POLARIS, SMALL-AMPLITUDE CEPHEID WITH UNIQUE PHYSICAL PECULIARITIES

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ABSTRACT. We present the results of our analysis of spectroscopic observations of α UMi (Polaris) obtained in 1994 (5 spectra) and 2001–2004 (30 spectra) and frequency analysis of all Polaris *RV* data collected during last 120 years. This analysis has confirmed the proposition about its overtone pulsations in first and second overtones with $P_2/P_1 = 0.81$, i.e. Polaris is double-mode Cepheid (DMC). Moreover, there are the presence of modes splitting for pulsations in these overtones caused by the presence of the three companions at the least with orbital periods of 48.6, 29.91 and 19.44 years, respectively. Since Polaris is located near the blue edges of the Cepheid instability strip for the fundamental mode and first overtone, and an abrupt decrease of the pulsational amplitude and its recent increase could be due to its binarity.

Key words: Stars: radial velocities; Cepheids: overtone pulsations; Cepheids: companions; Cepheids: α UMi

1. Introduction

As it has been mentioned in paper of Usenko et al. (2005) there are some specific features of Polaris which testify about its peculiar character:

1. Abrupt decrease of its pulsational amplitude during fourty years (5–6 km s^{-1} before 1950 (Roemer 1965) to 0.05 km s^{-1} in the 1990's (Fernie, Kamper, & Seager 1993)) and the beginning of one's increase during last 5-6 years (Hatzes & Cochran 2000).

2. According to fresh results of Turner et al. (2005) based on $O - C$ data of photometric and radial velocity estimates collected more than a hundred and fifty years, the pulsational period of Polaris has increased of 4.45±0.03 s yr^{-1} during the interval 1896-1958, - as an evidence of Polaris' redward crossing of Cepheids instability strip (hereafter CIS). Since 1963 the period's increase has slow down to 4.28±0.73 s yr^{-1}, at that in stepwise during three years.

3. Preceding frequency analyses of radial velocity data sets of 1987-88 (Dinshaw et al. 1989) and 1992-93 (Hatzes & Cochran 2000) revealed besides the main pulsational period of 3.97 day a presence of additional one of 45.3 or 40.2 days, respectively. This period's presence has been explained by the Polaris rotation, availability of cool or macroturbulent velocity spots, or else of nonradial pulsations.

2. Observations and frequency analysis

In 39 spectrograms were obtained by authors during 1994-2005 using 1 m telescope of Ritter Observatory, University of Toledo, Ohio, USA; 2.1 m telescope of McDonald observatory, Texas, USA; 6 m telescope of SAO RAS, Russia. DECH 20 package (Galazutdinov 1992) allows to make the measurements of radial velocities after the using of a thorium-argon lamp for the wavelength calibration. To avoid the differnces in velocities caused by the Doppler effect across full spectral range, we used the measuring the shifts in each spectral order with subsequent averaging to produce velocities. Obtained radial velocity data are given in Table 1.

Before the searching for Polaris periodicities we have collected all the radial velocity data obtained by different authors during the researching period of 1896-2004. These data were taken from Roemer (1965), Schmidt (1974), Arellano Ferro (1983), Kamper et al. (1984), Dinshaw et al. (1989), Fernie et al. (1993), Kamper (1996), Kamper & Fernie (1998), Hatzes & Cochran (2000) papers. Including our 39 estimates we have in total, 2118 *RV* values. Next step was using the PE-

