Cepheid radii and the CORS method revisited

V. Ripeti¹, F. Barone², L. Milano², and G. Russo¹ ³

¹ Dipartimento di Fisica, Università della Calabria
I-87036 Arcavacata di Rende (CS) Italy.

² Dipartimento di Scienze Fisiche, Università di Napoli Federico II
pad. 20 Mostra d’Oltremare, I-80125 Napoli, Italy.

³ INFN, Gruppo collegato di Cosenza, Dipartimento di Fisica
I-87036 Arcavacata di Rende (CS) Italy I-87036.
Affiliated to Osservatorio Astronomico di Capodimonte, Napoli.

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Abstract. We have refined the CORS method, introduced in 1980 for the computation of the cepheid radii, in order to extend its applicability to recent and extensive sets of observations. The refinement is based on the computation, from observational data only, of one of the terms of the solving equation, previously based only on precise calibrations of photometric colours. A limited number of assumptions, generally accepted in the literature, is used.

New radii are computed for about 70 cepheids, and the resulting P-R relation is discussed.

Key words: Stars: distances – Stars: oscillations of – Stars: fundamental parameters – Stars: Cepheids

1. Introduction

The importance of a proper knowledge of the radii of Cepheid variables is well known, in particular, but not only, in connection with the problem of the cosmic distance scale. Notwithstanding extensive studies by several authors (Caccin et al. 1981; Fernie 1984; Gieren 1986; Moffett & Barnes 1987; Gieren et al. 1989, Laney & Stobie 1995), there are still doubts on the correct period-radius relation. Almost all methods used for determining the radius of a cepheid from the photometric and spectroscopic (radial velocities) observations, are based on the classical Baade-Wesselink method (Wesselink, 1946). Gautschy (1987) published a review of the different methods; this comparative study outlines that the CORS method (Caccin et al., 1981, Sollazzo et al., 1981) had the most solid physical basis, together with the surface brightness technique by Barnes & Evans (1976). However, the CORS method suffered from two major drawbacks that have so far prevented its application to most observational data; that is the mathematically difficult formulation, and the need of a good and complete calibration of the colours, able to derive detailed temperatures and gravity curves. In particular, the second problem is solved so far only for the VBLUW observations by Pel (1976,1978). The first problem is instead not a true problem, because, as we will show, the whole CORS method reduces itself to the fitting of the data and to the solution of an implicit equation which, once written in computer form, requires a fraction of a second to be solved in terms of the cepheid radius.

The purpose of the present paper is to introduce a modification of the CORS method, by taking into account the surface brightness method, in order to allow the determination of cepheid radii for a wider set of data than it was originally conceived.

In the following we will first recall the original surface brightness and CORS methods, and then we introduce its modified version, discussing its characteristics. Last sections are devoted to the application of the method and to the discussion of the results.

2. The new method

2.1. The surface brightness method

The surface brightness method (Barnes & Evans, 1976), as used by Gieren et al. (1989), is based on the visual surface brightness $S_v$, defined as the following equivalent relations:

$$ S_v = V + 5 \cdot \log \alpha $$

(1)

$$ S_v = -10 \cdot \log T_e - \text{B.C.} + \text{const.} $$

(2)
electric corrections. Or, equivalently, the surface brightness parameter $F_{V}$, given by

$$F_{V} = \text{const.} - 0.1 \cdot S_{V} = \log T_{e} + 0.1 \cdot \text{B.C.} \quad (3)$$

An empirical relation has been found by Barnes & Evans (1976), which correlates $F_{V}$ to the Johnson $(V-R)_{0}$ index, corrected for interstellar reddening:

$$F_{V} = b + m \cdot (V - R)_{0} \quad (4)$$

where the angular coefficient $m$ is turn a function of the pulsational period (Moffett & Barnes, 1987):

$$m = -0.370 + 0.004 \cdot \log P \quad (5)$$

The practical application starts from the $(V-R)$ observations, which from (4) give $F_{V}$, which in turn from (3) give $S_{V}$, which in turn from (1) give $\alpha$. Expressing the linear diameter $D = 10^{-3} \cdot r \cdot \alpha$ (r being the distance in parsec) as $\Delta D + D_{m}$ ($\Delta D$ being the instantaneous displacement) and performing a regression analysis of $a$ against $\Delta D$, one obtains the mean diameter $D_{m}$, as well as the distance $r$.

