OBSERVATIONS OF CLASSICAL CEPHEIDS

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Reviewing the observations of Cepheids, I feel like a man who is holding a wide-angle camera out of the window, in order to get a picture of the large and complex building in which he is living himself. You know what can be expected of such an attempt: at best a highly distorted picture, with aberrations that are closely related to the photographer's position. I will do my best to reach out of the window as far as I can, but please be aware of the distorted perspective! It is obviously not possible to get all sides of the building into one picture, so I will limit myself to the "classical" Cepheids, leaving out the W Virginis and RR Lyrae variables.

New observations

In Table 1 I have listed the most important observational studies of Cepheids that have been made in the last five years. Rather arbitrarily I let this compilation start in 1973, and I should add that this table does not pretend to be a complete list of *all* Cepheid observations since 1973: only the more extensive sets of new data are given.

' Two aspects of these recent observations are immediately clear: the concentration on photometry - both photoelectric and photographic - of the continuous spectra, and the emphasis on the southern hemisphere. Of course the Magellanic Clouds constantly draw our attention to the south, but also the southern galactic Cepheids have been observed extensively during the last few years. In fact, we have now reached the situation that the

Table 1. Important sets of new observations of classical Cepheids since 1973

AUTHORS	REFERENCES	REMARKS
R. Wielen	1974, A&A Suppl. 15, 1 (also: 1973, A&A 25, 285	Space velocities for 45 nearby Cepheids.
B.F. Madore	1975, Ap. J. Suppl. 29, 219 (also: 1976, M.N.R.A.S. 177, 215)	UBV for 22 LMC, 15 SMC, and 46 southern galactic Cepheids (P > 11^d).
E.G. Schmidt	1976, Ap. J. 203, 466	R,I and b,y for 14 field Cepheids and 9 in open clusters, also 34 giants in or near clusters.
C.J. Butler	1976, A&A Suppl. 24, 299	Photographic B,V for 72 SMC Cepheids.
J.W. Pel	1976, A&A Suppl. 24, 413 (also: 1978, A&A 62, 75 and Walraven et al. 1964 B.A.N. 17, 520)	VBLUW for 170 galactic Cepheids and 238 super-giants (δ < +15°).
E. Janot-Pacheco	1976, A&A Suppl. 25, 159	UVBGR for 13 southern Cepheids.
N.R. Evans	1976, Ap. J. Suppl. 32, 399 (also: 1976, Ap. J. 209, 135)	UBVR and v_{rad} for 15 Cepheids.
K.A. Feltz, D.H. McNamara	1976, P.A.S.P. 88, 699, 709	$uvby\beta$ and khg for B and A stars near 12 Cepheids.
J.F.Dean, A.W.J.Cousins, R.A. Bywater, P.R.Warren	1977, Mem. R.A.S. 83, 69 1977, M.N.A.S.S.A. 36, 3 and paper in preparation	BVI for 60 southern galactic Cepheids.
O.J. Eggen	1977, Ap. J. Suppl. 34, 1, 33	UBVRI for 10 SMC, 11 LMC, 5 galactic, and 6 glob. cluster Cepheids, 50 glob. cluster (sub)giants; $uvby\beta$ for associations of ℓ CAR and RS PUP.
A.M. van Genderen	1977, A&A 54, 737 (also: 1969, B.A.N. 20, 317)	VBLUW for 25 Cepheids in SMC.
L. Szabados	1977, Comm. Hungarian Acad. Sc. 70	UBV for 38 northern Cepheids (P < 5^d), more work for longer periods in progress.
C.J. Butler	1978, A&A Suppl. 32, 83	Photographic B,V for 98 LMC Cepheids (larger LMC material in preparation by Wayman and Stift).
W.L. Martin	work in progress at SAAO	Photographic B,V for large number of Cepheids in LMC

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Cepheids in the southern Milky Way have been observed more thoroughly than their northern counterparts!

Table 1 represents an enormous effort by many observers, and in half an hour it is impossible to do justice to the many new results that can be found in these papers. I will try to summarize the main progress that has been made, and point out some of the problems that still have to be solved.

Colour excesses

The first problem that one encounters in the study of the continuum colours of Cepheids is that of interstellar extinction. From the extensive literature and the continuing discussions on this subject it is clear that, at least in our own galaxy, this first step towards the temperature scale is by no means the easiest one.

Although the different methods of reddening determination have not yet converged to generally accepted colour excesses, some progress has been made during the last five years. We still find differences in zeropoint, in the sense that on the whole all colour excesses of method A may differ by a fixed amount from those of method B. But there used to exist also much more serious systematic discrepancies between different reddening scales, that depended on the periods, or on the amount of reddening. One important result of the more recent photometric studies is, that these latter effects have largely disappeared now.

This is demonstrated most clearly by the two new southern surveys with the largest overlap, the BVI program of the SAAO observers (Dean, Warren, Cousins, and collaborators), and my own photometry in the Walraven VBLUW system. These studies have about 60 Cepheids in common, over the whole range of periods. When we compare these two extensive sets of reddening values, we note only a small zeropoint difference: the VBLUW excesses, transformed to $E(B-V)_J$, are on the average about $0\overset{m}{.}05$ smaller than the colour excesses derived by Dean et al. in the BVI system. This zeropoint difference should not be taken too seriously, however, as it could be re-solved by taking slightly different reddenings for the Cepheids in clusters and associations that were used in both studies to define the zero-points of the intrinsic Cepheid colours. More important than this minor disagreement is the small r.m.s. scatter in the relation between both sets of reddenings ($\pm 0\overset{m}{.}03$), and in particular the absence of period-dependent

effects.

Both methods use passbands at about 5500 and 4300 Å, but the VBLUW method combines these with L at 3840 Å to construct an intrinsic Cepheid locus, while the BVI system uses I at 8100 Å. Considering the very large difference in line-blocking between the L and I regions, I find it most reassuring that both methods produce reddening results that agree very well, regardless of the periods of the Cepheids.

The overlap of the BVI and the VBLUW colour excesses with those derived from six-colour data by Parsons and Bell (1975) is limited, but the agreement between these three reddening scales seems satisfactory, with only small differences in zeropoint, and no signs of period-dependent effects. On the other hand, these three studies all differ significantly from the colour excesses used by Sandage and Tammann (1968) in their calibration of the P-L-C relation. The latter excesses are essentially in the Kraft system.

This situation confirms the trend towards smaller reddenings that has been apparent for some years already. Since the pioneering work by Kraft in the early sixties, several investigators have pointed out that the reddenings based on the original Kraft calibration were probably overestimated, particularly for the longer periods. Not only the three papers mentioned above, but also much other recent work supports smaller reddening values, e.g. Canavaggia et al. (1975), Feltz and McNamara (1976), Schmidt (1975).

