# STUDIES OF GALACTIC CEPHEIDS: THE INASAN/SAI INTEGRATED PROGRAM

N.N. Samus[1,2,3], S.V. Antipin[2,1], L.N. Berdnikov[2], A.K. Dambis[2], N.A. Gorynya[1], A.S. Rastorguev[2]

[1] Institute of Astronomy, Russian Acad. Sci.
48, Pyatnitskaya Str., Moscow 119017 Russia, *samus@sai.msu.ru*
[2] Sternberg Astronomical Institute, Moscow University
13, University Ave., Moscow 119992 Russia
[3] Euro-Asian Astronomical Society
13, University Ave., Moscow 119992 Russia

ABSTRACT. We present the review of the main results of more than two decades of the Moscow program of Cepheid studies, carried out at the Institute of Astronomy (INASAN) and Sternberg Astronomical Institute (SAI). This program consists of extensive photometry and radial velocity measurements (the contribution from our team being the largest among observations of comparable precision), studies of period variations (permitting identification of the number of a particular star's current instability-strip crossing), detection of spectroscopic binaries among Cepheids, determinations of Cepheid radii, discoveries of double-mode Cepheids, studies of galactic structure, kinematics, and dynamics, etc.

**Key words**: Stars: variable: Cepheids.

## 1. Introduction

Our program of Cepheid studies, a joint project of the Sternberg Astronomical Institute of Moscow University (SAI) and the Institute of Astronomy of Russian Academy of Sciences (INASAN), is mainly devoted to classical Cepheids (DCEP and subtypes in the GCVS), though some of our results deal with Population II Cepheids (W Vir and BL Her stars, or CWA and CWB in the GCVS). Classical Cepheids are comparatively young stars in the Galaxy's thin disk, whereas Population II Cepheids are members of the thick disk and halo populations. Our team is engaged in Cepheid studies since the 1970s, the most active period of the program started in 1980s and is still under way. It is now time to summarize the most important results of the program.

Classical Cepheids remain very important in many fields of astrophysics and galactic research. The primary reason for their importance is that, thanks to the famous period–luminosity relation, Cepheids are objects with the most reliable distance scale. They are supergiants traceable at large distances and thus present a link between close objects, with trigonometric parallaxes, and distant parts of our Galaxy as well as extragalactic objects. An important period–age relation allows astronomers to estimate ages of stellar aggregates containing Cepheids in a very simple way. Cepheid period variations give insight into stellar evolution and permit identification of the number of a Cepheid's current crossing of the instability strip. Additional information on stellar evolution comes from double-mode Cepheids thanks to co-existence of two pulsation modes, with periods differently dependent on stellar parameters. Being radially pulsating stars, Cepheids permit application of the well-known Baade–Wesselink technique to their photometry and radial velocity measurements, so that we are able to determine their radii and to study the period–radius relation. Many Cepheids are members of binary systems with long periods (months or years), so it is possible to derive limits on the masses of their companions. As typical representatives of Population I, classical Cepheids are a good tool for studies of structure, kinematics, and dynamics of our Galaxy's thin disk.

## 2. Photometry and Spectroscopy

Twenty-five years ago L.N. Berdnikov initiated our program of high-precision Cepheid photometry, which is being continued till now. Initially, Cepheids were observed photoelectically, mainly using telescopes at the excellent conditions of Mt. Maidanak (Uzbekistan). Later on, our observations were continued at many other observatories in different countries (Russia, Uzbekistan, Australia, South Africa, Chile). Currently, we use both principal techniques of accurate photometric observations (photoelectric and CCD photometry).

The total number of our accurate $UBVRI$ measurements collected by now is approximately 75 000, for about 650 Cepheids. Many of these measurements can be found in numerous publications by our team. A recent version of the catalogue of our measurements is available in Internet (Berdnikov, 2006). Photoelectric and CCD measurements were supplemented by a large number of brightness estimates made in photographic plate stacks of different observatories, in particular, in the Sternberg Institute's and Harvard Observatory's plate archives. We collected published information on visual photometry, including that acquired during time intervals not covered with our observations. For some stars, the time span of available observations is up to 150 years or even more. Our photometric observations and data collected from the literature permitted us to compile the world's most complete data bank of Cepheid photometry.

