CEPHEID PULSATIONS FROM RADIAL VELOCITY MEASUREMENTS

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ABSTRACT. We discuss the results of our many-year program of Cepheid radial velocities concerning the Hertzsprung sequence in radial-velocity curves, double-mode Cepheids, the period–radius relation, binary Cepheids.

Key words: Variable stars: Cepheids.

1. Introduction

In this contribution, we present some results of our program based upon observations of Galactic Cepheids with a CORAVEL-type correlation spectrometer. The program uses the principal advantage of small-telescope programs, namely, the possibility to have plenty of observing time in the course of many years, combined with special advantages of the particular radial velocity spectrometer, namely, its outstanding effectiveness combined with quite modest requirements to the size of the telescope used and with the possibility to carry the spectrometer from one observing site to another, according to availability of telescopes and to weather conditions.

The spectrometer, ILS, was designed and built by Tokovinin (1987) in 1986. It uses the ideas first suggested by Felgett (1953) and by Griffin (1967) and then implemented for echelle spectrometers in the CORAVEL machine (Baranne et al., 1979). The general idea of a CORAVEL-type spectrometer is the following. An echelle spectrograph forms an image of a star's spectrum. In the focal plane, a physical mask is placed. It is actually an image of the spectrum of a "standard" star, in our case, of Arcturus; the positions of the mask corresponding to spectral lines are transparent, those between them are not. A special plane mirror added into the optical scheme oscillates at a frequency about 10 Hz so that the observed spectrum moves back and forth along the mask. The flux passing through the mask is minimal when the lines of the observed spectrum coincide with the "lines" of the mask. The light passing through the mask is then collected and measured with a photomultiplier. A special controller (in the earlier configuration of the instrument) or a computer (currently) serves to collect the measurements of light separately for 50 time intervals of each oscillation cycle of the plane mirror. Thus, we obtain a "generalized spectral line", actually corresponding, in our case, to 1500 lines in the spectrum of the program star or of Arcturus. The registered "line" covers the range of approximately ±25 km/s; but we can search for the radial velocity in a much wider interval, about ±300 to 500 km/s, using calibrated rotation of the diffraction grating of the spectrometer. The generalized line is then fitted to a relevant profile (usually, but not exclusively, Gaussian), and the position of its minimum determines the radial velocity. Preliminary reductions are performed already during observations, but more sophisticated software can be used off-line to improve accuracy. The reductions take into account all necessary corrections for the motion of the observer; the zero point correction, characteristic of similar instruments, is determined using observations of radial velocity standards acquired each night. The profile shape gives additional information about abundances or rotation.

The main technical characteristics of the ILS machine are the following. It can measure radial velocities of main-sequence stars with "normal" chemical abundances in the spectral type range approximately from F5 to M5; somewhat earlier giants can also be measured. The characterisctic accuracy for sufficiently bright stars in the middle of the spectral type range is ±0.3 to 0.5 km/s. The limiting magnitude for telescopes of the 1-m class is about $12^m.5$; in record cases, stars as faint as 14^m could be measured. The typical exposure time for brighter stars is about 5 min; for faint stars, it seldom exceeds 30 min.

Several instruments of CORAVEL-type design were built in the 1980ies or early 1990ies in different countries. By now, ILS seems to be one of very few survivors. Surely there are advantages in registering the complete spectrum with a CCD and then determining the radial velocity (and numerous other parameters) by means of purely digital reductions. However, instruments like the ILS have proved to be excellent machines for "the poor", the reductions are very simple, almost no additional technical support is needed, and you can bring your instrument to an isolated observatory and start observing the next night. We are going to continue the use of the ILS for several more years.

During 15 years of active exploitation of the ILS, it was used by several groups for rather many scientific programs, among them:
- orbits of binary and multiple stars;
- kinematics of the Galaxy;
- kinematics of stars in open and globular clusters;
- pulsations of stars (Cepheids and some others).

Here we'll discuss only the latter program.

2. Observations

Table 1: Telescopes and Observations of Cepheids.