Cepheids in clusters and associations

As indicated above, the zeropoint of the intrinsic colours of Cepheids ultimately rests upon the Cepheids in open clusters and associations. But even for these calibrating Cepheids the intrinsic colours and luminosities are not always as accurately known as one would like. This is partly due to the patchiness of interstellar extinction, partly to photometric inaccuracies. I expect therefore that a completely consistent system of absolute magnitudes and intrinsic colours for galactic Cepheids can only be established by doing more photometry of the open clusters and associations that contain Cepheids. Although a lot of work in this field has been done in the last few years, these few calibrating Cepheids are in so many respects a keystone in all studies of classical Cepheids, that new observ-

ational work on these objects is still fully justified. It would especial-
ly be valuable if some clusters could be re-observed with properly chosen
photometric systems that do not suffer from complications due to bandwidth
effects, and with reddening-free indices such as H_β; one obviously should
try to go as faint as possible on the main-sequence, in order to reduce
the uncertainty in the main-sequence fitting.

Schmidt (1976) has recently studied eight Cepheids in clusters with
R,I and Strömgren b,y photometry, but his observations do not cover the
cluster main-sequences. At the Leiden Southern Station we are working on
VBLUW photometry for clusters with Cepheids, but results are not yet
available. Eggen (1977) discusses uvbyβ photometry for the associations
that have been suggested as parent associations for the long-period
Cepheids ℓ CAR and RS PUP. Unfortunately, the observations by Eggen indi-
cate that these associations do not exist. This bad news is compensated
somewhat by the recent evidence for the membership of the 11-day Cepheid
TW NOR of the open cluster Lyngå 6 (Madore, 1975[a], 1975[b]; Van den Bergh
and Harris, 1976; Lyngå, 1977; Thé, 1977). Van den Bergh (1977) gives a
list of 14 cluster/association Cepheids. For this list he rejects as less
reliable the Cepheids in binaries (ℓ CAR, Polaris) and in reflection nebu-
lae (SU CAS, RS PUP), and the four Cepheids that are thought to be members
of h+χ PER (UY PER, VY PER, VX PER, SZ CAS). On the other hand, a number
of new cluster/association members appear in this table that were not
among the well-known 13 of Sandage and Tammann (1969): V367 SCT, CS VEL,
CV MON, T MON, TW NOR, VY CAR, SV VUL (for references see Van den Bergh,
1977).

The case of V367 SCT is particularly important, as this Cepheid is a
double-mode pulsator (Efremov and Kholopov, 1975; Madore and Van den Bergh,
1975; Madore et al., 1978). As the only known double-mode cluster Cepheid,
this star is very valuable in view of the well-known mass problems that
exist for Cepheids in general and for beat-Cepheids in particular. Stobie
(1977) shows that the pulsation mass derived for V367 SCT is consistent
with the pulsation masses for other cluster Cepheids, but that it leads
again to discrepancies with the evolutionary and double-mode mass esti-
mates.

Compared to the 13 Cepheids of Sandage and Tammann, the longer periods
may be represented slightly better in Van den Bergh's list, but the fact

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remains that we still have only a very small number of calibrating Cepheids at our disposal. This stresses once more: 1) that we should observe these Cepheids and their parent clusters as accurately as possible, 2) that the reliability of the dubious cluster/association Cepheids should be checked with additional observations (radial velocities and/or proper motions!), 3) that the search for new calibrating Cepheids should continue. Considering the fact that most massive stars are probably formed in associations, it is surprising how few long-period Cepheids have been found to be association members. This probably just means that our methods to detect such cases have not been very efficient.

Duplicity among Cepheids

A problem that has become somewhat prominent only relatively recently is that of duplicity among Cepheids. Since the early value by Abt (1959), who estimated that about 2% of the Cepheids are in binaries, the numbers have gone up considerably. Lloyd Evans (1968) estimates $\geq$ 15% for the binary percentage, while Janot-Pacheco (1976), Madore (1977) and Pel (1978) give values around 25%. As is shown by Madore (1977) it may be possible in many cases to correct for the presence of the companion, but this needs either rather detailed information about the observed composite energy distribution, or a priori assumptions. In any case we should keep in mind that part of the scatter in our empirical relations for Cepheids will be due to duplicity.

The existence of binary Cepheids also has its positive aspects: they are interesting from the point of view of stellar evolution, and, provided that detailed information can be obtained for the companions, they can even yield independent mass and luminosity estimates for the Cepheids.

As the binary companions of Cepheids are likely to be bluer than the Cepheids in most cases, their contribution to the combined colours will usually become smaller towards longer wavelengths. This is one advantage of photometry in the red part of the spectrum.

Ultraviolet colours

The red part of the spectrum has other advantages too: less line-blocking, less interstellar reddening, and good separation of temperature effects and interstellar reddening. Indeed we see that compared to the

"UBV-era" of ten, fifteen years ago, an increasing amount of Cepheid photometry is being done in the R and I bands. On the other hand, if we abandon the complex blue and ultraviolet part of the Cepheid spectrum altogether in favour of spectral regions that behave more like black-body radiation, the only photospheric parameter that we can determine is the effective temperature. Information on other physical parameters such as surface gravity and chemical composition is of course obtained best from those parts of the spectrum that deviate most from Planck's law. In this particular case this means that if we want photometric effective gravities for Cepheids, we need at least one passband shortward of the Balmer jump. One naturally thinks of the UBV U-band, and of the large body of UBV data that has been collected over the years.

The interpretation of (U-B) colours of Cepheids has always been problematic, however, due to complications with the U band that arise mainly from its great width and from the fact that the red flank of U extends slightly beyond the Balmer jump. It is therefore worthwhile to investigate whether the wealth of new photometric data that is now available (mostly in other systems than UBV) could possibly help us to solve the old problems with the UBV U-band.

To give you the answer right away: I am pessimistic in this respect! Let me make this clear in the following figure (Fig. 1), which shows a comparison of (U-B) with the three ultraviolet colours of the VBLUW photometry. The UBV data used here are from Wampler et al. (1961) and from Cousins and Lagerweij (1968).

In the region of the UBV U-band the Walraven system has three bands: one (L, with λ_{eff} at 3840 Å) just longward of the Balmer jump in the region of the higher Balmer lines, and two bands in the Balmer continuum (U at 3630 Å, and W at 3255 Å). Going across the Balmer jump from L to U and W, we note a drastic change in the temperature and gravity dependence of the colours. For F-G supergiants of a given composition, (B-L) is almost exclusively temperature-sensitive (the VBLUW and UBV B-bands are very similar), while (B-U) and (U-W) – Balmer jump and slope of the Balmer continuum, respectively – depend mostly on gravity. This explains the very different behaviour of these three colours during the Cepheid cycle.