Table 1: Observational data of α UMi

HJD 2400000+	Number of orders	RV ($\mathrm{km\,s^{-1}}$)	σ	NL
49512.615	9	-13.28	1.23	126
49579.824	9	-14.21	1.21	116
49603.853	15	-13.35	0.93	152
49637.792	9	-14.97	1.05	132
49648.810	9	-14.38	1.07	130
51240.612	22	-18.26	2.81	302
51360.538	22	-16.51	2.36	317
51361.536	22	-14.53	2.68	275
52192.858	28	-16.88	0.81	281
52416.655	9	-16.53	1.17	138
52417.616	9	-17.67	1.45	145
52421.679	9	-17.85	1.32	109
52426.667	9	-18.18	1.28	121
52427.650	9	-17.35	3.06	119
52435.634	9	-16.53	1.18	142
52441.673	9	-16.78	1.08	112
52514.575	18	-20.39	0.92	270
52515.588	25	-15.33	0.86	391
52782.543	26	-14.53	2.68	275
52833.741	9	-21.64	1.30	100
52837.678	9	-21.59	2.07	104
52839.746	9	-23.97	2.00	111
52861.560	20	-17.76	0.73	279
52867.562	20	-17.75	0.79	251
52869.570	20	-16.62	0.76	247
52891.600	26	-16.38	0.89	384
52952.700	9	-19.19	3.37	112
52986.692	9	-18.48	2.89	125
52986.709	9	-17.86	2.67	107
53005.595	9	-16.50	3.13	141
53015.167	20	-17.79	0.88	279
53019.108	20	-17.28	0.82	266
53072.165	20	-17.81	0.64	251
53072.631	20	-18.02	0.77	291
53073.622	20	-17.52	0.80	278
53162.191	20	- 9.52	0.64	309
53246.192	20	-16.50	0.73	281
53285.167	20	-17.08	0.85	304
53367.091	27	-20.51	3.84	261

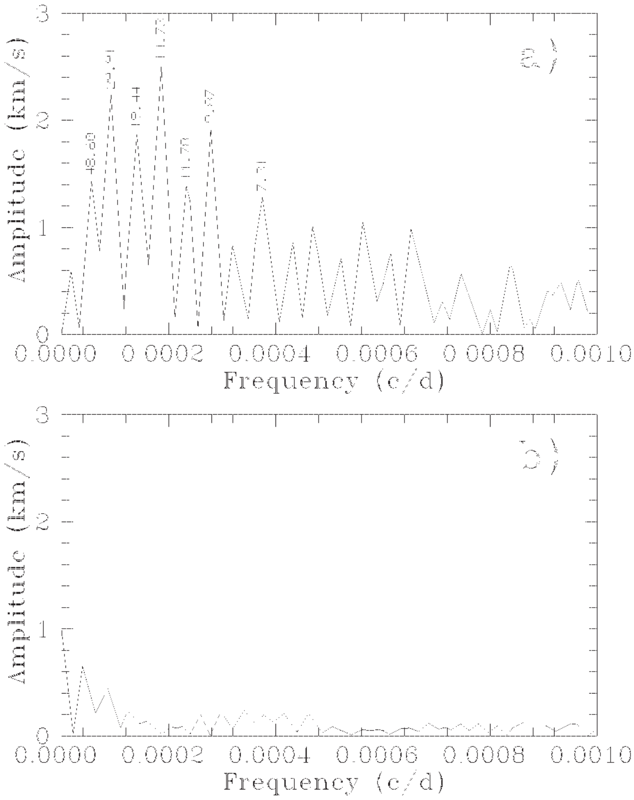

Figure 1: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to orbital periods (a) and to its spectral window (b).

RIOD 98 program (Sperl 1998) which allows to search for and fit sinusoidal patterns within a time series of data containing huge gaps. PERIOD 98 used tecniques Fourier and Fast Fourier analysis with minimization of residuals of sinusoidal fits to the data.

A Fourier amplitude spectrum was obtained over the frequency range 0-1 $\mathrm{d^{-1}}$ at a resolution of 0.00002 $\mathrm{d^{-1}}$. At that, the highest amplitude 2.504 corresponds to frequence of 0.0001862 $\mathrm{d^{-1}}$, or 5378.77 days (14.73 years), respectively (see Figure 1). At that the zero-point (γ - velocity) is equal to -15.446 $\mathrm{km\,s^{-1}}$.

2.1 Orbital periods

As seen in Figure 1: (a),- the highest peaks are located near zero frequence mark, - their frequences correspond to the longest periods, which could be interpret as orbital ones (see Table 2). And the results of spectral window (b) for these frequences confirm their truth.