About 20 years ago, we got access to the excellent instrument for radial velocity measurements, the CORAVEL-type correlation spectrometer designed and built by A.A. Tokovinin, and started regular observations of Cepheids in Moscow, Crimea (Simeiz and Nauchny), and at other observatories. Currently, the instrument is used in Simeiz, almost exclusively for our Cepheid program. It permits us to measure radial velocities for stars brighter than $12^m - 13^m$ with a good productivity, the characteristic accuracy (in the sense of external agreement) for tenth-magnitude stars is about 0.3 km $s^{-1}$. Three catalogues of our measurements, with the total number of observations about 6000, were published (cf. Gorynya et al., 1998a, and references therein), the observations from these publications are available in the electronic catalogue III/229 in VizieR (Gorynya et al., 1998b). Currently, the number of our radial velocity measurements for 165 Cepheids is about 10 000.

Our photometry as well as our radial velocities comprise a total of about 60% of all measurements of comparable precision available in the world.

## 3. Period Variations

The data bank on Cepheid photometry permits us to study period variations of Cepheids. The sample we used for period–variation studies contains about 230 Cepheids with observations covering 100–150 years. For the oldest known Cepheids, $\eta$ Aql and $\delta$ Cep, epochs of maxima usable for period-change studies span 230 years.

Most Cepheids are rather stable pulsators. However, small variations of their periods were already noticed decades ago. The theory predicts quite detectable period variations due to stellar evolution. Such variations are progressive and can be described with a more or less stable rate of period change. Thus, the $O - C$ diagram for evolutionary period variations should be a parabola, and the parabola's orientation (branches upwards or downwards) will be different for odd and even numbers of the star's instability-strip crossing. For different precursor main-sequence luminosities, the theory permits us to expect from 1 to 5 crossings of the instability strip during the life of a Cepheid. If the period-variation rate is precisely determined from observations, we can even hope to specify the particular number of the odd or even crossing (cf. Turner et al., 2006). Our analysis of Cepheid period variations is based on very accurate timings of maxima determined using a uniform technique, the computer version of the Hertzsprung method that takes into account the complete light curve, not only the data points immediately around the maximum (Berdnikov, 1992). This makes our findings concerning period variations especially reliable.

It was, however, noticed quite long ago that the character of period variations for many Cepheids was much more complex than the simple pattern of evolutionary variations outlined above. Many Cepheids demonstrate abrupt period changes or more or less irregular period variations, period increases can be followed by period decreases and *vice versa*, so that the overall period-variation picture is clearly determined not only by evolution. The causes of observed non-evolutionary period changes are still not completely understood, several mechanisms were suggested. Nevertheless, we find from our data that the evolutionary period variations, masked with those of different nature, can be detected for 90% of all Cepheids with observations covering 100 years or more. Figure 1 shows a typical example of the $O - C$ diagram revealing an evolutionary period increase (an odd crossing of the instability strip), while the $O - C$ diagram in Fig. 2 apparently permits us to identify the period increase (an odd crossing) also reliably, despite strong overlapping non-evolutionary period variations.

If the number of the particular instability-strip crossing is known, it should be taken into account when determining the Cepheid's distance. Equal periods can be met for Cepheids of different masses, at different instability-strip crossings. The period–luminosity relations for different crossings can differ by several tenths of a magnitude. Thus, detailed studies of Cepheid period variations are a tool for considerable improvement of the distance scale in the Universe.

## 4. Binary Cepheids

Cepheids can be members of binary star systems. Being supergiants, they have characteristic orbital periods in excess of a year. Though binarity of several

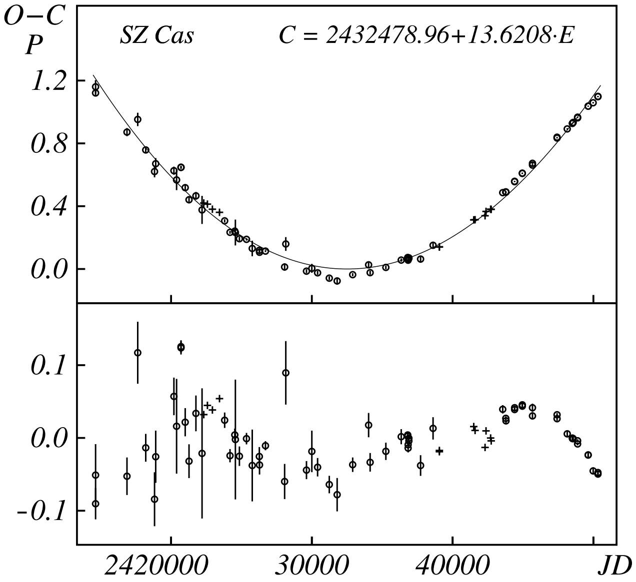

Figure 1: The $O-C$ diagram for SZ Cas showing an obvious period increase, corresponding to an odd crossing of the instability strip. The bottom panel shows residuals after fitting a parabola to the $O-C$ curve.