No	Telescope	Years	No. of observ.
1	70 cm, Moscow, Russia	1987–2000	867
2	60 cm, Nauchny, Crimea, Ukraine	1987–1990	47
3	200 cm, Shemakha, Azerbaijan	1988	2
4	122 cm, Abastumani, Georgia	1988	8
5	125 cm, Nauchny, Crimea, Ukraine	1989–1990	64
6	100 cm, Mt.Maidanak, Uzbekistan	1989–1993	283
7	100 cm, Simeiz, Crimea, Ukraine	1990–2000	3792
8	60 cm, Simeiz, Crimea, Ukraine	1990–1998	1902
9	200 cm, Mt.Rozhen, Bulgaria	1990	16
10	60 cm, Mt.Maidanak, Uzbekistan	1991	212
11	60 cm, Zvenigorod, Russia	1997	18

Grand total: 14 years, 1341 nights, 7211 observations of 144 Cepheids

In 1987–2000, we acquired more than 7000 observations of 144 Cepheids using 11 telescopes in 6 countries (Russia, Ukraine, Georgia, Azerbaijan, Uzbekistan, Bulgaria), from 60 cm to 2 m aperture. Table 1 shows some additional information on the telescopes. Mainly, telescopes of the 1-m class were used. Probably we may call our main instrument the 1 m telescope of the Simeiz Observatory (Crimea, Ukraine). The observatory is now a department of the Crimean Astrophysical Observatory, but, despite the disintegration of the Soviet Union, the telescope still belongs to the Institute of Astronomy, Moscow. Note also that we use, rather effectively, the 70 cm telescope of the Sternberg Astronomical Institute, installed in Moscow, in less than 10 km from the Kremlin! The observations have been continued in 2001, but the reductions have not been completed yet.

The specific feature of our program is that we try to obtain a good coverage of the pulsation velocity curve for each Cepheid during each year season. Our data base of original accurate radial velocity measurements for Cepheids currently appears to be the world-richest.

3. Results

Figure 1 shows characteristic radial velocity curves for Cepheids, folded with their pulsation periods. Note that the scatter of data points in the upper panel is very low, and the velocity curve looks not worse than good photoelectric light curves of Cepheids. Thus, if applying the Baade–Wesselink technique to determine Cepheid radii, the factor crucially limiting the accuracy is no longer the uncertainty in radial velocities. The two lower panels show examples looking not so nice. If the period of the Cepheid is correct and does not vary strongly, there can be two reasons for the increased scatter. The first of them is double-mode pulsation (middle panel).

We have observed several double-mode Cepheids and were able to separate the two pulsation modes in their radial velocities. EW Sct is a well-known double-mode Cepheid; its amplitude of radial velocity variations corresponding to the fundamental mode exceeds that corresponding to the first overtone. V458 Sct (Fig. 2) is a new double-mode Cepheid discovered by Antipin (1997). (Less than 20 double-mode Cepheids are currently known in the Galaxy, two of them recently discovered in Sternberg Institute by S.V. Antipin.) We have already accumulated enough observations of V458 Sct to separate its two modes in radial-velocity variations (Antipin *et al.*, 1999). For this star, the first overtone amplitude is larger; the same effect is revealed by the star's light curve, but the interpretation of the radial velocity curve in terms of energy is more straightforward, and coexistence of two oscillations, the first-overtone one with higher energy, poses a problem in front of the theory of stellar pulsations.

The second reason for the higher scatter is Cepheid binarity (bottom panel of Fig. 1). TX Del is an extreme case (it is not definite if the star is a classical Cepheid or a Population II Cepheid). We independently discovered the binarity of this star, first noted by Harris and Welch (1989). Its pulsation period is $6^d.17$; its orbital period is only 133^d, a very low value for binary Cepheids (remember that classical Cepheids

