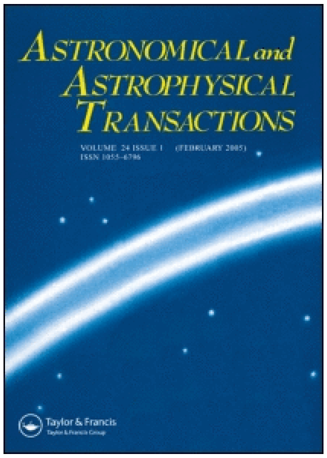

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STUDIES OF CLASSICAL CEPHEIDS

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We present a review of recent results of our photometric and spectroscopic studies of classical Cepheids. We have accumulated the world's richest set of original, accurate photometric observations and radial-velocity measurements for Galactic Cepheids. Our observations are available to the community in electronic form via ftp. A Cepheid data bank has been prepared, including original and published data. Using these data, improved period-luminosity relations have been derived. A catalogue of Cepheid light curve parameters, luminosities, and distances has been compiled. Indications of evolutionary period changes have been found in our extensive studies of the most rapidly evolving Cepheids. We have discovered a number of new spectroscopic-binary Cepheids, and determined orbital elements for several stars. Our estimate of the lower limit on the incidence of spectroscopic binary Cepheids is 22%. A new period-radius relation has been derived from Baade-Wesselink radii for 62 Cepheids.

KEY WORDS Cepheids, photometry, radial velocities

1 INTRODUCTION

Cepheids (in the following, we omit the adjective "classical") are principal distance indicators, so they have always attracted attention of investigators. In the 1920s-1960s, Cepheid studies conducted in Moscow (by P. P. Parenago, B. V. Kukarkin, P. N. Kholopov, Yu. N. Efremov, and their collaborators) were quite on the world level. Then, in the 1970s, the interest to Cepheids became much lower; its new growth began only in the 1980s, when Efremov initiated large-scale observations, first photoelectric, and then also spectoscopic ones.

Voluminous arrays of resulting observational data, combined with data from the literature, make it possible to carry out research on the world's best level. Below we discuss some of the results.

2 PHOTOELECTRIC OBSERVATIONS

In 1981, one of the authors (LNB) commenced regular photoelectric observations of northern Cepheids at Mt. Maidanak Observatory (Uzbekistan); since 1994, we observed also southern Cepheids at Las Campanas and Cerro Tololo Observatories (Chile) and at the South African Astronomical Observatory. Thanks to excellent weather conditions at these observatories, the "all sky" technique can be used almost always; as a result, 23 observing runs in 1981–1997 gave about 35 200 brightness measurements for 481 Cepheids. The majority of these observations are published in Berdnikov (1986, 1987b, 1992a–f, 1993), Berdnikov and Turner (1995a, b; 1998a, b), Berdnikov and Vozyakova (1995), Berdnikov *et al.* (1998b, c). We have estimated the accuracy of our observations from measurements of constant stars: in the V brightness range from 7^m to 14^m, the r.m.s. error of a single observation is close to $0\overset{m}{.}01$ in $UBV(RI)_C$ filters. Stars from equatorial Standard Areas (Landolt, 1983) were used as primary standards. Our technique of observation and reduction is described in detail in Berdnikov (1986), Berdnikov and Turner (1995a).

Our series of photoelectric observations of Cepheids is the world's richest ($\sim$ 45% of all the broad-band $UBVRI$ data in the world) and it corresponds to the best series of other researchers by the quality of observations. All our observations (including those unpublished) are available to INTERNET users at the following ftp address:

ftp.sai.msu.su/pub/groups/cluster/cepheids/

3 CEPHEID DATA BANK

Our observations, combined with those published by other authors, are the basis of our Cepheid data bank (Berdnikov, 1995). At the time of writing, we have recorded, on computer media, about 104 000 photoelectric observations and about 20 000 measurements of radial velocities. More than 90% of the photometric data in the bank are for Milky Way Cepheids; the rest of them are for Cepheids of other galaxies, mainly the Magellanic Clouds. Most observations of galactic Cepheids ($\sim$ 80 000) are in the broad-band $UBVRI$ system; there are also about 4000 infrared measurements plus observations in various intermediate-band and narrow-band photometric systems.