Comparing the VBLUW data now with (U-B)$_{UBV}$, we see that the (U-B)$_{UBV}$ curves are nearly identical with (B-L)! This means that the integral over
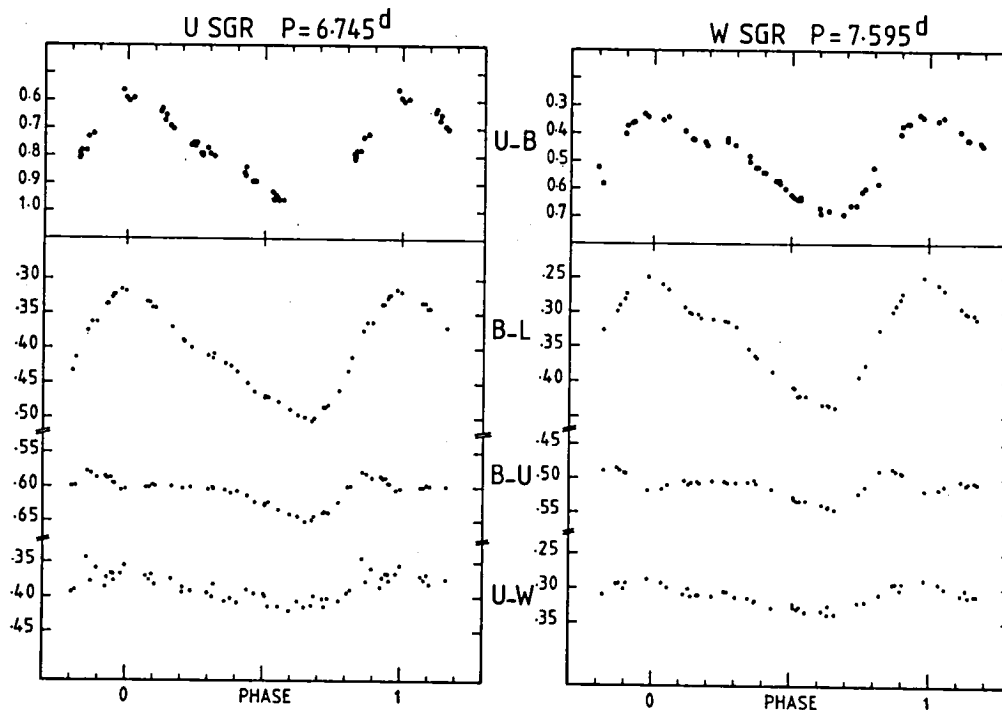
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Fig. 1. Cepheid colour curves in the ultraviolet colours (B-L), (B-U) and (U-W) of the VBLUW system compared with the UBV (U-B)-curves. The $\log_{10}$(intensity) scale of the VBLUW data has been adjusted to the UBV magnitude scale.

the U_{UBV} band is completely dominated by the flux in the long-wavelength tail, just longward of the Balmer jump. So for Cepheids and supergiants later than type A, this band, which was originally meant to give information about the Balmer jump, effectively is still in the Paschen continuum. This is quite understandable if we realize how steep the intensity drops below the Balmer jump for these cooler supergiants, but it makes $(U-B)_{UBV}$ practically useless as source of physical information for these stars. Even if we would solve the photometric complications caused by the varying effective wavelength of U_{UBV}, and the systematic differences between observers due to slightly different red wings of various U-filters, the contribution of log g in (U-B) could hardly be disentangled from the dominating temperature sensitivity.

I discuss this problem in some detail in order to underline a more general warning, both to future observers of Cepheids and to theorists who

compute light and colour curves for hydrodynamic Cepheid models: 1^O take care to use passbands with accurately known response curves, that fit well to the main features in the stellar spectra, and 2^O beware of the Balmer jump!

Temperature-colour relations, mass discrepancies

In Fig. 2 I have collected most of the temperature-colour relations that exist in the literature for Cepheids and intermediate to late-type supergiants. These relations have been obtained with widely different methods, and I will not go into any of the details of these, but it is striking that at both ends of the colour range the general agreement in temperature is quite reasonable, while in between there exist large differences. Around $(B-V)_o = 0\overset{m}{.}9$ the temperature estimates for class I supergiants may differ by as much as 800 K! Even for Cepheids, which form a much more sharply defined subgroup of supergiants, the differences between various authors are surprisingly large.

These differences are probably mostly due to uncertainties in the temperature calibrations, but partly also to the problems with colour excesses and intrinsic colours that we discussed before. It should be noted that the problem of interstellar extinction may enter the temperature determination for a Cepheid even twice. Firstly, the calibration of a temperature-colour relation often implies reddening corrections for one or more calibrating stars. Secondly, the reddening correction that we apply to a Cepheid determines where this star will lie on the temperature-colour relation.

Up to now I assume implicitly that there exists a unique relation between $(B-V)_o$ and T_{eff} for Cepheids, but some authors have questioned this uniqueness. Schmidt has pointed out in several papers (e.g. Schmidt, 1973) that $(B-V)_o$ may not be a good temperature indicator, and for this reason he has advocated the use of $(R-I)_o$. Schmidt's arguments against $(B-V)_o$ are supported qualitatively by my own temperature determinations for Cepheids, but quantitatively I find the non-uniqueness of the $T_{eff} - (B-V)_o$ relation less severe than suggested by Schmidt. This is illustrated in Fig. 3.