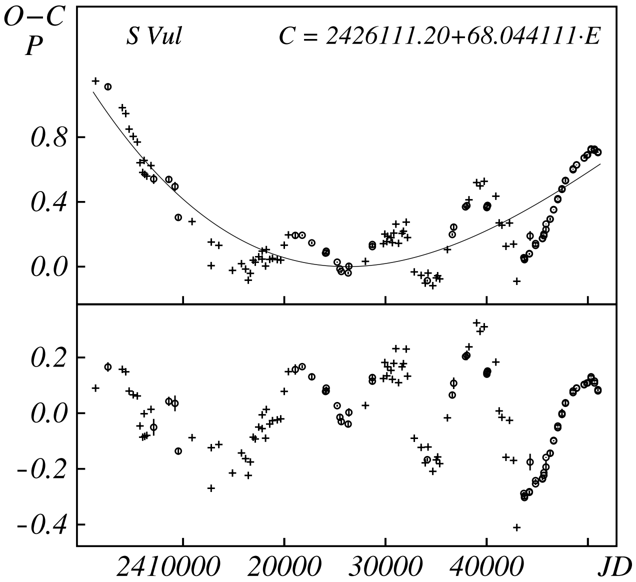

Figure 2: The $O-C$ diagram for S Vul showing a period increase, corresponding to an odd crossing of the instability strip, masked with non-evolutionary period variations.

Cepheids was suspected from possible light-time effect in their $O-C$ diagrams, the complex character of such diagrams (Section 3) makes this technique not very reliable. According to Szabados (2003), who strongly relies on the $O-C$ diagrams, the fraction of binaries among bright Cepheids approaches 90%. We are afraid that this is an overestimate, including wrong detections from $O-C$ diagrams and physically unrelated neighbors on the sky. In our opinion, to reliably discover a binary Cepheid, it is necessary to detect its orbital radial-velocity variations, to separate the star's orbital and pulsational velocity curves, and, if possible, to derive the parameters of the binary's components. The latter task is simplified thanks to the mass of the Cepheid component known from the pulsation theory. Of course we will be unable to detect some really binary Cepheids in a case of an unfavorable inclination of their orbits, but the same is true for the $O-C$ techniques.

Our team has excellent possibilities for studies of binary Cepheids thanks to our high-quality original radial velocities. We discovered (or suspected with good reason) five new spectroscopic-binary Cepheids (Gorynya et al., 1992, 1994; Samus et al., 1993; Gorynya et al., 1996) and were able to confirm many previously known ones. From our data, we estimate the lower limit on the incidence of spectroscopic binaries among classical Cepheids as 22% (Gorynya et al., 1996). For 20 Cepheids, including the new binaries, we were able to determine orbital elements and to estimate companions' masses.

During the recent years, several eclipsing Cepheids were discovered in external galaxies, primarily in the Magellanic Clouds. However, there were no known eclipsing Cepheids in our Galaxy. Very recently, Antipin et al. (2007) found the first Galaxy's eclipsing Cepheid, TYC 1031 01262 1. It should be noted that the star's position with respect of the Milky Way and its orbital period, 51 days, which is too short for sizes of supergiant classical Cepheids, suggest that TYC 1031 01262 1 is a Population II star. Interesting enough, the star shows strong brightness variations outside eclipses, also satisfying the orbital period (Fig. 2). It may indicate that the components of the binary are non-spherical, which is, however, unfavorable for stability of pulsations. Further observations of the star are evidently needed. The new binary resembles the three short-period Population II spectroscopic binaries without eclipses discussed by Harris and Welch (1989): IX Cas ($P = 110^d$), TX Del ($P = 133^d$), and AU Peg ($P = 53^d$), but TYC 1031 01262 1 has the shortest period of them all. TX Del and AU Peg were also in our program of binary-Cepheid studies from radial velocities, we detected the spectroscopic binarity of TX Del before learning about its discovery by Harris and Welsh. The existence of sufficiently close binaries among evolved Population II stars is not widely