We estimate the completeness of the data bank as at least 98% of published photoelectric observations and at least 90% of radial velocity measurements.

4 THE PERIOD-LUMINOSITY RELATION AND DISTANCES OF CLASSICAL CEPHEIDS

Usually distances r to Cepheids are calculated using the formula:

$$\log r = 0.2 \cdot (\langle m \rangle - \langle M \rangle + 5 - A),$$

where $\langle m \rangle$ and $\langle M \rangle$ are respectively the Cepheid's intensity-averaged apparent and absolute magnitudes, and A is the interstellar extinction. The $\langle m \rangle$ value follows from observations; thus, to calculate r, one needs to know the value of $\langle M \rangle$, which can be derived from the period–luminosity relation, and the value of A, determined as the product of the colour excess and a coefficient equal to the ratio of total to selective absorption.

More than a decade ago, Berdnikov and Efremov (1985), from six Cepheids – reliable members of four open clusters with well-determined photoelectric Hertzsprung–Russell diagrams – derived the following period–luminosity relation:

$$\langle M_V \rangle = -1.24 - 2.79 \cdot \log P. \tag{1}$$

To determine the distances to the clusters, they fitted their main sequences (MSs) to Kholopov's (1980) zero-age main sequence (ZAMS); colour excesses E_{B-V} for the calibration Cepheids were calculated using the period–intrinsic colour relation from Dean *et al.* (1977b), and the total V-band absorption was determined as the product $R_V \cdot E_{B-V}$, where R_V was a function of $(B-V)_0$, on average close to 3.45.

Some results of recent years make it necessary to revise the relation (1) as well as some aspects of the technique of distance determinations for Cepheids through equation (1). Thus, Berdnikov *et al.* (1996a) studied the interstellar extinction law for Cepheids and, in particular, found that the ratio of the V-band total absorption A_V to the colour excess E_{B-V} i.e. $R_V = A_V/E_{B-V}$, is equal to 3.26 ± 0.02, a value much lower than the above value of 3.45. This alone is quite sufficient to justify a revision of the Cepheid distance scale through the improvement of the period–luminosity relation. Note also that, by now, we know many more Cepheids – reliable members of galactic open clusters – and new data of photoelectric and CCD UBV photometry have been accumulated for the corresponding clusters, thus enabling us to redetermine their distances and colour excesses with considerably improved accuracy.

Moreover, by now, for a number of Cepheids, good photoelectric light curves in the red and infrared range have been published; accounting for interstellar reddening and abundance differences is considerably simplified for this range (cf., for instance, Madore and Freedman, 1991). Consequently, determining Cepheid distances, one can rely upon period–luminosity relations in infrared photometric bands, thus necessitating attempts to improve also these relations.

In order to improve the period–luminosity relation, we selected nine Cepheids, reliable members of seven open clusters of the Galaxy, from the list of 40 Cepheids in Efremov (1989). For the reasons described in Berdnikov and Efremov (1985), we did not use Cepheids in associations and stellar complexes. Additionally, we excluded CV Mon (in the cluster named after this star) and V367 Set (in NGC 6649), because of membership problems remaining unsolved for the corresponding clusters.

We determined distances to clusters fitting their main sequences to Kholopov's (1980) ZAMS, taking into account deviations due to evolution (using isochrones from Maeder and Meynet, 1991); colour excesses were derived from observations of blue cluster stars, on the base of their $U-B$ and $B-V$ colour indices. To calculate the interstellar absorption, we applied the formula $A_\lambda = R_\lambda \cdot E_{B-V}$ adopting E_{B-V}

for each Cepheid equal to the mean colour excess of the corresponding cluster and taking the interstellar extinction parameter, R_λ from Berdnikov *et al.* (1996a).