The effective temperatures and gravities for Cepheids that I derived from the VBLUW photometry are based upon a calibration of the VBLUW
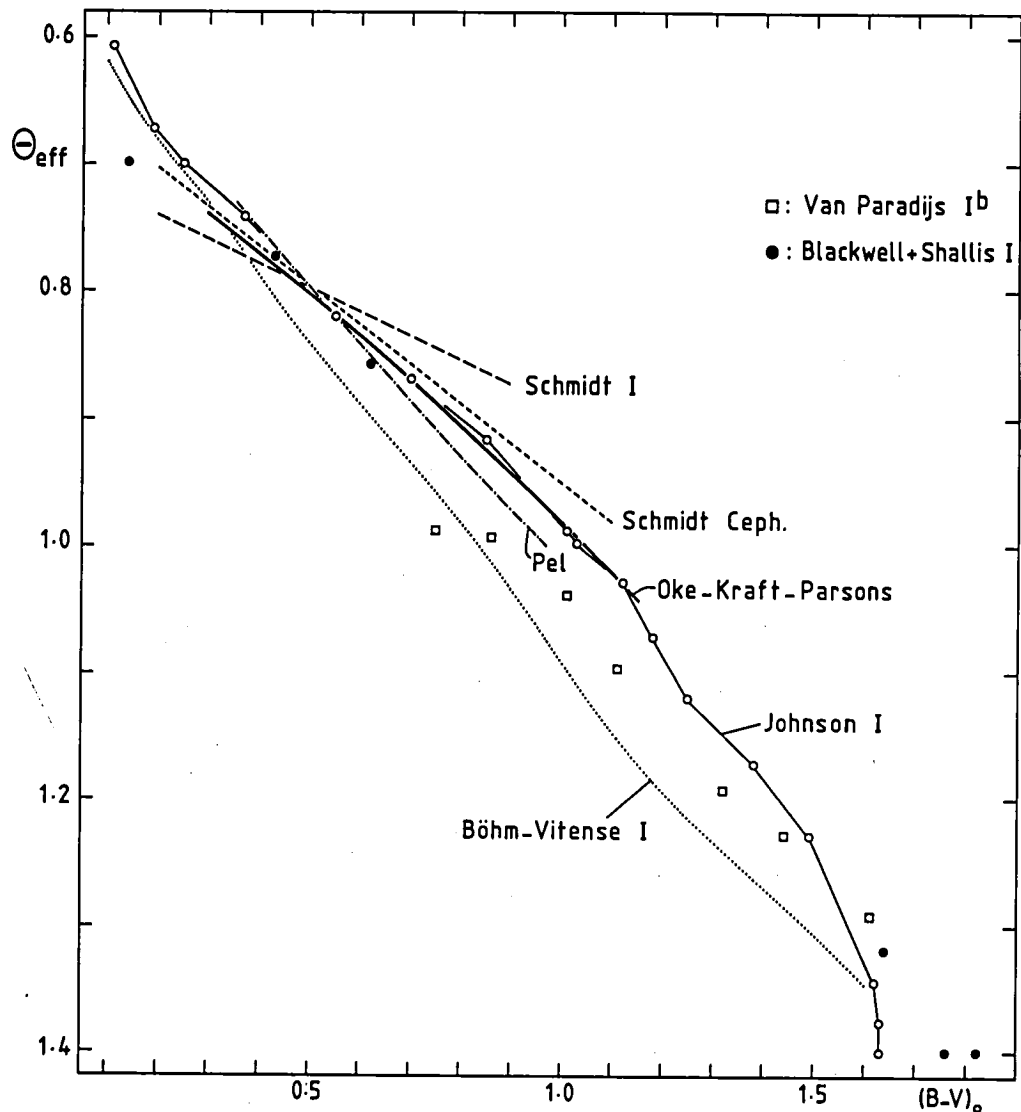
Fig. 2. Temperature-colour relations for Cepheids and supergiants.

Class I supergiants:

Johnson I	: Johnson (1966).
Böhm-Vitense I	: Average for I^a and I^b supergiants from Böhm-Vitense (1972).
Schmidt I	: Schmidt (1972).
Van Paradijs I^b	: 7 individual I^b supergiants. Van Paradijs (1973).
Blackwell + Shallis I	: 6 individual class I supergiants from Blackwell and Shallis (1977). For one star (δ CMa, at $(B-V)_o = 0.62$) E(B-V) was derived from VBLUW data, the other stars are within 200 pc, and small corrections were made according to $E(B-V) = 0^m3$ kpc^{-1}.

Cepheids:

Oke-Kraft-Parsons	: Oke (1961); Kraft (1961); Parsons (1971, 1974).
Schmidt Ceph.	: Schmidt (1972).
Pel	: average relation derived from Pel (1978).

The relation by Rodgers (1970) is not shown separately, as it lies very close to the Oke-Kraft-Parsons relation.
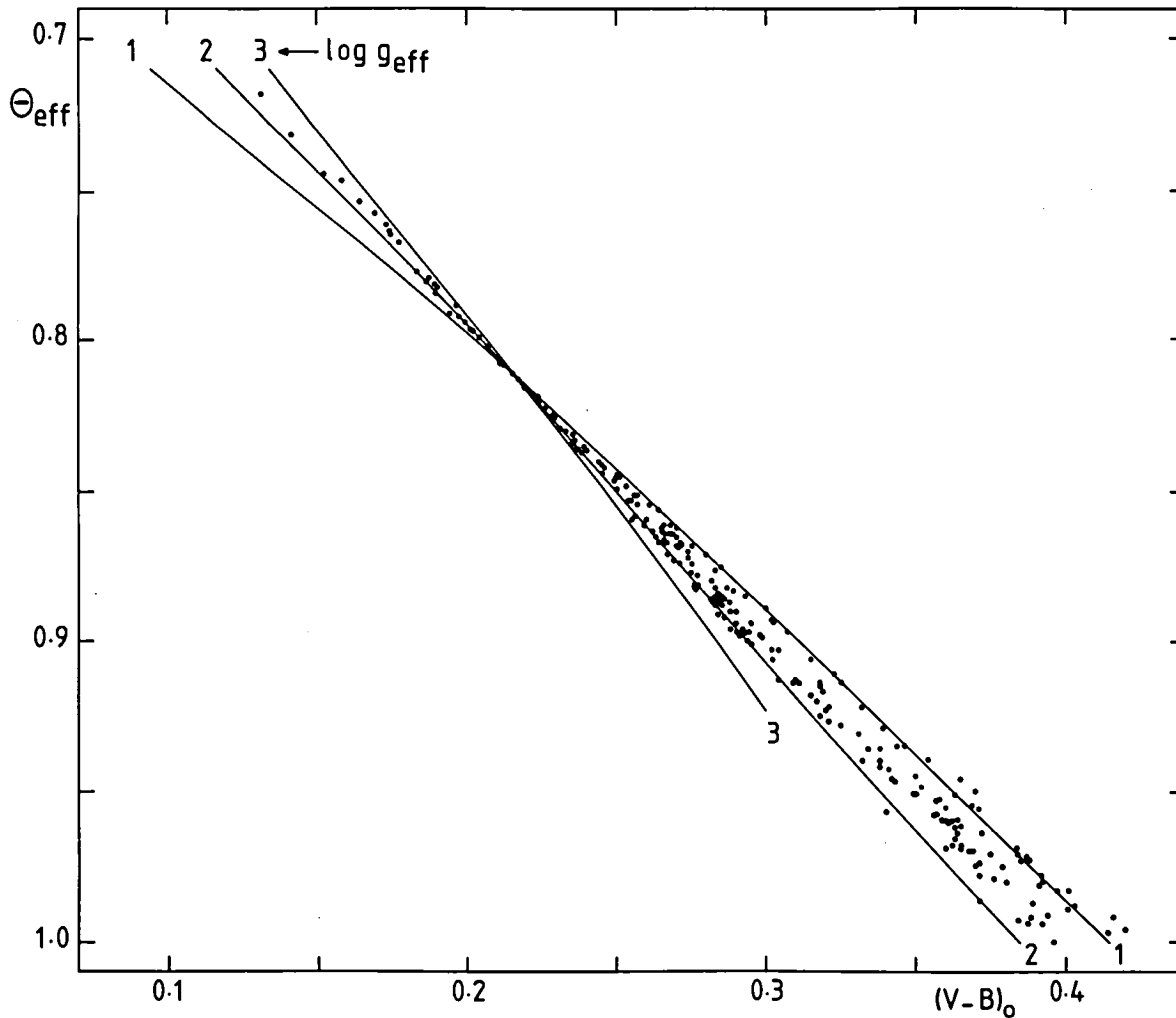
Fig. 3. Theoretical temperature-colour relations for $(V-B)_o$ (in $\log_{10}$ units) of the VBLUW system, for three different values of the effective gravity. The dots are the individual measurements for 10 bright Cepheids.

