometric and spectroscopic data for early-type eclipsing binaries using the Wilson–Devinney code with the goal of providing a homogeneous set of data on the properties of high-mass stars. We advocate performing simultaneous multicolour light-curve solutions, so as to keep the number of adjusted parameters at a minimum. The weighting scheme in such solutions should be considered carefully. In this paper we analyse the data for the double-lined systems V1182 Aql, CW Cep, AG Per and TT Aur. We discuss previous solutions for these systems and point out likely sources of error.

1 INTRODUCTION

Most information on the absolute dimensions of early-type stars has come from light and radial velocity curves. Although high mass systems are relatively rare, papers on their masses and radii do exist in reasonable numbers, including reviews by Hilditch & Bell (1987), Popper (1980), Harmanec (1988) and Hutchings (1975). In all of these reviews, information was taken from a large variety of sources. Unfortunately, the literature contains analyses based on techniques whose basic assumptions undermine or even invalidate their application to certain systems. For example, the Wood (1971) and Russell & Merrill (1952) methods model the stars as ellipsoids which results in a code which runs significantly faster than equipotential models. For detached systems these methods can accurately model the figures of the stars. However, semi-detached and overcontact systems cannot be reliably modelled as ellipsoids. In recent years use of the Wilson–Devinney model (Wilson & Devinney 1971, hereafter WD and Wilson 1979) has increased such that it is now the most widely used program (*IAU Triennial Report* 1988). Because it is based on the Roche model rather than an ellipsoid model, the WD method is capable of handling systems of all morphological types in its various modes of operation (Leung & Wilson 1977). Therefore we have chosen to use the WD code for our analyses, although there are other codes available that could be reliably used such as the LIGHT program (Hill 1979).

We have undertaken analyses of the photometric and spectroscopic data for early-type systems to improve knowledge of their properties. This paper is the first in a series of reports on the progress of this ongoing project. In this paper we examine the light and radial velocity curves of V1182 Aql, CW Cep, AG Per and TT Aur with the WD code.

2 COMPUTATIONAL METHOD

All of the systems in this study are double-lined. The first step in each solution was to analyse the radial velocity data with the WD code, assuming the components to be point masses. For systems with circular orbits the adjusted parameters were $a \sin i$ [projected semi-major axis of the relative orbit, i.e. $(a_1 + a_2) \sin i$], q (mass ratio of secondary to primary), and V_γ (systematic velocity). For eccentric orbits the eccentricity (e) and the longitude of periastron (ω) were also adjusted. Because of the small number of parameters and the relatively small correlation among them, solutions of radial velocity curves converge very quickly, typically in three to four iterations. For well-detached systems, such as AG Per and CW Cep, the spectroscopy provides the most accurate estimate of the mass ratio and q was held fixed during the light curve solution. In semi-detached and overcontact systems, q can be reliably extracted from the light curve and both solutions with q adjusted and q fixed at the spectroscopic value were found. None of the systems studied showed significant differences between q_{sp} and q_{ph}.

Light curves in at least two pass-bands are available for each of these systems. In many published photometric solutions, light curves in different colours have been solved separately with the inconsistent result that wavelength-independent parameters, such as orbital inclination, are different for different wavelengths. The best estimate for the parameters in a least-squares solution comes not from a weighted mean of the separate solutions, but from a simultaneous solution of all of the available data (Wilson 1979; Van Hamme & Wilson 1984; Eichhorn 1990). In our solutions wavelength-independent parameters were constrained to be the same in all pass-bands. With *unweighted* simultaneous, multi-pass-band solutions the different corrector (DC) algorithm will pay most attention to the light curve with the most scatter, which is not what is desired. The WD code allows for a weighting of the light curves through the input variable SIGMA. The value of SIGMA for each light curve should be an estimate of the root-mean-square error of an observation in that pass-band. Often simultaneous solutions are published without mention of the relative weights. Clearly, such information is necessary to judge the validity of a solution. The WD code also allows for the weighting of the data points by light level through the variable NOISE, which is 1 for weights inversely proportional to the light level and 2 for weights inversely proportional to the square of the light level.

To avoid possible systematic errors, we have avoided the use of normal points in our solutions. We are presently studying the effects of using normal points and the results will be published elsewhere.