For details, we refer the reader to Berdnikov *et al.* (1996b); here we would like to present only the resulting relations:

$$\begin{aligned}
\langle M_B \rangle &= -3.13 - 2.40(\log P - 1), \\
\langle M_V \rangle &= -3.88 - 2.87(\log P - 1), \\
\langle M_{R_c} \rangle &= -4.27 - 2.97(\log P - 1), \\
\langle M_R \rangle &= -4.45 - 3.13(\log P - 1), \\
\langle M_{I_c} \rangle &= -4.53 - 3.07(\log P - 1), \\
\langle M_I \rangle &= -4.78 - 3.18(\log P - 1), \\
\langle M_J \rangle &= -5.06 - 3.37(\log P - 1), \\
\langle M_H \rangle &= -5.37 - 3.52(\log P - 1), \\
\langle M_K \rangle &= -5.46 - 3.52(\log P - 1),
\end{aligned} \tag{2}$$

and to mention that the dispersion of M_λ decreases with increasing wavelength. Berdnikov *et al.* (1996b) showed that, for determinations of Cepheid distances, one should prefer infrared period–luminisity relations, in particular, that for the K band, showing the lowest dispersion ($0^{\rm m}_{.}05$); additionally, the IR range is free from strong lines of metals, so the resulting distances should be only slightly influenced by differences in stellar abundances.

An additional advantage of using the K band is that the total absorption in this band is by an order of magnitude lower than in the V band, being equal to $A_K = 0.274 \cdot E_{B-V}$. So even for a very large error in the $(B-V)_0$ intrinsic colour (and consequently in the E_{B-V} colour excess, in the order of $0^{\rm m}_{.}2$, which is close to the overall width of the period – $\langle B \rangle_0 - \langle V \rangle_0$ colour diagram (Dean *et al.*, 1977b), the error of the total absorption A_K will not exceed $0^{\rm m}_{.}05$ (and the r.m.s. error will definitely be lower than $0^{\rm m}_{.}02$), i.e. it will remain lower than the dispersion of the K-band period–luminosity relation (Berdnikov *et al.*, 1996b). Thus, the period – intrinsic colour relation from Dean *et al.* (1977b), which can result in considerable errors in the E_{B-V} colour excess and consequently in the visual-band absorption, is quite useable for determinations of the K-band interstellar absorption.

A problem in using the K-band period–luminosity relation for the determinations of Cepheid distances follows from the fact that reliable IR light curves are available only for slightly more than 50 Cepheids, whereas BV light curves are available for 473 stars. An approach to the solution of this problem was suggested by Berdnikov *et al.* (1996a): if we know average apparent (not absorption-corrected) $\langle B \rangle$ and $\langle V \rangle$ magnitudes, then, for a known period of the Cepheid and ΔR_9, the difference of galacticentric distances of the Cepheid and the Sun (needed to account for the influence of the radial abundance gradient in the Galaxy), we can define, rather accurately, a relation between $\langle V \rangle$ and $\langle K \rangle$ values:

$$\begin{aligned}
\langle K \rangle \;\; = \;\; & \langle V \rangle + 0.093(\pm 0.047) - 0.685(\pm 0.048) \log P \\
& -2.950(\pm 0.036)(\langle B \rangle - \langle V \rangle) + 0.040(\pm 0.016)\Delta R_9 .
\end{aligned} \tag{3}$$

The r.m.s. error of a determination of $\langle K \rangle$ from equation (3), for known $\langle B \rangle$ and $\langle V \rangle$ values, is about $0\overset{m}{.}1$. Table 7 in Berdnikov *et al.* (1996a) contains parameters of similar relations making it possible to determine $\langle K \rangle$ from $\langle V \rangle$ and $\langle m_\lambda \rangle$ (where m_λ can be one of the magnitudes B, R, I, R_C, or I_C). The table shows that errors in $\langle K \rangle$ (as well as the values of the coefficient of ΔR_9) are much lower if one uses R and I, not B and V, bands.