2.2. The original CORS Method

The CORS method also starts from (1), but proceeds mathematically by differentiating it with respect to the phase, multiplying by the colour index $(B-V)$ and integrating over the whole cycle; after substituting:

$$\dot{R}(\phi) = -p \cdot P \cdot u(\phi) \quad (6)$$

it yields to the following equation, in which $\phi$ is the phase

$$a \int_{0}^{1} \log \{R_{0}(\phi) - p \cdot P \int_{\phi_{0}}^{\phi} u(\phi') \cdot d\phi'\} (B - V)(\phi') \cdot d\phi + \int_{0}^{1} (B - V)(\phi) \cdot \dot{V}(\phi) \cdot d(\phi) + \int_{0}^{1} (B - V)(\phi) \cdot \dot{S}_{V}(\phi) \cdot d(\phi) = 0 \quad (7)$$

where $a = 5/\log_{e} 10$,

$$B = \int_{0}^{1} (B - V)(\phi) \cdot \dot{V}(\phi) \cdot d(\phi) \quad (8)$$

$$\Delta B = \int_{0}^{1} (B - V)(\phi) \cdot \dot{S}_{V}(\phi) \cdot d(\phi) \quad (9)$$

$P$ is the period, $u$ the radial velocities and $p$ is a conversion factor (Parsons, 1972; Gieren et al. 1989). The practical application of the CORS method starts from a fitting of data with respect to the phase $\phi$ by means, e.g., of Fourier series. The data are given by the $V$ magnitude, the $(B-V)$ and $(V-R)$ colour indexes, and the radial velocities $u$.

The fit is easily obtained with an interactive procedure on a computer terminal with graphical capabilities; afterwards, the fitted curves are used to compute in an automated way the term $B$, the term $\Delta B$, the derivatives and eventually to solve eq. (7) to obtain $R_{0}$, the radius at an arbitrary phase $\phi_{0}$; $\phi_{0}$ is usually taken at the minimum of the radial velocity curve, but its choice is inessential; the mean radius comes from integrating twice eq. (6).

We will now show how the two methods can be used together, to obtain what we will call the modified CORS method.

From eq. (4) we can obtain $F_{V}$, and from it, we can obtain $S_{V}$, using also eq. (3) and (5):

$$S_{V} = \text{const.} - 10 \cdot F_{V}$$

$$= \text{const.} - 10 \cdot m \cdot (V - R)_{0} - 10 \cdot b \quad (10)$$

$$= \text{const.} + (3.7 - 0.04 \cdot \log P) (V - R)_{0}$$

The value of the constant is of no importance in our case, since we are interested in computing $\Delta B$; this term, given by eq. (9), is the area of the loop described by the star in the plane $S_{V}$ vs $(B-V)$. If we make the transformation of variable from $S_{V}$ to $(V-R)_{0}$, given by eq. (10), then:

$$\Delta B = \int_{0}^{1} (B - V)(\phi) \cdot \dot{S}_{V}(\phi) \cdot d(\phi)$$

$$= (3.7 - 0.04 \cdot \log P) \cdot \int_{0}^{1} (B - V)(\phi) \cdot (V - R)_{0}(\phi) \cdot d(\phi) \quad (11)$$

Since the derivative of $(V - R)_{0}$ with respect to the phase is, in first approximation, the same as the one of $(V-R)$, we get from eq. (11), with $c=3.7-0.04\cdot \log P$:

$$\Delta B = c \int_{0}^{1} (B - V)(\phi) \cdot (V - R)(\phi) \cdot d(\phi) \quad (12)$$

Let us pose $C = \int_{0}^{1} (B - V)(\phi) \cdot (V - R)(\phi) \cdot d(\phi)$, which represents the area of the loop described by the star in the plane $(V-R)$ vs $(B-V)$, we get to the final formulation, given the following observations:

i) the light curve
ii) the colour curve $(B-V)$
iii) the colour curve $(V-R)$
iv) the radial velocity curve

and the quantities, all based on the above observations:

i) $B$=area of the loop $(B-V)$ vs $V$
ii) $C$=area of the loop $(V-R)$ vs $(B-V)$

The radius $R_{0}$ at an arbitrary phase is obtained from the equation:

$$a \int_{0}^{1} \log \{R_{0}(\phi) - p \cdot P \int_{\phi_{0}}^{\phi} u(\phi') \cdot d\phi'\} (B - V)(\phi') \cdot d\phi + \int_{0}^{1} (B - V)(\phi) \cdot \dot{V}(\phi) \cdot d(\phi) + \int_{0}^{1} (B - V)(\phi) \cdot \dot{S}_{V}(\phi) \cdot d(\phi) = 0$$

where $c = 3.7 - 0.04 \cdot \log P$ and $p = 1.39 - 0.030 \cdot \log P$.