The WD code allows for non-synchronous rotation of the components in the input parameters F_1 and F_2 where F is defined as the ratio of the rotation angular speed to the average orbital angular speed. In a circular orbit case the proper value of F for synchronism is unity. For an eccentric orbit, however, the value of F for synchronism is not as obvious. Tidal forces should synchronize the rotation at periastron and F should be the ratio of the angular rotation speed at periastron to the average angular orbital speed. A little algebra shows that, for synchronism,

$$F=\frac{\sqrt{(1+e)/(1-e)}}{(1-e)},$$

where e is the orbital eccentricity.

In order to avoid weakening the solutions, we have held certain quantities fixed at their expected theoretical values. The bolometric albedo and the gravity darkening exponent for each component were held fixed at 1.0, as expected for stars with radiative envelopes. Limb darkening coefficients were estimated from the tables of Carbon & Gingerich (1969). Depending on the available data, the mean temperature of the primary was estimated from the spectral type or, preferably, the value of $(B-V)_0$ and the calibrations of Flower (1977).

To alleviate correlation problems the method of multiple subsets (Wilson & Biermann 1976) was used. The adjusted parameters were broken up into smaller subsets. For each iteration the corrections for one subset were applied until the corrections in the subsets for each parameter were an order of magnitude smaller than the probable errors computed from the main set of all adjusted parameters. Errors from our solutions are always given as probable errors.

3 THE INDIVIDUAL SYSTEMS

3.1 V1182 Aquilae

V1182 Aquilae (HD 175514, SAO 124049) has been the subject of photoelectric and spectroscopic investigations by Vitrichenko (1971) and Bell, Hilditch & Adamson (1987, hereafter BHA). Vitrichenko found the orbit to be slightly eccentric and estimated the mass ratio to be 0.38 based on the effect of the secondary's hydrogen lines on the composite hydrogen spectrum. Giuricin & Mardirossian (1981) analysed Vitrichenko's unfiltered light curve with the WINK program (Wood 1971) and found the system to be semi-detached with the primary filling its lobe. BHA, using the LIGHT program (Hill 1979) to analyse their extensive Strömgren four colour observations, concluded that the system was detached.

An analysis of the BHA radial velocities with the WD code resulted in a mass ratio of 0.34 ± 0.01 which is slightly different from the value of 0.36 ± 0.01 given by BHA, probably because of our inclusion of the proximity effects. The value of $a \sin i$ is $18.9 \pm 0.3\ R_\odot$ and the systemic velocity is $+6.8 \pm 2.4$ km s^{-1}.

The photometric analysis was done in mode 2 of the WD program, which is appropriate for a detached system. The vby observations of BHA were used for a simultaneous solution in three colours. The u data were not used due to the inability to model the Balmer jump accurately. The relative weighting of the three light curves was based on the root-mean-square errors given by BHA. For each curve the weights were inversely proportional to the light level (NOISE = 1) based on an empirical estimate of the variation of the scatter with light level. The temperature of the primary was set to 36 250 K from the calibration of spectral types given by Flower (1977). The photometric parameters are given in Table 1 and the absolute dimensions in Table 2. Fig. 1 shows the BHA data and the final light curve solutions, including the u light curve which shows the fitting problems. A considerable improvement in the residuals resulted when we adjust ϕ_0 (a phase shift for the entire light curve, formally the phase at which primary conjunction would occur if $\omega = 90°$) which supports the conclusion of BHA that

Table 1. Parameter values.