Thus, if a Cepheid has not been observed in the K band, its averaged $\langle K \rangle$ value can be estimated from observations in the visual range.

As a result, we can suggest the following technique for the determination of Cepheid distances (Berdnikov *et al.*, 1996b):

(1) From the Dean *et al.* (1977b) period–colour relation, determine the intrinsic colour index, $(\langle B \rangle - \langle V \rangle)_0$, and the colour excess, E_{B-V}.

(2) Using (3) or another suitable equation from Table 7 in Berdnikov *et al.* (1996b), from average $\langle V \rangle$ and $\langle m_\lambda \rangle$ magnitudes (m_λ being the magnitude measured with a B, R, I, R_C, or I_C filter), determine the average $\langle K \rangle$ value (if it was not determined directly from observations).

(3) Correct $\langle K \rangle$ for the interstellar reddening using the formula:

$$\langle K \rangle_0 = \langle K \rangle - 0.274 E_{B-V}.$$

(4) Determine the star's absolute magnitude, $\langle M_K \rangle$, from the formula:

$$\langle M_K \rangle = -5.46 - 3.52(\log P - 1).$$

(5) Determine the true distance modulus:

$$DM_0 = \langle K \rangle_0 - \langle M_K \rangle.$$

(6) Calculate the Cepheid's distance, R:

$$\log R = 0.2(DM_0 + 5).$$

Berdnikov *et al.* (1996b) show that this procedure (in the case of the $\langle K \rangle$ value not following directly from observations but determined from known average magnitudes in the visual range) gives more accurate results than immediate application of the $\log P - M_{I_c}$, $\log P - M_{R_c}$, $\log P - M_I$, $\log P - M_{I_C}$ (and especially $\log P - M_V$) periods–luminosity relations. Moreover, the formulas used to calculate $\langle K \rangle$ from known magnitudes in other filters take into account differences in abundances of heavy elements, and the $\langle K \rangle$-band period–luminosity relation itself is not sensitive to such differences, so the Cepheid distances based upon the above procedure can be considered free from systematic errors resulting from abundance differences.

5 THE CATALOGUE OF CEPHEID LIGHT CURVE PARAMETERS, LUMINOSITIES, AND DISTANCES

Photometric characteristics of Cepheids, like the period of brightness variations, amplitude, and mean brightness, belong to principal observing parameters useable for studies of properties of Cepheids themselves as well as for determinations of their distances and luminosities. These data can also be used to reconstruct the spatial distribution of Cepheids in order to study the structure and kinematics of the galactic disc, to check predictions of the theory of stellar pulsations and the theory of advanced stages of stellar evolution.

We used the broad-band observations from our data bank to compile a catalogue of light curves for all Cepheids having photoelectric observations. For each Cepheid, in each of the $BVRI$ Johnson filters and $(RI)_C$ Kron - Cousins filters, we first selected observations best representing the light curve. In most cases, these were either our observations or observations published by Gieren (1981), Dean *et al.* (1977a), Coulson and Caldwell (1985), Moffett and Barnes (1984) or Font *et al.* (1996), their photoelectric systems practically coinciding with ours. We approximated the curve, as a whole or in fragments, with a Fourier series (with 3–25 terms), with an interpolation spline, or with a polynomial of the second or third power; then, the fragments were sewn together, forming a so-called standard curve. After this, we reduced the rest of the observations, by means of a least-squares technique described in Berdnikov (1992g), to the system of the standard curve and improved the standard curve itself using combined observations.

From the resulting standard curve, we determined light curve parameters: maximal brightness, amplitude, and intensity-averaged brightness. To calculate the latter, magnitudes were converted to intensities, and the area below the light curve was computed; then, we divided the area into two equal parts with a straight line parallel to the abscissa and converted the intensity of this straight line's ordinate back into magnitudes.