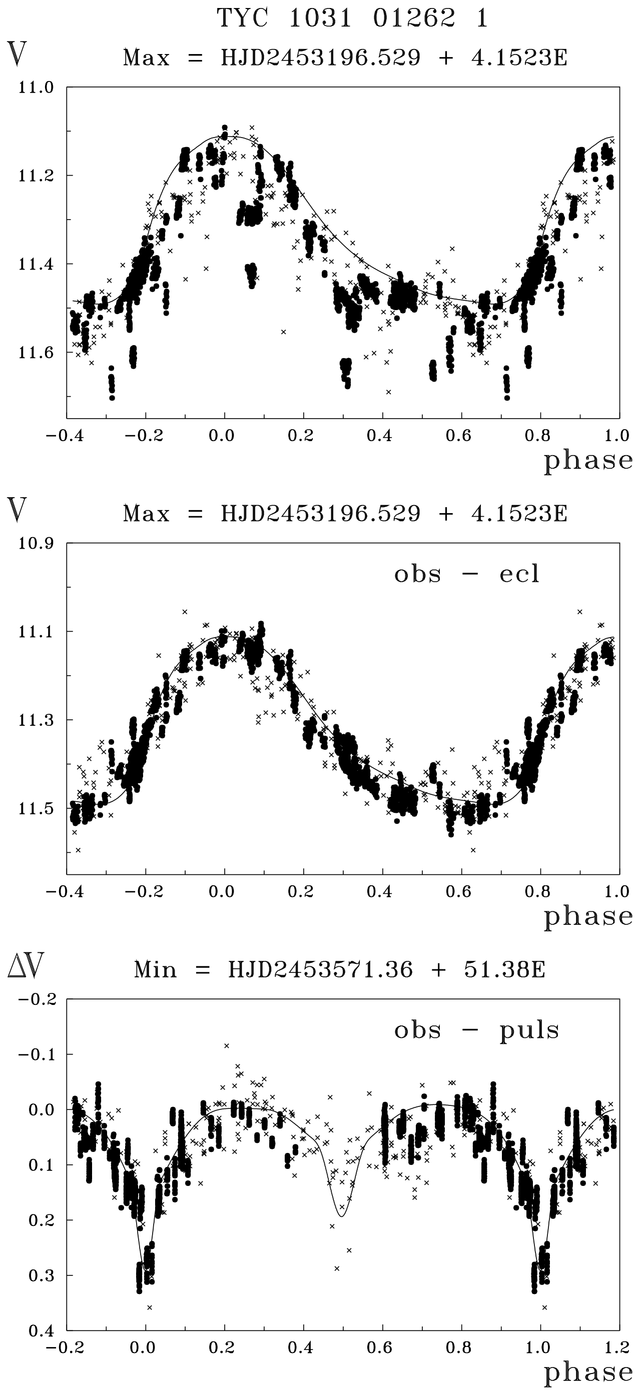

Figure 3: The light curves of TYC 1031 01262 1. Top: observations folded with the pulsation period. Middle: same, with orbital variations removed. Bottom: observations with the pulsational variations removed, folded with the orbital period.

recognized and quite interesting for understanding the Galaxy's old populations.

## 5. The Baade–Wesselink Analysis. Identification of Cepheid Pulsation Modes.

It is well known that radial velocities of radially pulsating variable stars combined with their multicolor photometry can be used to determine their physical characteristics, in particular radii, using the Baade–Wesselink technique. In essence, the color information gives insight into variations of the effective temperature, the magnitude difference at different phases reflects the radius ratio, and the integral of the radial velocity curve is the difference of the radii at corresponding phases multiplied by a known correction factor. The particular version of the method we use is the technique described by Balona (1977) and somewhat improved by us. The result of the method's application to a particular pulsating star is its mean radius as well as the curve of the radius variations during the pulsation cycle. We are now working on new modifications of the method taking into account the most current understanding of the physics of stellar pulsations.

The results of our Baade–Wesselink studies of classical Cepheids using our original photometry and radial velocities were summarized in Sachkov et al. (1998). From 62 Cepheids, a period–radius relation for the fundamental mode was determined. Some Cepheids clearly deviate from the relation, they should probably be identified with first-overtone pulsators.

Note that mode identification for our Galaxy's classical Cepheids is not straightforward, whereas the data for different galaxies (like OGLE data for the LMC) show two different period–luminosity relations, for the fundamental and first-overtone modes, separated by about 0.15 in $\log P$ (according to the pulsation theory, $P_1/P_0 \approx 0.71$, where $P_0$ is the fundamental-mode period and $P_1$, that of the first overtone). The mode ambiguity is an important uncertainty source for Cepheid distances. If a star is wrongly classified as a first-overtone pulsator, a lumunosity error of about $0.65^m$ will be introduced.