colours (Lub and Pel, 1977) by means of the model atmosphere fluxes of Kurucz (1975, 1978). These theoretical fluxes are for hydrostatic, plane-parallel atmospheres in LTE, but they include the blanketing by nearly one million atomic lines by means of opacity distribution functions. Fig. 3 gives the theoretical relations between inverse effective temperature and $(V-B)_o$ for different values of surface gravity. $(V-B)_o$ is the VBLUW equivalent of $(B-V)_o$ in the UBV system. The plotted points are the individual measurements for ten bright Cepheids that cover the whole range of periods. The theoretical colours do not cover the minima of the long-period

Cepheids completely, so points cooler than $\Theta = 1$ have been omitted. The divergence for different gravities at the cool end in Fig. 3 is clear, but the spread around the mean temperature-colour relation for Cepheids is not too disturbing. Near $(V-B)_o = 0.4$ the detailed temperature determinations scatter around the mean relation by $\pm$ 75 K at most. To make the comparison with other relations in Fig. 2, I adopted the following mean temperature-colour relation (V-B in $\log_{10}$ units):

$$\Theta_{eff} = 0.552 + 1.331(V-B)_o - 0.582(V-B)_o^2$$

The transformation of this relation into $(B-V)_o$ is probably slightly gravity-dependent, but this uncertainty can be neglected for the present purpose.

The temperature scale for Cepheids automatically leads us to the well-known "mass-discrepancy" problem. Since the various kinds of Cepheid mass-discrepancies appeared in the literature, around 1970, a very large number of papers have dealt with the problem of Cepheid masses. In fact, the mass-discrepancies are responsible for a considerable part of the recent revival in Cepheid research. However, as the subject will be discussed in detail in the next session of this meeting, I will make a few short remarks only.

There are several ways of estimating Cepheid masses: "pulsation masses" M_{puls} (from the pulsation equation for Cepheids with known luminosities and temperatures), "bump masses" M_{bump} (from non-linear Cepheid models and observed phases of bumps in light- and velocity-curves), and "double-mode masses" M_{beat} (from period ratios of mixed-mode pulsators). As is well-known, each of these masses usually turns out to be smaller than evolutionary masses M_{ev}, derived from evolutionary tracks (for more detailed discussions see e.g. Fricke et al., 1972; Iben and Tuggle, 1972[a]; Cox et al., 1977; Stobie, 1977).

The temperature scale has no effect on M_{bump}, M_{beat} and M_{ev}, but M_{puls} depends strongly on the temperature ($P \propto L^{0.83}.M^{-0.66}.T_{eff}^{-3.45}$, see Iben and Tuggle, 1972[b]). As I pointed out at the Russell Symposium last year (Pel and Lub, 1978), it is possible to remove most of the discrepancy between M_{ev} and M_{puls} if we adjust the luminosities of Cepheids to the revised distance of the Hyades, and use the new smaller colour excesses and
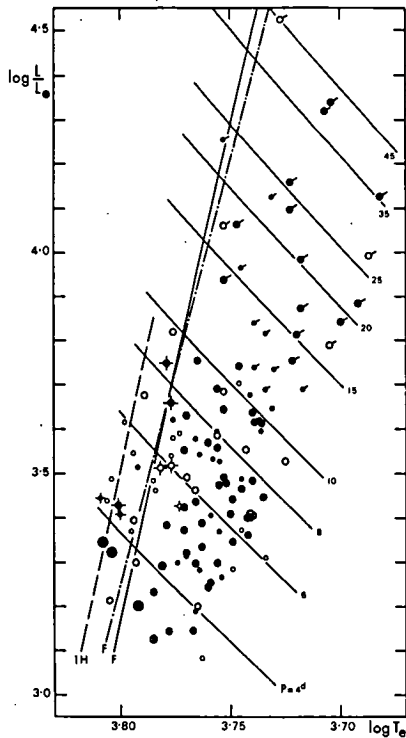
Fig. 4. Cepheids from the VBLUW survey in the HR-diagram. Luminosities were computed from the observed periods and temperatures, the pulsation equation, and a mass-luminosity relation for Cepheids (both relations taken from Iben and Tuggle, 1975). The composite fundamental ("F", full curve) and first harmonic ("1H", dashed) blue edges from Iben and Tuggle are given, as well as the fundamental blue edge ("F, dot-dash) from King et al. (1975); all for Y = 0.28, Z = 0.02, and the M-L relation of Iben and Tuggle (1975).
Open symbols: stars with known or suspected companions; ✔ : long-period Cepheids for which the equilibrium temperature was computed from appropriate time-averages of the observed colours; ⊙ : double-mode Cepheids; ✛ : likely overtone pulsators, plotted at the position corresponding to P_o.

lower temperatures from the VBLUW survey. The change in the adopted temperatures is the most important factor here. Not only are the VBLUW temperatures lower than most previous temperature scales (particularly that of Schmidt), but the difference increases for longer periods. This is just what we need to remove the increase of $(M_{ev} - M_{puls})$ towards longer periods.

When adjustments are made to the luminosities and temperatures of Cepheids, we should check of course whether this does not create a new discrepancy between the observed and theoretical blue edges in the HR-diagram. Of the several ways of locating a Cepheid in the theoretical HR-diagram, I have chosen the following. Assuming that the Cepheid masses are consistent with evolutionary masses, we can adopt a Cepheid mass-luminosity relation from evolution theory (e.g. the M-L relation from Iben and Tuggle, 1975) to eliminate M from the pulsation equation. With known period and temperature we can then solve for the luminosity, which fixes the Cepheid's position in the HR-diagram. The result is shown in Fig. 4 (see also: Pel and Lub, 1978). The agreement of the distribution of the observed Cepheids with the theoretical blue edges of Iben and Tuggle (1975) and King et al. (1975) is very satisfactory. Of the 14 stars that lie to the left of the fundamental blue

edge, 7 are suspected to have blue companions, 2 are double-mode Cepheids, and 4 may be overtone pulsators (I will come back to these later).

It seems therefore that we may solve the general Cepheid mass problem from the observational side, by properly calibrating the observed data in terms of luminosity and effective temperature. We are stil left, however, with two other mass discrepancies where little can be done observationally: in both cases the important observables are rather well established numbers (a period and a phase for M_{bump}, and two periods for M_{beat}).