Having reduced about 80 000 observations from our Cepheid data bank, we get 473 classical Cepheids with reliable light curves (at least in two filters, including V), compared to 363 stars in the previous version of the catalogue (Berdnikov, 1987a).

For all 473 Cepheids, we determined luminosities and distances using the above method. Doing this, we assumed that low-amplitude Cepheids (DCEPS type according to the classification adopted in GCVS-IV, Kholopov *et al.*, 1985–1987) pulsate in the first overtone and divided their GCVS-IV periods by 0.7.

The resulting catalogue was published by Berdnikov *et al.* (1998d).

6 A STUDY OF CEPHEID PERIOD CHANGES

The principal objective of this part of our work is to search for evolutionary period changes in the most rapidly evolving Cepheids. We have studied (Berdnikov and Pastukhova, 1994a, b, 1995; Berdnikov *et al.*, 1997) period stability for all of 45 known small-amplitude Cepheids (DCEPS according to the fourth edition of the General Catalogue of Variable Stars – Kholopov *et al.*), and (Berdnikov, 1994) for seven northern sky long-period DCEP Cepheids ($P > 30$ days). We used Berdnikov's (1992g) version of the well-known Hertzsprung method to determine the times of brightness maxima.

Our analysis revealed evolutionary period changes in five Cepheids (X Lac, V473 Lyr, GY Sge, EU Tau, and ET Vul) and confirmed such changes in another five Cepheids (SZ Cas, Y Oph, Polaris, S Vul, and SV Vul). Their $O - C$ diagrams show that evolutionary period changes in these 10 Cepheids are virtually always accompanied by wavelike cyclic oscillations in $O - C$ residuals (with time scales of 10–20–30 years); these oscillations are sometimes superimposed by cyclic oscillations of smaller amplitudes and periods. The latter, in turn, often consist of straight-line segments.

In cases when the amplitude of the above-mentioned oscillations of $O - C$ residuals is small compared to the progressive period change, the parameters of the parabola defining the evolutionary part of the period changes can be determined with much confidence. However, for a number of stars the amplitude of the oscillations is comparable to the progressive period change. Identification of evolutionary period changes in such Cepheids (V496 Aql, GI Car, SU Cas, IR Cep, V396 Cyg, V609 Cyg, V1467 Cyg, V1726 Cyg, UY Mon, and CI Per) becomes a very difficult task.

The situation is complicated still further, when the "period" of the cycle mentioned above is comparable to the interval of observations under consideration. In this case it is impossible to identify evolutionary period changes (EV Aql, VY Cas, NY Cas, V379 Cas, BB Cen, DT Cyg, V532 Cyg, DX Gem, EV Set, and SZ Tau).

Unfortunately, for nearly half of the investigated Cepheids, the available observational data are not enough to search for evolutionary changes in their periods.

The relative rates of period changes, $\log(\Delta P/P)_{100}$, for more than 20 Cepheids can be compared with theoretical values. Figure 1 shows a plot of $\log(\Delta P/P)_{100}$ versus $\log P$: the dots show the observed data, and the heavy lines are theoretical relations for the first, third, and fifth crossings of the instability strip (Saitou, 1989). The location of these lines depends on the abundances of helium and heavy elements; in Figure 1, their location corresponds to the chemical composition $Y = 0.28$ and $Z = 0.02$.

The scatter of experimental data points in Figure 1 is rather large; it is close to the scatter for the few theoretical models used to calculate the location of the lines. In addition, calibrations and statistical relations whose coefficients are not as yet sufficiently reliable are used to plot the theoretical calculations in the $\log(\Delta P/P)_{100}$–$\log P$ diagram (Saitou, 1989). As a result, the zero points of the theoretical $\log(\Delta P/P)_{100}$–$\log P$ relations for different crossings of the instability strip are somewhat uncertain, and this uncertainty is most probably systematic in nature. Therefore, the crossing number cannot be unambiguously determined for each individual Cepheid from a comparison of the experimental and theoretical data shown in Figure 1.