If we follow Gieren et al. (1989), or $c=3.7$ and $p=1.36$ in our approximation.
The assumptions and approximations which are behind this formulation are the following:

i) the observational data give a good coverage of the pulsational period, and do not show big noise, so that the Fourier fitting (or any other fitting which guarantees the periodicity of the data) is a good approximation to the observations.

ii) the photometric and spectroscopic observations are simultaneous, or at least separated by few tens of pulsational cycles, so that no phase-shift is present in the terms of eq. (13).

iii) the correlation of eq. (5), given by Moffett & Barnes (1987) represents a good approximation to the data.

iv) the proportionality between \( \Delta B \) and \( C \) is valid; this was already proved in general terms by Onnenbo et al., (1985), and therefore what we found here is just a confirmation, particularly valid for the colours (B-V) and (V-R).

v) the colours are not affected by other contributions, e.g. the presence of companions to the cepheid (see Russo et al. 1981).

3. Stability of the method

We want to study here the characteristics of the method, that is the sensitivity of the method to the parameters and data present in eq. (13). First of all, the left side of eq. (13) is a function of the following parameters: observational data (\( V, B-V, V-R, u \)); constants (c and \( p \)); the variable \( R \). This function has a zero \( R_0 \) at a value which is determined numerically; it is important to study the behaviour of such function, with respect to \( R \). Fig. 1 gives the plot of the above function for \( \delta Cep \); it is a well-behaved function whose zero can safely be determined. The plot varies of course according to the star, but the general shape is similar.

Since the terms \( B \) and \( c \cdot C \) in eq. (12) are additive terms, their effect is to move the whole curve by a vertical shift, thus changing the value of \( R_0 \). This explains the importance of the loops for both \( B \), the area in the plane (\( V, B-V \)) and \( C \); the area in the plane (\( B-V, V-R \)). However, the observational data enter in these quantities only globally, that is all data together combine to give \( B \) and \( C \), and this means that errors on individual points have less influence on the final value of \( B \) and \( C \), and hence of \( R_0 \). However, the evaluation of \( B \) and \( C \) is very dependent on the regularity of the curve: if the noise of the data is high, and the data have a large scatter around the fitted curve in the planes (\( \phi, V \)), (\( \phi, B-V \)), (\( \phi, V-R \)) then the area of \( B \) and \( C \) may be not well determined. Fig. 2 shows the plot of the magnitude-colour and colour-colour loops for \( \delta Cep \). From this figure it is clear that the scatter in colour-colour loop is more critical with respect to that of the colour-magnitude loop, so that the term \( \Delta B \) will be more influenced by the eventual poor quality of the data. In any case, since the area described by the colour-colour loop is very small (due to the characteristic of \( \Delta B \) to be a correction term) it is reasonable to expect that the error introduced in this way will be very small; an occurrence already noticed by Sollazzo et al. (1981), (see their Fig. 8).

For what concerns the dependence on the conversion factor \( p \), Fig 3 shows the value of \( R_0 \) obtained for \( \delta Cep \), W Sgr and SZ Tau, for five different values of \( p \); a change of 0.05 in \( p \) corresponds to a change of 3.5\% in \( R_0 \).

4. Application of the method

4.1. The samples

In order to apply the method, we searched the literature for high-quality sets of observational data. We considered mainly two large and homogeneous sets of data: one from Moffett & Barnes (1980, 1984) (MB hereafter, BVRI photometry), Barnes et al. (1987,1988) (BMS hereafter), Wilson et al. (1989) (WBCM hereafter, radial velocities), and the other from Bessier et al. (1994) (BBB hereafter, Geneva System Photometry), Bessier et al. (1994) (BBMD hereafter, CORAVEL radial velocities).