Cox et al. (1977) have recently proposed inhomogeneous envelope models with helium-enriched surface layers as a way to solve both the M_{bump} and the M_{beat} mass anomalies. In a subsequent paper, Cox et al. (1978) discuss Cepheid winds as a mechanism that can produce the high helium abundance ($Y \sim 0.75!$) that is needed in the hydrogen and helium ionization zones to change M_{beat} and M_{bump} in the right direction (upwards). A very attractive aspect of this idea is that two mass problems may be solved at once, but there are problems too, as the authors of the theory point out themselves (e.g. instability of heavy helium layers on top of layers with normal composition). Although it is not easy to determine the abundance of helium in the spectra of cool supergiants, it is obviously very important that the observers try to check whether a Y-value as high as 0.75 is consistent with spectroscopic evidence.

There is one observational remark that I would like to make about the bump Cepheids. It is often stated that the bump phenomenon disappears around periods of 17 days, but I think that this statement is mainly based on photometry that is not complete or accurate enough to show sufficient detail. Not only are the bumps for 17 and 18 days Cepheids often very pronounced, but there clearly exist bumps at longer periods as well, with phases that fit to the Herzsprung sequence. Good examples from the VBLUW survey are: RZ VEL ($20^d.4$), WZ SGR ($21^d.8$), WZ CAR ($23^d.0$), VZ PUP ($23^d.2$), RY VEL ($28^d.1$). Even at the longest periods one finds signs of bumps, which start climbing the descending branch of the lightcurve again. I mention this point, as the existence of long-period bump-Cepheids is relevant to the theory of surface helium enrichment by Cepheid winds (no significant He-enrichment can be obtained above 8 $M_\odot$, so more massive Cepheids with bumps may still be a problem), and also to the identification of bumps with resonances between fundamental and second overtone (Simon and Schmidt,

1976; Simon, 1977).

Radial velocity studies and radius determinations

Up to now I have been discussing mainly photometric results, as most observational work on Cepheids of the last five years has been photometric. There are, however, a number of important studies on radial velocity curves that have appeared since 1973. The only reason that I included only one of these in Table 1 is, that most discussions of Cepheid radial velocity curves are based on velocity data that have been in the literature for quite some time already.

When discussing radial velocity curves, we all think of the Baade-Wesselink method to obtain Cepheid radii. The virtues of this method are well known: by combining radial velocity curves with photometric light- and colour-curves we can in principle obtain all basic parameters of a Cepheid without needing direct distance information. The method has its problems too, as is equally well-known. Evans (1976) has analyzed in detail the effects of many different observational errors on the Wesselink radius solutions, and her results are not too reassuring about the accuracy that can be obtained. To quote some examples: an uncertainty of 1 km s^{-1} in the γ-velocity can cause a 10% error in R; a change of only $0^m.01$ in the descending branch of a colour-curve results even in 15% radius error.

Several authors have tried to avoid some of these problems by modifications of the original Baade-Wesselink method. Balona (1977) has applied a maximum likelihood method to solve R from observed V,(B-V) and radial velocity curves for 54 well-observed Cepheids. This work was not listed in Table 1, but I should mention that it is partly based on new radial velocity observations by Lloyd Evans, which are however not published.

A very interesting method to determine Cepheid radii and distances has been applied by Barnes et al. (1977). Instead of deriving the surface brightness F_v from $(B-V)_o$, as Wesselink did (Wesselink, 1969), they use the linear relation between $(V-R)_o$ and F_v discovered by Barnes and Evans (1976). As they point out, the method is nearly independent of interstellar extinction. The scatter in some of the resulting radius curves is large, mainly due to insufficient accuracy of the photometry, but there is no reason why this should not be improved. The method has clearly great potential value, as it yields radii and distances in a straightforward way,

avoiding some of the problems related to the calibration of Cepheid luminosities.

Once the radius of a pulsating star is known, we can fix its mass from the period and the pulsation relation. This gives us again a mass estimate which can be compared with the various other mass determinations. Dr. A.N. Cox has just completed a comparison in this context of the radius determinations by Balona, Evans, and Barnes et al. As he will discuss his results in the next session of this conference, I will not go into this aspect of Cepheid radii here.

One problem that all Baade-Wesselink and related radius determinations have in common, is the necessity of accurate phase-matching between light- and radial velocity curves. This phase-matching is of course done most accurately by simultaneous photometric and spectroscopic observations, but here one is hampered by the fact that spectroscopic observations are usually so much slower than photometry. The situation would improve considerably if more Griffin-type radial velocity machines would become available. Dr. Balona informed me that at the SAAO the Griffin technique is presently being used for radial velocity measurements of pulsating stars while photometry is carried out simultaneously. If sufficient observing time is available for this work, we may soon have accurate radius curves for many more Cepheids.

The Magellanic Clouds

Let me finally say a few words about the nearest extragalactic Cepheids. Compared to the problems with distance and interstellar extinction for Cepheids in our own galaxy, the Magellanic Cepheids have the great advantage of being at essentially the same distance and of much less interstellar reddening. But this is where the advantages stop: in all other respects the observers have to struggle with the faintness of most Cepheids in the clouds, and with the problems of crowding. Although progress has been made through the large amount of photometry that has become available in the last few years, we are still far from a clear picture about the basic parameters of the Magellanic Cepheids, and there is probably much more hard work needed before we can solve some of the most frustrating uncertainties.

The discussions of Magellanic Cloud Cepheids concentrate mostly on comparisons of the P-L-C, P-L and P-C relations in the clouds and in the

galaxy. There is no time to discuss the many determinations of these rela-
tions in any detail, but let me give some representative numbers to give
an impression about the present state of affairs. The coefficient of the
colour term in the empirical P-L-C relation is still very uncertain, both
in the clouds and in the galaxy. According to Feast (1977) the work by
Martin on the LMC indicates a value in the range of 1.5 to 3.5. Assuming a
mean value of this coefficient of 2.52, Feast lists a number of recent de-
terminations for the log P coefficient in the P-L-C relation. These range
between 3.4 and 4.0 (values for the clouds and the galaxy). Again quoting
Feast, the slope of the P-L relation ranges from 2.3 (for the galaxy, from
Balona's work) to 3.1 (Gascoigne, for the LMC). It is obviously unfair to
compare numbers in this manner, without discussing the details, but this
gives at least some idea about the level of accuracy that we have to con-
sider.

One problem that has become more and more outstanding during the last
few years, is that of possible composition differences between LMC, SMC
and the galaxy. As Gascoigne has pointed out (1974), a difference in metal
abundance may have a noticeable effect on the luminosity that we derive for
a Cepheid. I expect that the VBLUW photometry of cloud Cepheids by Van
Genderen may provide important clues here, as the VBLUW system allows a very
interesting way of estimating metallicity that is largely independent of
temperature, gravity and reddening (see Pel and Lub, 1978). Unfortunately
the method works best for the maxima of the short-period Cepheids, which
means that very long integrations on faint stars are needed.