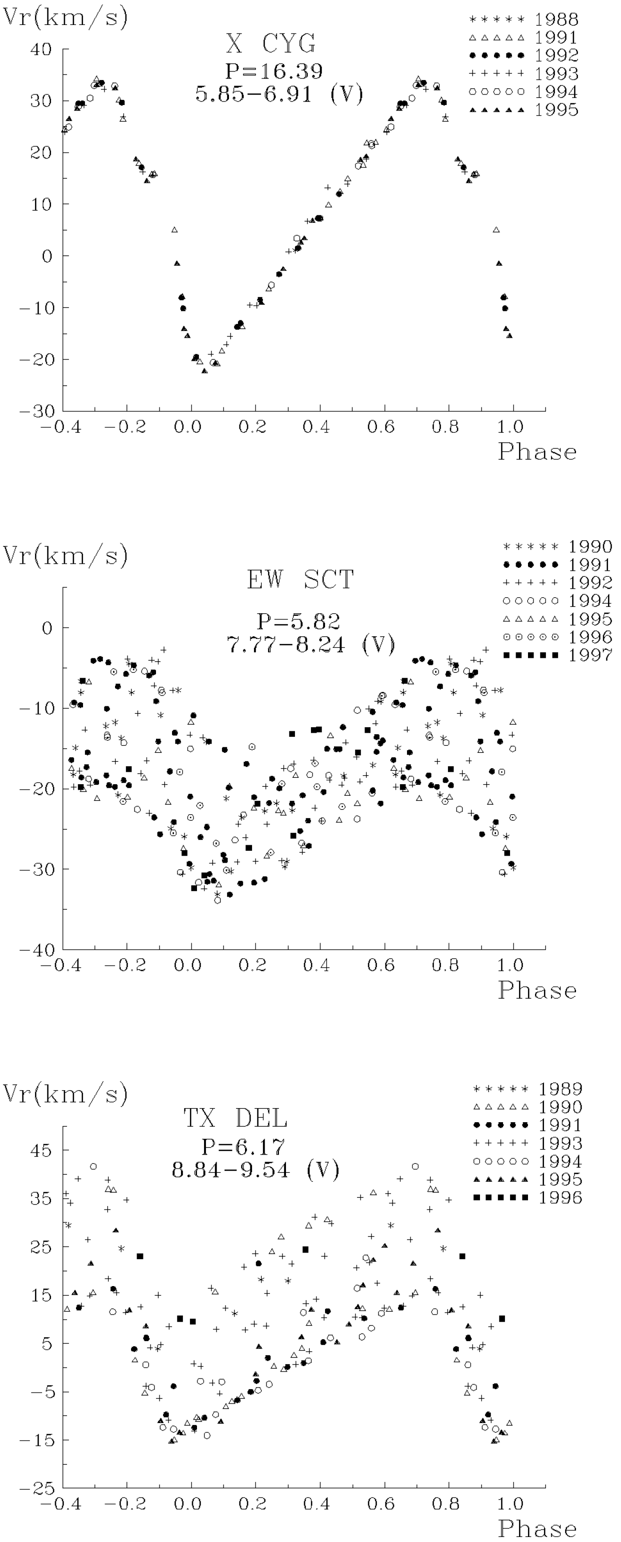

Figure 1: Radial velocity curves for three Cepheid, folded with their pulsation periods. See text for explanations.

are supergiants). Its separated pulsational and orbital velocity curves show comparable amplitudes. The star is rather unusual for binary Cepheids, even its velocity curve based on observations of a single year reveals quite obvious signatures of binarity.

We discovered the binarity of the classical Cepheids V496 Aql, BY Cas, VY Cyg, VZ Cyg, MW Cyg. A number of stars have been suspected in binarity from our data. Figure 3 is the velocity curve of the newly-discovered binary Cepheid V496 Aql (Samus and Gorynya, 2001). Table 2 presents a summary of our results on spectroscopic binary Cepheids. Our observations show that at least 22% Cepheids are binaries (Gorynya *et al.*, 1996); however, we consider much higher estimates of some other authors, like 50% or more, to be too high.

As noted above, our data are very advantageous for determinations of Cepheid radii using the Baade–Wesselink technique. Here we make extensive use of the detailed data base on Cepheid photometry compiled and supported in Moscow by Berdnikov (1995). From our original radii of 62 Cepheids, we derived the period–radius relation in the form (Sachkov et al., 1998):

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

The radii derived with the Baade–Wesselink technique are very improtant as a tool to distinguish between different pulsation modes for Cepheids.

From our observations, we also have studied the Hertzsprung sequence, a relation quite well known for Cepheids as a dependence of their light curve shapes upon the period value but here revealed, for the first time, in their radial velocity curves rather than in their light curves (Gorynya, 1998).

4. Some prospects

In the recent years, we have entered a most fruitful collaboration with Dr. Pawel Moskalik (Warsaw) who uses our data for Fourier decomposition of radial velocity curves. This sensitive tool of research also makes it possible to study the Hertzsprung sequence as well as to reveal resonances between different pulsation modes. Currently, Dr. Moskalik studies our most recent observations and gives us advice on our program of observations, indicating insufficient coverage of velocity curves for stars of interest, hints to binarity, etc. In the nearest future, we are planning to continue this cooperation. Also, we try to apply our instrument to different variability type, but this is arleady outside the scope of this presentation.