Parameter	V1182 Aql	CW Cep	AG Per	TT Aur
a	21.0 $R_\odot$ ± 0.3	23.25 $R_\odot$ ± 0.08	13.68 $R_\odot$ ± 0.07	11.2 $R_\odot$ ± 0.3
e	0.0	0.0377 ± 0.002	0.0528 ± 0.002	0.0
ω	---	70°.20 ± 1°.02	297°.07 ± 1°.03	---
F_1	1.0	1.079	1.113	1.0
F_2	1.0	1.079	1.113	1.0
ϕ_0	0.9974	0.0042	0.9997	0.9989
i	63°.84 ± 0°.09	82°.85 ± 0°.05	81°.36 ± 0°.26	86°.54 ± 0°.03
T_1	36,250 K	25,412 K	16,930 K	24,800 K
T_2	27,500 K ± 0 K	23,539 K ± 0 K	15,683 K ± 58 K	18,205 K ± 26 K
Ω_1	2.734 ± 0.003	5.010 ± 0.011	5.670 ± 0.012	3.759 ± 0.011
Ω_2	2.937 ± 0.010	6.246 ± 0.022	6.628 ± 0.032	3.115
q	0.34 ± 0.01	0.939 ± 0.006	0.910	0.628 ± 0.004
r_1(pole)	0.413±.001	0.246±.001	0.211±.001	0.316±.001
r_1(point)	0.478±.001	0.259±.001	0.218±.001	0.342±.002
r_1(side)	0.436±.001	0.250±.001	0.214±.001	0.325±.002
r_1(back)	0.453±.001	0.256±.001	0.217±.001	0.335±.002
r_2(pole)	0.209±.001	0.181±.001	0.164±.001	0.318±.001
r_2(point)	0.226±.002	0.184±.001	0.167±.001	0.452±.001
r_2(side)	0.213±.001	0.182±.001	0.165±.001	0.332±.001
r_2(back)	0.222±.002	0.184±.001	0.166±.001	0.364±.001
$L_1/(L_1+L_2)$	0.878 (v) 0.877 (b) 0.875 (y)	0.686 (B) 0.683 (V)	0.659 (B) 0.655 (V)	0.626 (B) 0.612 (V)

Table 2. Absolute dimensions.

Parameter	V1182 Aql	CW Cep	AG Per	TT Aur
M_1	35.5 $M_\odot$ ±1.8 $M_\odot$	11.7 $M_\odot$ ±0.1 $M_\odot$	4.53 $M_\odot$ ±0.08 $M_\odot$	6.6 $M_\odot$ ±0.6 $M_\odot$
M_2	12.1 $M_\odot$ ±0.6 $M_\odot$	11.0 $M_\odot$ ±0.1 $M_\odot$	4.12 $M_\odot$ ±0.08 $M_\odot$	4.2 $M_\odot$ ±0.3 $M_\odot$
R_1	9.16 $R_\odot$ ±0.13 $R_\odot$	5.86 $R_\odot$ ±0.5 $R_\odot$	2.96 $R_\odot$ ±0.02 $R_\odot$	3.66 $R_\odot$ ±0.1 $R_\odot$
R_2	4.53 $R_\odot$ ±0.06 $R_\odot$	4.28 $R_\odot$ ±0.3 $R_\odot$	2.28 $R_\odot$ ±0.02 $R_\odot$	3.84 $R_\odot$ ±0.1 $R_\odot$
log $L_1/L_\odot$	5.12	4.11	2.82	3.65
log $L_2/L_\odot$	4.03	3.71	2.46	3.17

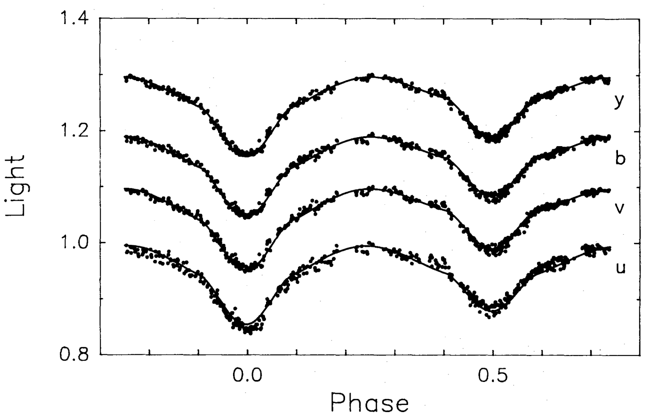

Figure 1. Strömgren *uvby* observations of V1182 Aql by BHA and the computed curves with the elements of Table 1. The *u* observations were not used in the solution for the photometric elements, but are plotted here to show the discrepancies that result from the inability to model the Balmer jump.

their ephemeris is somewhat uncertain. The final solution found $\phi_0 = 0.9974$.

There are some disagreements between our solution and that of BHA, notably in the inclination, the luminosity ratios, and the size of the secondary. They find $i = 61°.3 \pm 0°.2$ while our solution converged at $i = 63°.84 \pm 0°.09$. For a system which has such a low inclination, it is important that the inclination be determined as accurately as possible because of the sin i dependence of the absolute dimensions. Because of the rapid variation of sin i in this range, even small errors in i can have large effects on the absolute dimensions. We also find the secondary to be smaller and less luminous than given by BHA. Unfortunately, the estimation of the luminosity ratio from the relative strengths of He I λ4026 is too severely limited by the inherent errors to be reliable (BHA).