Another subject where conflicting results have been given recently, is
that of pulsation amplitudes. From photometry in the clouds both Yakimova
(1973) and Madore (1976[b]) find the Cepheids with largest light- and
colour-amplitudes on the cool side of the instability strip, while Butler
(1976[b]) finds a small effect in the opposite direction. The behaviour of
the pulsation amplitude in the instabilaty strip is important as amplitude
may be a useful extra parameter to locate a Cepheid in the HR-diagram
(Kraft, 1960; Sandage and Tammann, 1971), and furthermore because the
amplitude may provide information about the mode of pulsation.

In relation to this problem I would like to mention a result that I ob-
tained recently from the VBLUW data of galactic Cepheids (see also Pel and
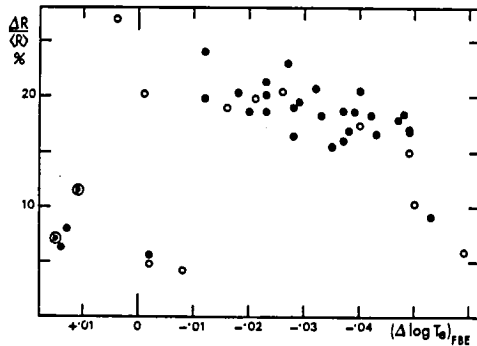Lub, 1978). This is shown in Fig. 5. Here I have plotted the photometric

Fig. 5. The behaviour of radius amplitude across the instability strip. The amplitudes of the radius curves ($\Delta R/\langle R\rangle$) are derived from the VBLUW photometry of galactic Cepheids. Symbols as in Fig. 4. $(\Delta \log T_e)_{FBE}$ is the distance in effective temperature at constant L from the fundamental blue edge (Y = 0.28, Z = 0.02) of Iben and Tuggle (1975). Note the increase in amplitude towards the blue edge, and the discontinuity at the blue edge ($\Delta \log T_e = 0$).

radius amplitudes of the bright Cepheids in the interval $3.24 < \log L/L_\odot < 3.60$ as a function of distance in temperature to the fundamental blue edge of Iben and Tuggle (1975), with $\Delta \log T_e$ measured at constant luminosity (see Fig. 4). In Fig. 5 we note an increase in amplitude towards the blue edge, and then a discontinuity to a small group of hot stars with small amplitudes. Two of these are double-mode Cepheids, I suspect that the others are overtone pulsators. The diagram reminds very much of the behaviour of type-ab and type-c RR Lyrae stars. The overtone candidates in Fig. 5 all belong to the class of Cepheids with symmetric, small-amplitude lightcurves that are sometimes called "s-Cepheids", and which have often been thought to be first-harmonic pulsators (e.g. Ivanov and Nikolov, 1976). From Fig. 5 we can draw three conclusions: 1) amplitude is not a very suitable parameter to locate a Cepheid inside the strip, 2) the double-mode Cepheids are found near the blue edge, and may be related to the fundamental-overtone transition, 3) this result for galactic Cepheids supports the result of Butler for the Magellanic Clouds.

Coming back to the extragalactic Cepheids now, you have noticed that I scetched the situation in the Magellanic Clouds as still rather unsatisfactory, and it is clear that for Cepheids in other galaxies, at even greater distances, the observational problems will even become worse. Many extragalactic Cepheids have been observed only once, and I am sure that we will run into discrepancies as soon as these stars are re-observed with slightly different methods.

These observational uncertainties may look rather disturbing, but on the other hand I am optimistic. We know more about Cepheids than about most other types of stars. There is probably no other field in stellar astronomy

where theory and observation touch in so many details, and where both sides are bound by so many consistency requirements. If we just keep trying to get all pieces of this chinese puzzle together, we may eventually be rewarded by an extremely rigid framework of distances and basic stellar parameters.

References

Abt, H.A.: 1959, Astrophys. J. 130, 769

Balona, L.A.: 1977, Monthly Notices Roy. Astron. Soc. 178, 231

Barnes, T.G., Evans, D.S.: 1976, Monthly Notices Roy. Astron. Soc. 174, 489

Barnes, T.G., Dominy, J.F., Evans, D.S., Kelton, P.W., Parsons, S.B., Stover, R.J.: 1977, Monthly Notices Roy. Astron. Soc. 178, 661

Blackwell, D.E., Shallis, M.J.: 1977, Monthly Notices Roy. Astron. Soc. 180, 177

Böhm-Vitense, E.: 1972, Astron. Astrophys. 17, 335

Butler, C.J.: 1976[a], Astron. Astrophys. Suppl. 24, 299

Butler, C.J.: 1976[b], Roy. Obs. Bull. 182, 159

Butler, C.J.: 1978, Astron. Astrophys. Suppl. 32, 83

Canavaggia, R., Mianes, P., Rousseau, J.: 1975, Astron. Astrophys. 43, 275

Cousins, A.W.J., Lagerweij, H.C.: 1968, Monthly Notices Astron. Soc. S. Africa 27, 138

Cox, A.N.: 1978, Astrophys. J., to be published

Cox, A.N., Deupree, R.G., King, D.S., Hodson, S.W.: 1977, Astrophys. J. 214, L127

Cox, A.N., Michaud, G., Hodson, S.W.: 1978, Astrophys. J., in press

Dean, J.F.: 1977, Monthly Notices Astron. Soc. S. Africa 36, 3

Dean, J.F., Cousins, A.W.J., Bywater, R.A., Warren, P.R.: 1977, Mem. Roy. Astron. Soc. 83, 69

Dean, J.F., Warren, P.R., Cousins, A.W.J.: 1978, Monthly Notices Roy. Astron. Soc., to be published

Efremov, Yu.N., Kholopov, P.N.: 1975, Perem. Zvezdy 20, 133

Eggen, O.J.: 1977, Astrophys. J. Suppl. 34, 1, 33

Evans, N.R.: 1976, Astrophys. J. Suppl. 32, 399

Feast, M.W.: 1977, review given at ESO workshop on the Magellanic Clouds, Geneva April 1977, unpublished