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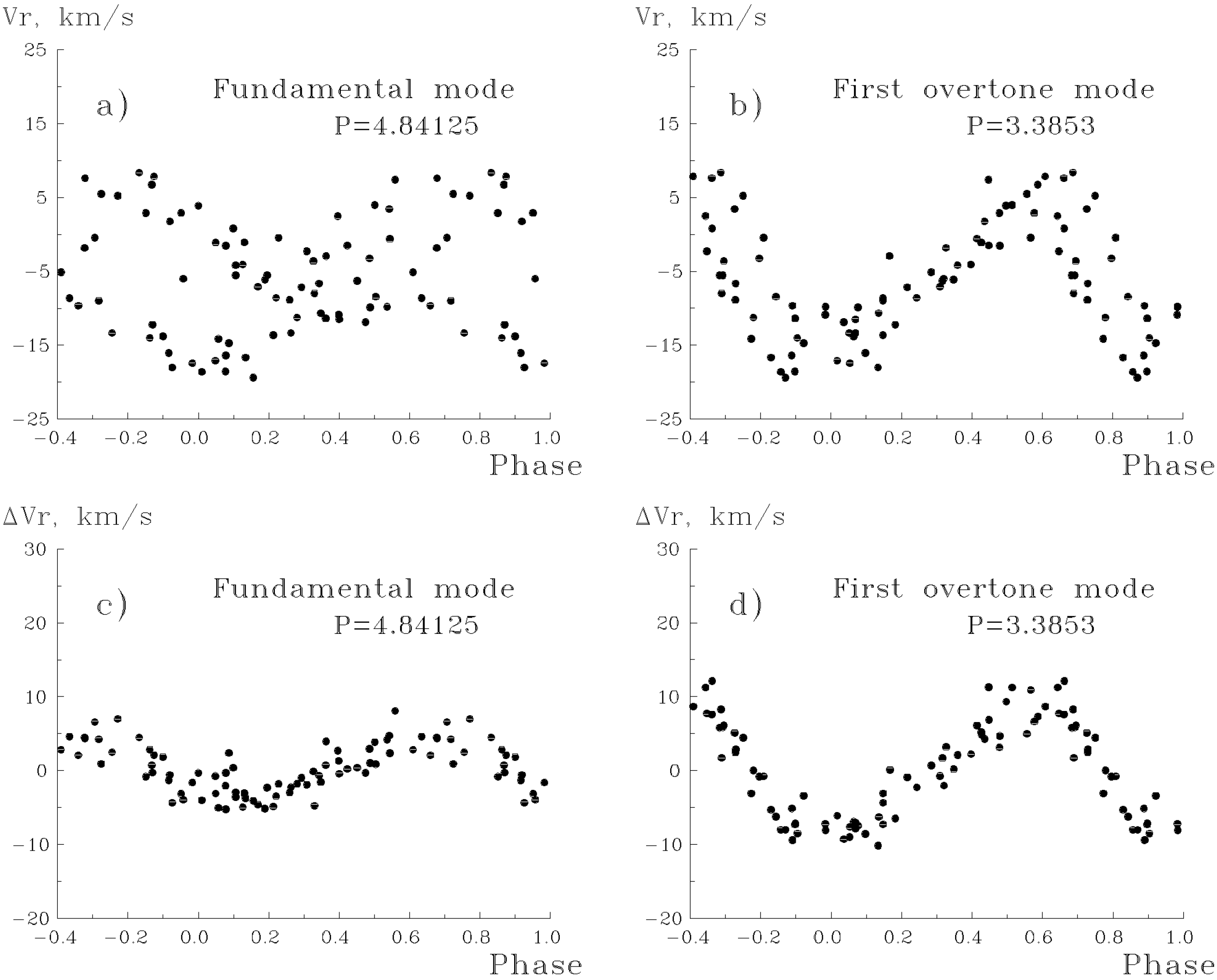

Figure 2: The radial velocity curves for the double-mode Cepheid V456 Sct: (a) folded with the period of the fundamental mode; (b) folded with the period of the first overtone; (c) same as for panel (a), but with the first overtone pulsations removed; (d) same as for panel (b), but with the fundamental mode pulsations removed.