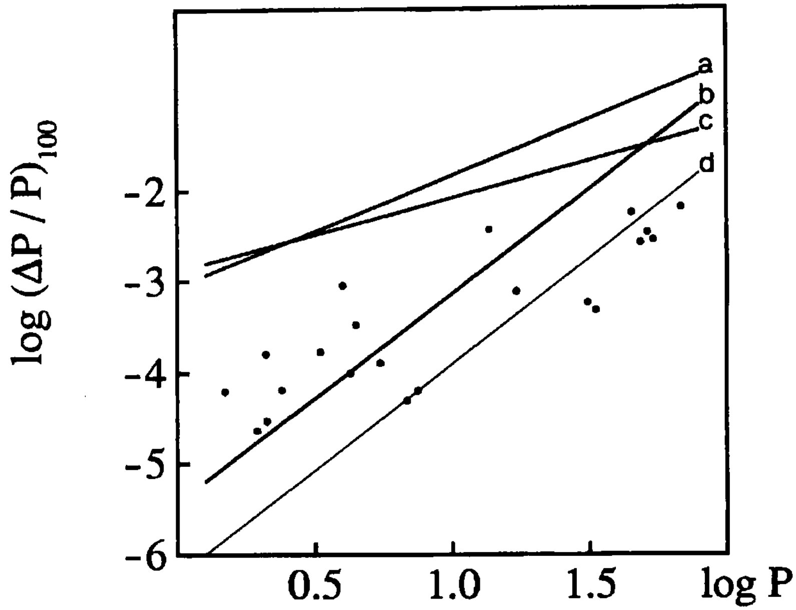

Figure 1 The plot of $\log(\Delta P/P)_{100}$ versus $\log P$. The dots show our observed data, and the heavy lines are theoretical relations for the first (*a*), second + third (*b*), and fourth + fifth (*c*) crossings of the instability strip (Saitou, 1989); the thin line (*d*) is the experimental relation obtained by Saitou (1989) for normal classical Cepheids in the second and third crossing of the instability strip.

However, some conclusions can be reached by assuming that the low-amplitude Cepheids are all observed during the same crossing of the instability strip. In particular, this immediately rules out their belonging to the fifth crossing, because Cepheids with short periods (which is observed for most of the DCEPS stars) have masses for which the greatest possible number of crossings of the instability strip is three. In Figure 1, the assembly of DCEPS is closest to the line corresponding to the third crossing. However, given the above discussion, this identification cannot be considered reliable.

The experimental $\log(\Delta P/P)_{100}$–$\log P$ relation obtained by Saitou (1989) for normal classical Cepheids in the second and third crossing of the instability strip is indicated in Figure 1 by the thin line. The low-amplitude Cepheids lie considerably higher, with the distance between the thin line and the assembly of DCEPS stars being approximately the same as the distance between the theoretical relations for the third and the first crossings. We conclude, therefore, that the low-amplitude Cepheids are most probably in the stage of the first crossing of the instability strip, thereby confirming Efremov's (1968) surmise that low-amplitude pulsations of classical Cepheids arise during the first crossing of the instability strip. Note again that we reached this conclusion by assuming that the DCEPS variables are all observed during the same crossing.

7 RADIAL VELOCITY MEASUREMENTS

In 1985, a correlational spectrometer – radial-velocity meter (CORAVEL type) was inaugurated at the Sternberg Institute (Tokovinin, 1987; the present configuration of the instrument is described in Berdnikov *et al.*, 1994). The spectrometer enables us to determine radial velocities of stars in the F5–M5 range, down to $V \approx 13$ with 1-m telescopes, with a characteristic accuracy around 0.5 km s^{-1}. Since 1987, the programme of observations includes Cepheids. Two major catalogs of Cepheid radial velocities, measured by us, have been published (Gorynya *et al.*, 1992a, 1996b); they contain about 3600 velocity values for 102 Cepheids. Since then, our team of observers obtained about 2000 additional measurements. Our series of original high-quality radial velocity measurements of Cepheids is currently the world's richest.