3.2 AG Persei

AG Per, a member of the ξ-Persei association, has been the subject of photoelectric studies by Güdür (1978) and Woodward & Koch (1987, hereafter WK). Popper (1974) thoroughly discussed his spectroscopic observations. The early observational history is discussed by Güdür. Because of their more complete phase coverage, we chose to analyse Güdür's yellow and blue observations. The mass ratio was held fixed at 0.91, the value given by Popper. To compute absolute dimensions we used Popper's spectroscopic solution.

Mode 2 of WD was employed for the photometric solution. Adjusted parameters were e, ω, ϕ_0, i, T_2, Ω_1, Ω_2 (surface potential of each component), L_1 (relative monochromatic luminosity of the primary), and l_3. For systems with $e \neq 0$, ϕ_0 should be included as an adjustable parameter because the phase of conjunction is difficult to determine from the times of minima. Convergence of ϕ_0 is usually very rapid and it can then be dropped from the set of adjusted parameters. The temperature of the primary was held fixed at 16 930 K based on the $(B-V)_0 = -0.18$ given by Popper (1974). The two light curves were weighted equally and we used NOISE = 2.

WK point out the necessity of accounting for the third light of the visual companion 1 arcsec away, which Güdür (1978) did not do in his solutions. Our solution converged on values of $l_3 = 0.10 \pm 0.02$ (in units of total system light, $l_1 + l_2 + l_3$, at phase 0.25) for both the B and V light curves, which is slightly less than the value that WK assumed. The only other major difference between our solution and those of WK is in the value of ω. We find $\omega = 297° \pm 1°.0$ while WK find $\omega = 288°$ but do not state the precision of their determination which makes a comparison somewhat difficult. Table 1 gives the photometric parameters and Table 2 the absolute dimensions. Fig. 2 shows the Güdür observations and the computed light curves.

3.3 CW Cephei

CW Cep (HD 218066) is a member of the III Cep association (Blaauw, Hiltner & Johnson 1959). Photoelectric observations and discussions of light curve solutions have been given by Abrami & Cester (1960), Nha (1975) and Söderhjelm (1976). The spectroscopic observations have been discussed by Popper (1974). The point-mass radial velocity solution by the WD code arrived at a value of $q = 0.934 \pm 0.006$, in excellent agreement with Popper, and it was held fixed during the light curve solution. The other spectroscopic parameters were $a \sin i = 23.07 \pm 0.08\ R_\odot$ and $V_\gamma = -13.85 \pm 0.63$ km s^{-1}.

The photometric solution of the Abrami & Cester data was done in mode 2, with NOISE = 2 and the yellow and blue curves weighted equally. The adjusted parameters were e, ω, ϕ_0, i, T_2, Ω_1, Ω_2 and L_1. The primary temperature, $T_1 = 25\,412$ K, was adopted based on the B0.5 V spectral

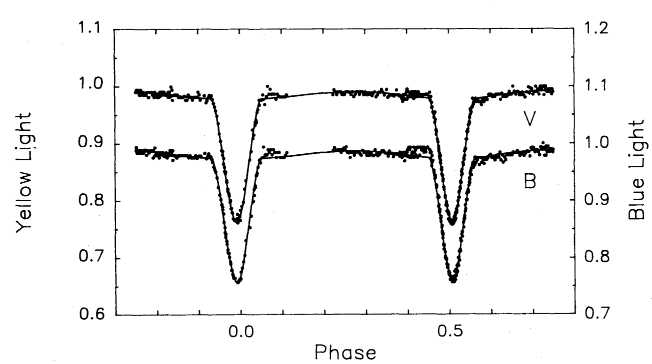

Figure 2. Comparison of the computed curves and the observations of AG Per by Güdür (1978).