Besides the period–radius relation, an important tool of mode diagnostics is the Fourier analysis of light curves. We attempted to apply the neural network technique to $V$-band light curves of more than 400 galactic Cepheids using OGLE data on LMC Cepheids as a training sample (Zabolotskikh et al., 2005). As expected, most Cepheids classified as DCEPS (small amplitudes, rather symmetric light curves) in the 4th edition of the General Catalogue of Variable Stars (GCVS; Kholopov, 1985–1987) turned out to be first-overtone pulsators, but we detected 9 stars with GCVS classification leading to a wrong mode identification. Zabolotskikh et al. (2005) suggested new Cepheid period–radius relations, separately for the fundamental-mode pulsators,

$$\log R = 1.08(\pm 1.01) + 0.74(\pm 0.01) \log P,$$

and for the first-overtone pulsators,

$$\log R = 1.19(\pm 1.01) + 0.74(\pm 0.01) \log P.$$

They have the same slope but differ in the zero point.

A Fourier analysis of radial velocity curves is also of interest, the results are easier to interpret from the point of view of the pulsation theory. Such studies are also under way in our team (N.A. Gorynya in cooperation with P. Moskalik, Warsaw). New radial-velocity observations are arranged to ensure complete phase coverage of velocity curves, which was already successfully achieved for most program stars.

## 6. Double-Mode Cepheids

Double-mode Cepheids are met not very frequently in our Galaxy and only among Cepheids with comparatively short pulsation periods. Most of them exhibit simultaneously excited pulsations in the fundamental mode and the first overtone, with rare cases of the co-excited first and second overtones (the particular modes are identified by comparison of the observed period ratios to theoretical predictions). Triple-mode stars (Antipin, 1997) are extremely rare, it is not clear if they should be analyzed with Cepheids or with RR Lyrae stars. Studying simultaneous pulsations in two modes, it is possible to derive masses and radii and get additional insight into evolution of Cepheids.

Currently, 23 double-mode Cepheids are known in our Galaxy; five of them were discovered at the SAI. Whereas the first stars were found photographically (the first SAI discovery was V367 Sct; Efremov and Kholopov, 1975), our most recent discovery (ASAS 062726+0111.6; Antipin, 2006) was made in the data publicly available from the ASAS-3 automatic survey (Pojmanski, 2002).

## 7. The Period–Luminosity Relation

It is widely known that the period–luminosity relation is the most important relation for Cepheids, it is this relation that makes Cepheids so important for galactic and extragalactic studies. Small revisions of the period–luminosity relation can have serious consequences for our understanding of many “hot” problems of astrophysics and even cosmology.

Berdnikov et al. (1996) revised the period–luminosity relation using the best modern data for 9 Cepheids in 7 open star clusters. The distances to the open clusters were accurately determined by main-sequence fitting. They were able to derive the parameters (both the zero point and slope) of the consistent period–luminosity relations in the Johnson $BVRI$, Cousins $(RI)_C$, and CIT $JHK$ bands. As an example, the $V$-band period–luminosity relation is:

$$< M_V >= -3.88 - 2.87(\log P - 1).$$

The near-infrared relations are particularly useful because of much lower influence of interstellar extinction at large wavelengths.

The period–luminosity relations from Berdnikov et al. (1996) agree with our findings from statistical parallaxes (see next Section).

## 8. Cepheids and the Structure and Kinematics of our Galaxy

Being objects with the most accurate distance scale (in the sense of random errors), Cepheids are very suitable objects for studies of the structure and dynamics of the Galaxy’s disk. These stars are relatively young, they outline star formation regions and local spiral arms. By means of cluster analysis in a 5 pc×5 pc region around the Sun, more than 60 Cepheid complexes, with sizes from 600 pc to 1.4 kpc, have been revealed (Berdnikov et al., 2006).

It is known that studies in the optical domain are seriously hindered with large and irregular interstellar extinction of light, causing observational selection effects that are strong and difficult to correct for. Selection effects are not that important if we use kinematics instead of magnitudes and local densities. For this reason, kinematical effects due to spiral density waves are often used to study the local spiral pattern. Photometric parallaxes of Cepheids, combined with their precise radial velocities, Hipparcos and Tycho-2 proper motions are quite usable to analyze such kinematical effects. We detected a radial periodicity in residual velocities of Cepheids and other young objects, it permitted us to independently estimate the distance between the spiral arms of our Galaxy as 2 kpc (Mel’nik et al., 1999).