There were 26 variables in common between the two sets; in these cases, in general, we used photometry from MB (we proceed in this way either because these data was generally more accurate than those in the Geneva system, or because the presence of the V-R colour allowed us to use
4.2. Particular stars

There were eight stars from BMS and WCBCM whose radial velocities curves were too poor to be used; they are: FF Aql, RU Cam, RW Cas, TU Cas, SU Cyg, AU Peg, VX Pup, S Sge.

For other two stars of the same sample: RW Cam and VY Cyg, the method did not reach the convergence, probably due to the poor quality of the data.

SW Tau was excluded because it is a Population II Cepheid.

From the BBMD sample we excluded from our computation V440 Per, which have convergence problems; CO Aur and V367 Sct because they are double or triple mode; the double stars DL Cas and V465 Mon because of problems in separating the orbital motion from the radial velocity curve.

4.3. Double stars

From the literature is possible to find indications about the doubleness of several cepheids; in particular, following BBM, BBMD and Pont et al. (1994) the following variables result to be double: SU Cas, DD Cas, VZ Cyg, DX Gem, ζ Gem, RZ Gem, Z Lac, T Mon, S Nor, SV Per, Y Sct, U Sgr, W Sgr. Among these double stars, only U Sgr shows an anomalous position in Fig 4 (see below).

5. Results

In Table 1 we report the results of our analysis for all stars of our sample for which the CORS method reached the convergence; from left we report in the order: name of the cepheid; period; radial velocity data source; photometric
Table 1. Results from our method and comparison with previous determinations with the Surface Brightness Method by Gieren et al. (1989). The last two columns show the radius determined in this work.