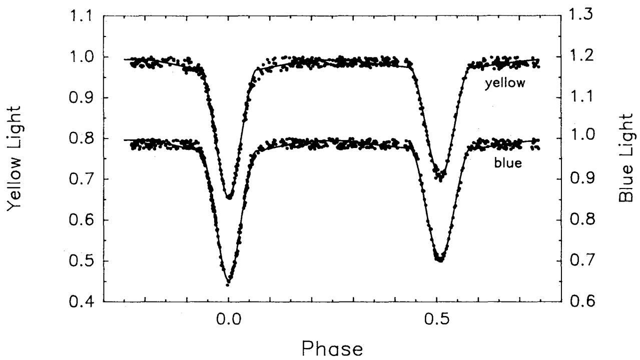

Figure 3. Abrami & Cester (1960) observations and the computed light curves for CW Cep.

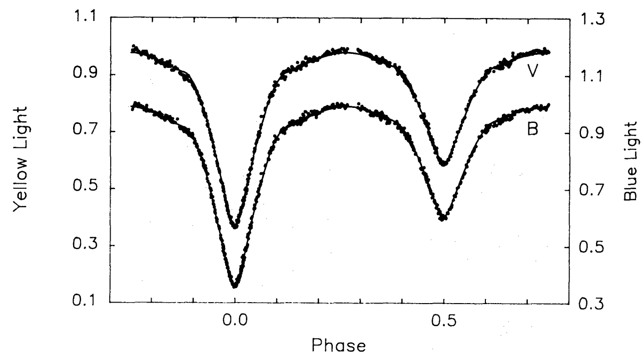

Figure 4. WPC observations of TT Aur along with the computed curves from the elements of Table 1.

type and Flower's (1977) calibrations. The model atmospheres option of the WD code was also used.

Söderhjelm (1976), constraining the luminosity ratio based on determinations of the Δm between the components given by Petrie (1950) and Rachkovskaya (1971), found significantly different values for the fundamental parameters of the system than those given by Nha (1975). Our solution is listed in Table 1, and the absolute dimensions are given in Table 2. Fig. 3 shows the Abrami & Cester data and the theoretical light curve. There seems to be too much ellipsoidal variation in the theoretical curve and numerous attempts to reduce it (adjusting the rotation rates and the gravity darkening exponents) failed to make any significant improvements. Inspection of the normal point light curves of Nha shows that there is more ellipsoidal variation in his observations than is apparent in the Abrami & Cester observations, which have considerable scatter between the eclipses. Söderhjelm's observations are too scarce between eclipses to resolve the disparity. One might surmise radial pulsations of the stars driven by the eccentric orbit, but such oscillations should show a θ variation rather than the 2θ variation required by the observations. CW Cephei is an extremely interesting and important system because of the eccentric orbit and the large relative radii of the two stars. Its rate of apsidal motion also provides for a determination of the internal structure parameter. This system warrants further photoelectric and spectroscopic (preferably simultaneous) studies.

3.4 TT Aurigae

TT Aur (HD 33088) has been the subject of photoelectric investigations by Kulkarni & Lokanadham (1978), Bell & Hilditch (1984, hereafter BH) and Wachmann, Popper & Clausen (1986, hereafter WPC). WPC discuss the most recent spectroscopic material. Recent light curve solutions based on these data sets are discussed by Giuricin, Mardirrossian & Mezzetti (1984, hereafter GMM) and Bell, Adamson & Hilditch (1987, hereafter BAH). We analysed the B and V data of WPC, adjusting i, T_2, Ω_1, q and L_1. The temperature of the primary was fixed at 24 800 K as estimated by WPC.

Previous investigators have agreed that TT Aur is a semi-detached system with the less-massive secondary filling its Roche lobe. There is, however, some uncertainty as to the mass ratio. From their spectroscopic observations, WPC find $q = 0.678$, and BAH find $q = 0.68$. A solution of the WPC data with the WD code, including proximity effects, resulted in $q = 0.62 \pm 0.04$. Both WPC and BAH discuss the possible blending effects, and when BAH make blending corrections they find $q = 0.645$. BH found that the best fit to their B light curve was achieved for $q = 0.614$. Since TT Aur is semi-detached, the photometric mass ratio is probably more reliable than the spectroscopic one because of the blending effects. Table 1 shows the results of the mode 5 solution (attempts to use mode 2 always found the secondary filling the lobe) of the WPC data, with NOISE = 1 and the two light curves weighted by $\sigma_B = 0.005$ and $\sigma_V = 0.008$. The mass ratio converged to 0.628 ± 0.004, which is in good agreement with our radial velocity solution. The absolute dimensions of the system are shown in Table 2. Fig. 4 shows the WPC observations and the theoretical light curves in B and V.