Using a technique based on the maximum likelihood principle, it is possible to analyze the field of Cepheid spatial velocities (Zabolotskikh et al., 2002). The resulting complete set of kinematical characteristics (mainly based on the cited paper) contains the rotation curve parameters for the Cepheid subsystem (the local disk rotation velocity of $206 \pm 10$ km s$^{-1}$, the Oort’s constant $A = 17.5$ km s$^{-1}$kpc$^{-1}$), the axes of the residual velocity ellipsoid ($14 \pm 1$, $9 \pm 0.5$, $7 \pm 1$ km s$^{-1}$), the perturbation amplitudes ($7 \pm 2$ and $2 \pm 0.5$ km s$^{-1}$), the pitch angle of the spiral pattern ($7^\circ \pm 1^\circ$), and the phase angle of the Sun ($85^\circ \pm 15^\circ$). The statistical parallax method applied to the 3D velocity field confirms the short distance scale of Cepheids, corresponding to the distance modulus of the Large Magellanic Cloud close to $18.3^m$.

*Acknowledgements.* It is a pleasure to acknowledge the financial support of our Cepheid studies from the Russian Foundation for Basic Research and the Program of Support for Leading Scientific Schools of Russia.

## References

Antipin S.V.: 1997, *Astron. and Astrophys.*, **326**, L1.

Antipin S.V.: 2006, *Perem. Zvesdy Prilozh.*, **6**, No. 9.

Antipin S.V., Sokolovsky K.V., Ignatieva T.I.: 2007, *Mon. Not. R. Astron. Soc.*, **379**, L60.

Balona L.A.: 1977, *Mon. Not. R. Astron. Soc.*, **178**, 231.

Berdnikov L.N.: 1992, *Sov. Astron. Lett.*, **18**, 207.

Berdnikov L.N.: 2006, *A Catalogue of Cepheid Observations* (http://www.sai.msu.su/groups/cluster/CEP/ PHE/cepheids-16-03-2006.zip).

Berdnikov L.N., Efremov Yu.N., Glushkova E.N., Turner D.G.: 2006, *Odessa Astron. Publ.*, **18**, 26.

Berdnikov L.N., Vozyakova O.V., Dambis A.K.: 1996, *Astron. Letters*, **22**, 839.

Efremov Yu.N., Kholopov P.N.: 1975, *Inform. Bull. Var. Stars*, No. 1073.

Gorynya N.A., Rastorguev A.S., Samus N.N.: 1996, *Astron. Letters*, **22**, 175.

Gorynya N.A., Samus N.N., Rastorguev A.S.: 1992, *Inform. Bull. Var. Stars*, No. 3776.

Gorynya N.A., Samus N.N., Rastorguev A.S.: 1994, *Inform. Bull. Var. Stars*, No. 4130.

Gorynya N.A., Samus N.N., Rastorguev A.S. et al.: 1998a, Astron. Letters, **24**, 815.

Gorynya N.A., Samus N.N., Sachkov M.E. et al.: 1998b, VizieR III/229 (http://cdsarc.u-strasbg.fr/viz-bin/Cat?III/229).

Harris H.C., Welch D.L.: 1989, *Astron. J.*, **98**, 981.

Kholopov P.N. (ed.): 1985–1987, *General Catalogue of Variable Stars*, Vols. I–III, Moscow: Nauka.

Mel'nik A.M., Dambis A.K., Rastorguev A.S.: 1999, *Astron. Letters*, **25**, 518.

Pojmanski, G.: 2002, *Acta Astron.*, **52**, 397.

Sachkov M.E., Rastorguev A.S., Samus N.N., Gorynya N.A.: 1998, *Astron. Letters*, **24**, 377.

Samus N.N., Gorynya N.A., Kulagin Yu.V., Rastorguev A.S.: 1993, *Inform. Bull. Var. Stars*, No. 3934.

Szabados L.: 2003, *Inform.Bull. Var.Stars*, No.5394.

Turner D.G., Abdel-Latif M.A.-S., Berdnikov L.N.: 2006, *Publ. Astron. Soc. Pacific*, **118**, 410.

Zabolotskikh M.V., Rastorguev A.S., Dambis A.K.: 2002, *Astron. Letters*, **28**, 454.

Zabolotskikh M.V., Sachkov M.E., Berdnikov L.N. et al.: 2005, in: *The Three-dimensional Universe with GAIA*, ESA Publ. SP-576, 707.