Our Cepheid radial velocity programme has several subprogrammes, among them:

(1) discoveries of new spectroscopic-binary Cepheids, determinations of orbits;

(2) studies of double-mode Cepheids;

(3) determinations of Cepheid radii using the Baade–Wesselink technique.

We have been able to discover a number of new spectroscopic-binary Cepheids: MW Cyg (Gorynya *et al.*, 1992b), VZ Cyg (Samus *et al.*, 1993), BY Cas (Gorynya *et al.*, 1994). A number of suspects have been announced in the remarks to our catalogs. Having accumulated long series of radial velocity measurements, we determined orbits for the new spectroscopic binaries and improved orbital elements for several known spectroscopic-binary Cepheids (Gorynya *et al.*, 1995, 1996a; Rastorgouev *et al.*, 1997). As a result, we could separate orbital and pulsational motions and use spectroscopic-binary Cepheids in our Baade–Wesselink studies.

From our data, the lower limit on the incidence of spectroscopic binaries among Cepheids is estimated to be 22% (Gorynya *et al.*, 1996a). Our estimate is rather close to that derived by Mermilliod and Mayor (1992) from measurements of radial velocities for red giants in open clusters.

In order to study radial velocities of double-mode Cepheids, it is necessary to accumulate a very large number of measurements (if possible, up to 100 and even more). So far, we have achieved this level only for one star (EW Set; Samus and Gorynya, 1991). Nevertheless, Sachkov (1997a) presented velocity curves of five double-mode Cepheids separately for both modes and thus was able to include these stars in the Baade–Wesselink analysis.

For our analysis of Cepheid radii, we selected the modification of the Baade–Wesselink technique suggested by Balona (1977). Its main advantage is insensitivity to interstellar absorption. In our realization of the method, we solve the non-linear problem. We are also able to use either a complete light (and velocity) curve or, for instance, exclude the ascending branch where shock-wave phenomena can bias the results.

Sachkov *et al.* (1998) have presented a detailed analysis of the influence of errors of photometric and radial-velocity measurements on the determined radii. It is shown that the realistic error estimate for radii exceeds the formal uncertainties (derived in the maximum-likelihood calculations) by a factor of 2–2.5 and reaches at least 15%.

Using our rich and homogeneous series of radial-velocity observations and photometry from our data base (Berdnikov, 1995), with special attention to spectroscopic and photometric observations being quasi-simultaneous, Sachkov *et al.* (1998) derived radii for 62 Cepheids. They obtained a revised period–radius relation for classical Cepheids:

$$\log R = 1.23(\pm 0.03) + 0.62(\pm 0.03)\log P.$$

The Baade–Wesselink analysis of s-Cepheids (Sachkov, 1997b) shows that some of the stars attributed to the DCEPS type in the GCVS do not deviate from the period–radius relation for normal Cepheids and thus may be fundamental-mode pulsators, whereas the majority of s-Cepheids form a parallel relation, presumably corresponding to the first overtone. If we accept the above interpretation and reduce all periods to the fundamental mode ($P_0 = P_1/0.71$), the resulting combined period–radius relation does not significantly differ from our relation for normal Cepheicls.

Unfortunately, we come to the conclusion that, given the realistic estimate of the uncertainties of radii, it is currently not possible to improve the Cepheid distance scale based upon their radii.

8 CONCLUDING REMARKS

The scope of this paper does not include our results in the field of using Cepheids as distance indicators in galactic disc studies. The results we have been able to achieve here (Berdnikov and Efremov, 1989, 1993; Dambis *et al.*, 1995; Glushkova *et al.*, 1998; Berdnikov *et al.*, 1998a) also correspond to the world's best level.

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