Feltz, K.A., 1976, Publ. Astron. Soc. Pacific 88, 709

Feltz, K.A., McNamara, D.H.: 1976, Publ. Astron. Soc. Pacific 88, 699

Fricke, K., Stobie, R.S., Strittmatter, P.A.: 1972, Astrophys. J. 171, 593

Gascoigne, S.C.B.: 1974, Monthly Notices Roy. Astron. Soc. 166, 25P

Iben, I., Tuggle, R.S.: 1972[a], Astrophys. J. 173, 135

Iben, I., Tuggle, R.S.: 1972[b], Astrophys. J. 178, 441

Iben, I., Tuggle, R.S.: 1975, Astrophys. J. 197, 39

Ivanov, G.R., Nikolov, N.S.: 1976, Astrophys. Letters 17, 115

Janot-Pacheco, E.: 1976, Astron. Astrophys. Suppl. 25, 159

Johnson, H.L.: 1966, Ann. Rev. Astron. Astrophys. 4, 193

King, D.S., Hansen, C.J., Ross, R.R., Cox, J.P.: 1975, Astrophys. J. 195, 467

Kraft, R.P.: 1960, Astrophys. J. 132, 404

Kraft, R.P.: 1961, Astrophys. J. 134, 616

Kurucz, R.L.: 1975, in *Multicolour Photometry and the Theoretical HR-diagram*, A.G. Davis Philips, D.S. Hayes (eds), Dudley Observatory Reports 9, 271

Kurucz, R.L.: 1978, Astrophys. J. Suppl., to be published

Lloyd Evans, T.: 1968, Monthly Notices Roy. Astron. Soc. 141, 109

Lub, J., Pel, J.W.: 1977, Astron. Astrophys. 54, 137

Lyngå, G.: 1977, Astron. Astrophys. 54, 311

Madore, B.F.: 1975[a], Astron. Astrophys. 38, 471

Madore, B.F.: 1975[b], Astrophys. J. Suppl. 29, 219

Madore, B.F.: 1976[a], Monthly Notices Roy. Astron. Soc. 177, 215

Madore, B.F.: 1976[b], Roy. Obs. Bull. 182, 151

Madore, B.F.: 1977, Monthly Notices Roy. Astron. Soc. 178, 505

Madore, B.F., Van den Bergh, S.: 1975, Astrophys. J. 197, 55

Madore, B.F., Stobie, R.S., Van den Bergh, S.: 1978, Monthly Notices Roy. Astron. Soc. 183, 13

Oke, J.B.: 1961, Astrophys. J. 134, 214

Parsons, S.B.: 1971, Monthly Notices Roy. Astron. Soc. 152, 121

Parsons, S.B.: 1974, in: *Stellar Instability and Evolution*, P. Ledoux, A. Noels, A.W. Rodgers (eds), D. Reidel Publishing Company, Dordrecht, IAU Symp. No. 59, 56

Parsons, S.B., Bell, R.A.: 1975, in *Multicolour Photometry and the Theoretical HR-diagram*, A.G. Davis Philip, D.S. Hayes (eds), Dudley Observatory Reports 9, 73

Pel, J.W.: 1976, Astron. Astrophys. Suppl. <u>24</u>, 413

Pel, J.W.: 1978, Astron. Astrophys. <u>62</u>, 75

Pel, J.W., Lub, J.: 1978, in *The HR diagram - The 100th Anniversary of Henry Norris Russell*, A.G. Davis Philip, D.S. Hayes (eds), D. Reidel publishing company, Dordrecht, in press

Rodgers, A.W.: 1970, Monthly Notices Roy. Astron. Soc. <u>151</u>, 133

Sandage, A.R., Tammann, G.A.: 1968, Astrophys. J. <u>151</u>, 531

Sandage, A.R., Tammann, G.A.: 1969, Astrophys. J. <u>157</u>, 683

Sandage, A.R., Tammann, G.A.: 1971, Astrophys. J. <u>167</u>, 293

Schmidt, E.G.: 1972, Astrophys. J. <u>174</u>, 605

Schmidt, E.G.: 1973, Monthly Notices Roy. Astron. Soc. <u>163</u>, 67

Schmidt, E.G.: 1975, Monthly Notices Roy. Astron. Soc. <u>170</u>, 39^P

Schmidt, E.G.: 1976, Astrophys. J. <u>203</u>, 466

Simon, N.R., Schmidt, E.G.: 1976, Astrophys. J. <u>205</u>, 162

Simon, N.R.: 1977, Astrophys. J. <u>217</u>, 160

Stobie, R.S.: 1977, Monthly Notices Roy. Astron. Soc. <u>180</u>, 631

Szabados, L.: 1977, Comm. Hungarian Acad. Sc. <u>70</u>

Thé, P.S.: 1977, Astron. Astrophys. <u>60</u>, 423

Turner, D.G.: 1977, Astron. J. <u>82</u>, 163

Van den Bergh, S., Harris, G.L.H.: 1976, Astrophys. J. <u>208</u>, 765

Van den Bergh, S.: 1977, in *Décalages vers le Rouge et Expansion de l'Univers*, C. Balkowski, B.E. Westerlund (eds), éditions du C.N.R.S., Paris, IAU Coll. No. 37, 13

Van Genderen, A.M.: 1969, Bull. Astron. Inst. Neth. <u>20</u>, 317

Van Genderen, A.M.: 1977, Astron. Astrophys. <u>54</u>, 737

Van Paradijs, J.A.: 1973, Astron. Astrophys. <u>23</u>, 369

Walraven, J.H., Tinbergen, J., Walraven, Th.: 1964, Bull. Astron. Inst. Neth. <u>17</u>, 520

Wampler, J., Pesch, P., Hiltner, W.A., Kraft, R.P.: 1961, Astrophys. J. <u>133</u>, 895

Wesselink, A.J.: 1969, Monthly Notices Roy. Astron. Soc. <u>144</u>, 297

Wielen, R.: 1974, Astron. Astrophys. Suppl. <u>15</u>, 1

Yakimova, N.N.: 1973, Soobshch. Gos. Astron. Inst. Shternberga <u>177</u>, 19

Discussion

Fernie: You pointed out the advantages of the Walraven photometric system. Do you think that it is almost an ideal system? For example, how does it compare with the Stromgren system?

Pel: They are very similar. You cannot transform Stromgren and Walraven photometry directly, because the transformations are very complicated. When you look at the two-color diagrams, calibrated for temperature, gravity and composition, the features found in one system are found in the other. I think that in the case of the hotter (OB) stars, the extra band in the Balmer continuum of the Walraven system offers clear advantages. For the intermediate temperature range, they are more or less equivalent. Both, of course, lack a band at longer wavelength. We are thinking of trying to extend the present system with a band somewhere around R, since photometry at long wavelengths should be done. In fact, it is very important to do. However, the UV region must not be neglected.

A. Cox: Do you have a simple explanation or speculation for the discrepancies of Kraft's color excesses?

Pel: He calibrated his color excesses at the shorter periods only, and he had to extrapolate his G-band photometry for the longer period stars. There is a zero-point difference of the more recent color excess scales relative to all systems based on the Kraft system. However, that's not hard to get and it's not a serious problem. At the longer periods, the differences are really large, $0^m.15$ to $0^m.18$! I think that is because the G-band photometry runs into gravity problems there.

Sareyan: Do you check transmission of the red window in U filter?

Pel: That was one more complication I didn't mention.