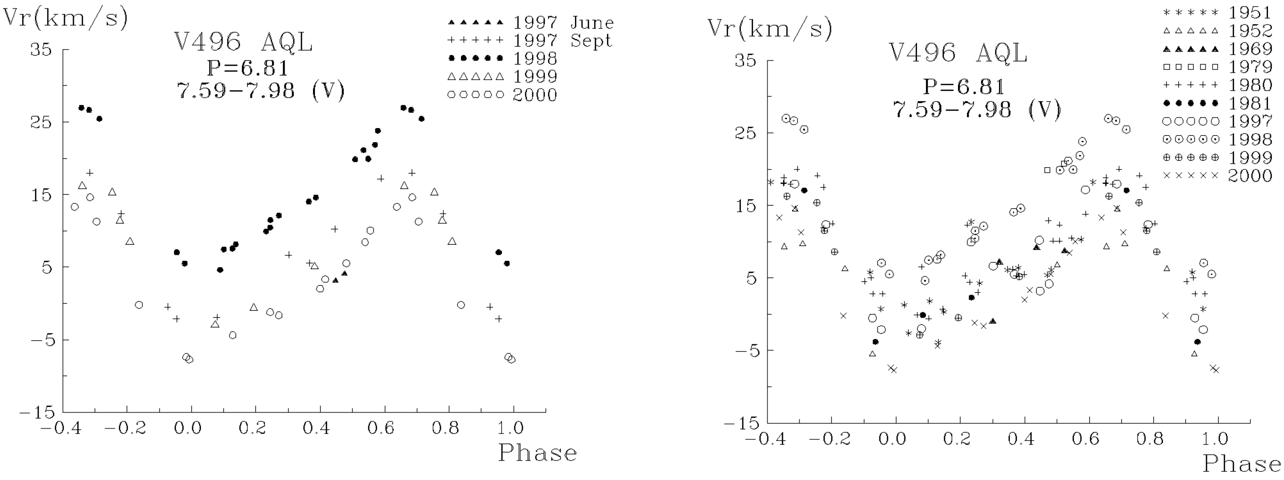

Figure 3: The radial velocity curves for the binary Cepheid V496 Aql, folded with its pulsation period. Top: from our observations only; bottom: with data from the literature added.

Table 2: Results for binary Cepheids.

Cepheid	$P_{\rm puls}$, d	$P_{\rm orb}$, d	$a \sin i$, AU	$f(m)$, $M_\odot$	M_1, $M_\odot$	M_2, $M_\odot$
FF Aql	4.4709	1432.2	0.67	0.02	5.5	$\geq 1 \pm 0.2$
V496 Aql	6.8072	1447(573)	–	–	–	–
RX Cam	7.9122	1116	1.2	0.19	6.5	$\geq 2.5 \pm 0.2$
SU Cas	1.9495	407.2	0.13	0.002	4	–
BY Cas	3.2223	563	–	0.04	–	–
DL Cas	8.0007	684.4	–	0.2784	–	–
SU Cyg	3.8456	549.25	1.42	1.27	5.0	≥ 5
VY Cyg	7.8570	941	–	–	–	–
VZ Cyg	4.8644	1483	1.39	0.16	5.5	$\geq 2 \pm 1.5$
MW Cyg	5.9547	437.3	0.25	0.011	6	$\geq 0.8 \pm 0.05$
V532 Cyg	3.2838	388?	–	0.0001?	–	–
V1334 Cyg	3.3325	1947(1463)	–	–	–	–
TX Del	6.1659	133.3	0.17	0.037	6	$\geq 1.25 \pm 0.15$
Z Lac	10.8860	376.9	0.54	0.14	6	$\geq 0.8 \pm 0.1$
T Mon	27.0333	25000	–	–	–	–
AU Peg	2.4115	53.34	0.22	0.49	4	$\geq 2.7 \pm 0.2$
AW Per	6.4636	1911?	–	0.016?	–	–
S Sge	8.3823	675.75	0.93	0.23	$\cong 6.5$	$\geq 1.1 \pm 0.05$
V350 Sgr	5.1539	1481.8	1.34	0.15	$\cong 5.5$	$\geq 2.1 \pm 0.2$
BQ Ser	4.2712	136 or 1009	–	0.005	–	–
SZ Tau	3.1489	1244?, 240?	–	–	–	–
EU Tau	2.1025	980?	–	–	–	–

Remarks to Table 2.

SU Cyg: A triple system.

TX Del: 1) If considered a classical Cepheid:
$M_1 = 6.0 M_\odot$; $M_2 \geq 1.25 \pm 0.15 M_\odot$
2) If considered a Population II Cepheid:
$M_1 \cong 0.7 M_\odot$; $M_2 \geq 0.35 \pm 0.05 M_\odot$

AU Peg: 1) If considered a classical Cepheid:
$M_1 = 4 M_\odot$; $M_2 \geq 2.7 \pm 0.2 M_\odot$
2) If considered a Population II Cepheid:
$M_1 \cong 0.7 M_\odot$; $M_2 \geq 1.2 \pm 0.1 M_\odot$

AW Per: The first known SB2 Cepheid.

BQ Ser: CEP(B) with $P_0 = 4^d.27073$ and $P_1 = 3^d.012$.

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