Another point of debate is which component is the larger one. BH and GMM find the more massive primary to be the larger star, while WPC find the secondary to be significantly larger. Inspection of the light curves of GMM show that their fit to the Kulkarni & Lokanadham (1978) data is not very good. Their inability to model the light curves adequately probably results from their adoption of Joy & Sitterly's (1931) mass ratio of 0.80 and from their application of Wood's (1971) model to a semi-detached system. The disagreement between WPC and BH lies in the difference of their adopted mass ratios. Our photometric solution shows that the secondary is larger than the primary, although not by nearly the amount that WPC find. In terms of the relative radii, we are in better agreement with BAH who find the secondary to be just slightly larger than the primary.

4 A PLEA FOR V348 CARINAE OBSERVATIONS

Recent photometric and spectroscopic work on V348 Carinae has been done by Hilditch & Lloyd Evans (1985). We tried to find a solution to their data on this potentially very massive system ($M_T \sim 70\ M_\odot$), but the data is not of sufficient quality for reliable results, as the minima of the eclipses are not very well defined. It is apparent from the light curve that the system is either overcontact or very close

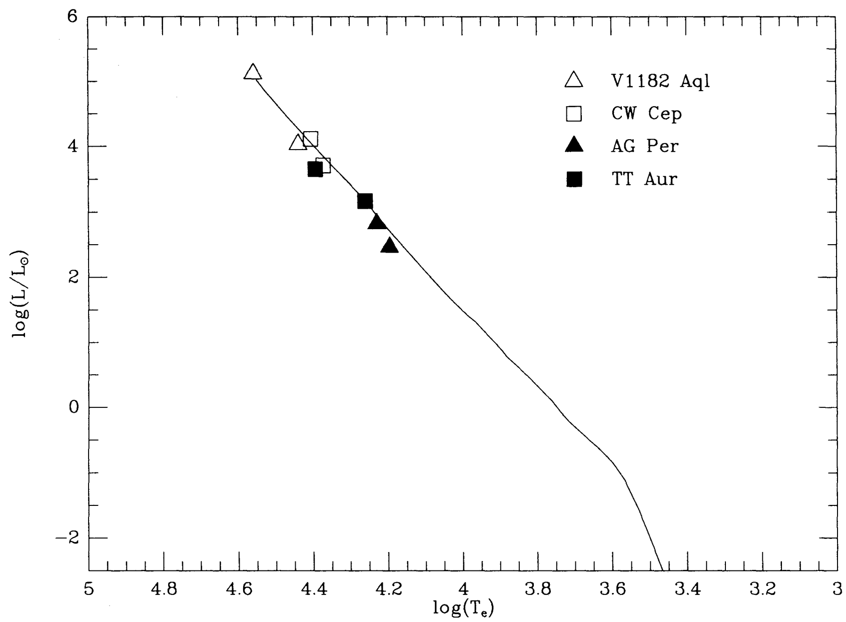

Figure 5. HR diagram showing the eight stars of this paper and the main sequence of Habets & Heintze (1981).

to being so, and therefore a reliable mass ratio could be estimated from a good set of photoelectric observations. This system is of particular interest because of its long period (5.6 d) and stars in *B*-type systems with periods greater than 5 d should evolve to core hydrogen exhaustion before reaching their limiting lobes.

5 CONCLUSIONS

We have analysed the available data for four early-type, double-lined eclipsing binaries with the Wilson–Devinney light/radial velocity curve synthesis program. V1182 Aql is found to have a smaller and less luminous secondary than previously believed. Improved values of the mass ratio and relative radii are found for TT Aur. For the well-detached systems AG Per and CW Cep, slight improvements in the absolute dimensions have been derived. Fig. 5 shows the location of the stars in the HR diagram along with the main sequence of Habets & Heintze (1981).

ACKNOWLEDGMENTS

The author would like to thank Dr R. E. Wilson for many helpful discussions concerning the systems in this paper. Earl McDow of Digital Equipment Corporation arranged for the loan of a DECStation 3100 on which many of the calculations of this paper were done.

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