| Cepheid | Period (days) | Photometric source | Rad. Vel. source | Surf. Brigh. radius (R☉) | CORS radius (R☉) | new CORS radius (R☉) |
|---------|---------------|--------------------|------------------|--------------------------|------------------|----------------------|
| U Aql   | 7.024100      | MB                 | BMS              | 54.65                    | 55.5             | 61.3                 |
| η Aql   | 7.176779      | MB                 | BMS              | 54.93                    | 57.1             | 56.7                 |
| FM Aql  | 6.114340      | MB                 | BMS              | 54.82                    | 58.8             | 60.6                 |
| TT Aql  | 13.755290     | MB                 | BMS              | 97.62                    | 86.0             | 95.3                 |
| V496 Aql| 6.807164      | MB                 | BMS              | 45.52                    | 39.2             | 36.4                 |
| RT Aur  | 3.728220      | MB                 | BMS              | 32.90                    | 41.6             | 42.2                 |
| SY Aur  | 10.144698     | MB                 | BMS              | 61.59                    | 69.4             | 66.3                 |
| RX Cam  | 7.912190      | MB                 | BMS              | 76.00                    | 57.3             | 58.9                 |
| CF Cas  | 4.87514       | MB                 | BMS              | 46.90                    | 50.2             | 50.2                 |
| DD Cas  | 9.81274       | MB                 | BBMD             | 85.12                    | 72.5             | 79.2                 |
| FM Cas  | 5.809232      | MB                 | BBMD             | 62.05                    | 49.9             | 49.9                 |
| SU Cas  | 1.949317      | MB                 | BBMD             | 29.20                    | 32.5             | 32.5                 |
| SY Cas  | 4.071110      | B                  | BBMD             | 48.00                    | 52.7             | 52.7                 |
| V636 Cas| 8.375490      | BBB                | BBMD             | 74.10                    |                  |                      |
| δ Cep   | 5.366269      | MB                 | BBMD             | 41.60                    | 50.2             | 52.8                 |
| CR Cep  | 6.232870      | MB                 | BBMD             | 58.60                    | 56.9             | 56.9                 |
| X Cyg   | 16.385692     | MB                 | BBMD             | 118.13                   | 89.6             | 96.2                 |
| DT Cyg  | 2.499086      | MB                 | BBMD             | 37.90                    | 42.9             |                      |
| SZ Cyg  | 15.109642     | MB                 | BMS              | 117.74                   | 83.8             | 87.3                 |
| V2 Cyg  | 4.8644        | MB                 | BBMD             | 37.17                    | 44.4             | 47.3                 |
| V386 Cyg| 5.257655      | MB                 | BMS              | 41.86                    | 38.1             | 40.8                 |
| V532 Cyg| 3.283612      | MB                 | BMS              | 38.20                    | 45.2             |                      |
| RZ CMa  | 4.254926      | MB                 | BMS              | 39.40                    | 42.8             |                      |
| RY CMa  | 4.678425      | MB                 | BMS              | 33.10                    | 35.8             |                      |
| TW CMa  | 6.995374      | MB                 | BMS              | 57.28                    | 63.3             | 64.8                 |
| ζ Gem   | 10.149955     | MB                 | BBMD             | 64.94                    | 73.5             | 86.2                 |
| W Gem   | 7.913960      | MB                 | BMS              | 50.66                    | 56.6             | 60.7                 |
| BB Gem  | 2.308207      | BBB                | BBMD             | 31.40                    |                  |                      |
| DX Gem  | 3.136379      | MB                 | BBMD             | 41.80                    | 41.1             |                      |
| RZ Gem  | 5.529162      | MB                 | BMS              | 52.49                    | 61.4             | 68.2                 |
| X Lac   | 5.44447       | MB                 | BBMD             | 64.71                    | 74.3             | 71.2                 |
| Y Lac   | 4.323776      | MB                 | BMS              | 50.27                    | 50.7             | 51.7                 |
| Z Lac   | 10.8866000    | MB                 | BMS              | 68.88                    | 83.8             | 86.8                 |
| BG Lac  | 5.531938      | MB                 | BMS              | 45.42                    | 36.9             | 35.8                 |
| RR Lac  | 6.416190      | MB                 | BBMD             | 45.61                    | 45.1             | 46.4                 |
| BE Mon  | 2.70551       | BBB                | BBMD             | 29.70                    |                  |                      |
| T Mon   | 27.022600     | MB                 | BBMD             | 172.19                   | 170.5            | 188.3                |
| CV Mon  | 5.378793      | MB                 | BMS              | 43.10                    | 49.2             |                      |
| SV Mon  | 15.232780     | MB                 | BMS              | 100.64                   | 119.6            | 130.7                |
| V508 Mon| 4.133608      | BBB                | BBBMD            | 56.10                    |                  |                      |
| S Nor   | 9.764244      | BBB                | BBMD             | 57.20                    |                  |                      |
| TW Nor  | 10.78531      | M                  | BBMD             | 67.50                    |                  |                      |
| V340 Nor| 11.28871      | BBB                | BBMD             | 71.60                    |                  |                      |
| Y Oph   | 17.126780     | MB                 | BMS              | 71.88                    | 123.3            | 112.2                |
| BF Oph  | 4.067695      | MB                 | BMS              | 35.87                    | 31.2             | 32.4                 |
| GQ Ori  | 6.816127      | MB                 | BMS              | 72.44                    | 54.6             | 54.7                 |
| AW Per  | 6.463720      | MB                 | BMS              | 47.34                    | 54.6             | 54.8                 |
| SV Per  | 11.129318     | MB                 | BMS              | 63.97                    | 65.9             | 79.9                 |
| VX Per  | 10.889040     | MB                 | BMS              | 77.27                    | 63.7             | 62.1                 |
| X Pup   | 25.961000     | MB                 | BMS              | 118.04                   | 156.1            | 164.1                |
| RS Pup  | 41.415000     | MB                 | BMS              | 262.60                   | 205.7            | 207.9                |
| AQ Pup  | 29.839810     | MB                 | BMS              | 197.20                   | 124.8            | 145.9                |
| WX Pup  | 8.937050      | MB                 | BMS              | 76.54                    | 66.1             | 63.1                 |
| RV Sco  | 6.061388      | MB                 | BMS              | 49.29                    | 42.2             | 48.3                 |
| V500 Sco| 9.316862      | MB                 | BMS              | 53.12                    | 63.3             | 72.8                 |
| Y Sct   | 10.341650     | MB                 | BMS              | 83.52                    | 62.4             | 71.5                 |
| EV Sct  | 3.091047      | MB                 | BBMD             | 30.90                    | 36.6             |                      |
| U Sgr   | 6.745363      | BBB                | BBMD             | 60.03                    | 34.5             |                      |
| W Sgr   | 7.594935      | MB                 | BBMD             | 63.28                    | 53.0             | 58.6                 |
| X Sgr   | 7.012630      | MB                 | BMS              | 49.77                    | 56.5             | 58.6                 |
Cepheid Period Photometric Rad. Vel. Surf. Brigh. CORS new CORS
source source radius (R☉) radius (R☉) radius (R☉)

Y Sgr 5.773400 MB BMS 50.04 60.7 61.4
BB Sgr 6.637117 MB MB 42.12 50.0 53.5
AP Sgr 5.057936 MB BMS 44.02 42.6 50.0
YZ Sgr 9.553606 MB MB 84.2 136.0
V350 Sgr 5.154557 MB BMS 47.80 41.8 46.0
EU Tau 2.102182 BBB BBMD 20.6
ST Tau 4.034299 MB BMS+BBMD 41.41 46.6 47.1
SZ Tau 3.149138 MB BBMD 37.83 41.8 44.8
T Vul 4.435453 MB BBMD 38.24 48.8 48.8
U Vul 7.990821 MB BBMD 56.54 57.9 61.1
X Vul 6.31949 MB BBMD 46.24 61.5 68.4
SV Vul 45.00061 BBB BBMD 202.15 189.5

Fig. 4. Left: Period-Radius relation obtained from CORS method without ΔB; Right: as before, but with ΔB.

Table 2. Comparison of coefficients of Period-Radius relation (log R = a log P + b) between this paper and selected other works available in literature

| Method             | a         | b         | Source                          |
|--------------------|-----------|-----------|---------------------------------|
| Theory             | 0.692 ± 0.006 | 1.179 ± 0.006 | Fernie (1984)                   |
| Theory             | 0.70      | 1.17      | Cogan (1978)                    |
| Theory             | 0.72      | 1.07      | Karp (1975)                     |
| Surf. Bright.      | 0.743 ± 0.023 | 1.108 ± 0.023 | Gieren et al. (1989)           |
| Surf. Bright.      | 0.751 ± 0.026 | 1.070 ± 0.008 | Laney & Stobie (1995)          |
| LMC cepheids       | 0.716 ± 0.010 | 1.139 ± 0.009 | Di Benedetto (1994)            |
| CORS without ΔB    | 0.622 ± 0.029 | 1.226 ± 0.026 | This paper                     |
| CORS with ΔB       | 0.606 ± 0.037 | 1.263 ± 0.033 | This paper                     |
method (Gieren et al. 1989); radius obtained with CORS (without ΔB term); as before but with the ΔB term. These data are plotted in Fig 4 were we present the Period-Radius relation as a result of CORS method in two cases, with and without ΔB respectively; the solid lines superimposed represent a least square fit to our data that leads to the following Period-Radius relation (74 cepheids) without the ΔB term in eq. (13):

\[
\log R = (0.619 \pm 0.032) \log P + (1.229 \pm 0.028) \tag{14}
\]

If we exclude from our fit X Lac (it shows a clear phase shift) and U Sgr (double star) we obtain a slightly better error:

\[
\log R = (0.622 \pm 0.029) \log P + (1.226 \pm 0.026) \tag{15}
\]

Now, if we consider the ΔB term in eq. (13) for cepheids with BVRI photometric observations (65 stars) we obtain:

\[
\log R = (0.614 \pm 0.040) \log P + (1.260 \pm 0.036) \tag{16}
\]

And excluding the large scattering YZ Sgr (poor radial velocity data) we obtain:

\[
\log R = (0.666 \pm 0.037) \log P + (1.263 \pm 0.033) \tag{17}
\]

Our Period-Colour relations are reported also in Tab. 2 in comparison with other selected results from the literature. We note that our P-R relations show a slope slightly shallower than either the more recent determinations via Baade-Wesselink methods, or theoretical determination. Moreover the use of a second colour (i.e. the inclusion of ΔB in the determination of radius) goes in the sense to reduce further on the slope. Since we use (at least partially) the same data of Gieren et al. (1989) it is surprising to find such a different result. Anyway, in their recent paper, Laney and Stobie (1995) applied a Surface Brightness method to a set of 31 Cepheids, using different pairs of magnitudes and colours, from (V,B-V) to (K,J,K), and found a dependence of the P-R relation from the colours used, in the sense that the slope is shallower if "blue" colours are used instead of the infrared ones. This could partially explain our shallower slope in the P-R relations, since our two determinations of R depend either from two or three "blue" colours.

6. Conclusions

We have presented a method for computing Cepheid radii, which merges the CORS and the Surface Brightness method into a single, easy to use method applicable to observations in different photometric systems. An interesting feature of this method is its independence from the knowledge of the reddening corrections, at least within the limits of an assumption that the derivative of (V - R)₀ is the same as the one of (V-R).

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