As seen from Table 2, the highest amplitude frequencies f_{O2} and f_{O4} corresponds well to long since known orbital period (29.9 yr according to Dinshaw et al. 1989) and half of one, respectively. Frequency f_{O7} make up a quarter of orbital period. At the same time we obtained two divisible frequences f_{O3} and

Table 2: Possible orbital periods of α UMi

No.	Frequency (c/d)	Amplitude (km s^{-1})	Period (days/years)
f_{O1}	0.00005573	1.43374864	17750.01/48.60
f_{O2}	0.00009247	2.23957558	10923.08/29.91
f_{O3}	0.00014060	1.86965268	7100.00/19.44
f_{O4}	0.00018620	2.50423271	5378.77/14.73
f_{O5}	0.00023307	1.38833452	4303.04/11.78
f_{O6}	0.00027867	1.92205718	3604.06/9.87
f_{O7}	0.00037494	1.27912952	2669.17/7.31

Table 3: Possible pulsational periods of α UMi

No.	Frequency (c/d)	Amplitude (km s^{-1})	Period (days)
f_{P1}	0.25188093	0.80356599	3.970129896
f_{P2}	0.25189359	0.75975109	3.969930253
f_{P3}	0.25191766	0.94085008	3.969550986
f_{P4}	0.25198733	1.22003231	3.968453520
f_{P5}	0.25201773	0.88336295	3.967974809
f_{P6}	0.31057769	0.45598194	3.219806273
f_{P7}	0.31058276	0.57387475	3.216513541
f_{P8}	0.31093616	0.49965752	3.216094234
f_{P9}	0.05876390	0.73047045	17.017250819
f_{P10}	0.05885130	0.62139714	16.991978218

f_{O6}, thereas the reduction ratio of f_{O1}/f_{O5} is closely approximated to 4. It follows that Polaris system has probably, in addition, some more orbital periods. If 19.44 - years period could be interpret as orbital one of Jovian-like body (Hatzes & Cochran 2000) then 48.6 - years period seems to be mysterious. Probably quite we have to do with presence of more cool companion than known one of later on $F4V$ spectral type (Evans et al. 2002).

2.2 Pulsational periods

3.97 - days pulsational period (frequency near to 0.25 c/d) is seen clearly in Figure 2. But we can see more surprising picture.

Judging from this figure it is clearly visible frequence splitting. Like in first subsection we represent these frequences in tabular form (see Table 3).

So, the single highest amplitude peak corresponds to pulsational period of 3.96845352 days (f_{P4}). Let suppose to consider it to be the main period. Then the presence of more high frequences the left of it could be explain by following. If we can consider the reliable orbital period of 29.91 yr as a *beat period*, then a sum of its frequence with one of main pulsational period gives the total frequence of 0.251894879 c/d, i. e. it corresponds well with the observed one f_{P2} from Table 3! This unexpected fact finds the confirmations in case if the orbital periods of 48.6 and 19.44 yrs we would be consider as the beat periods too: the expected

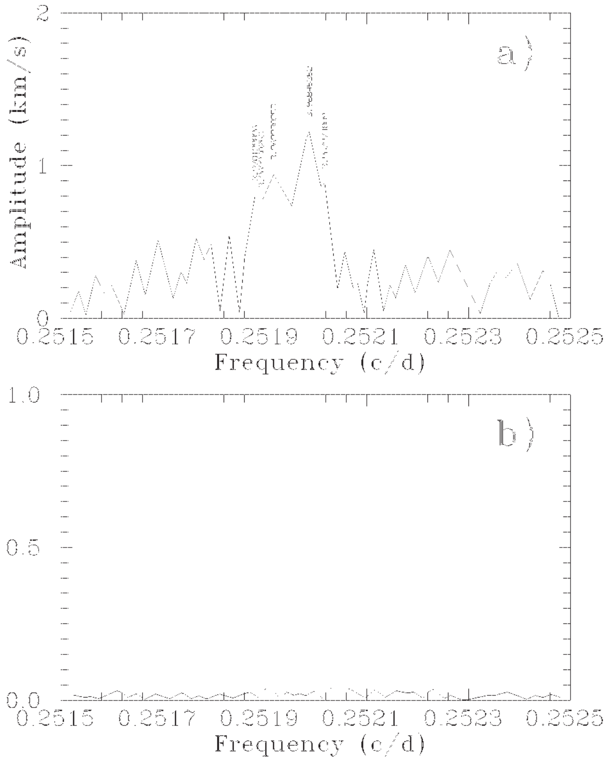

Figure 2: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to main pulsational period (a) and to its spectral window (b).

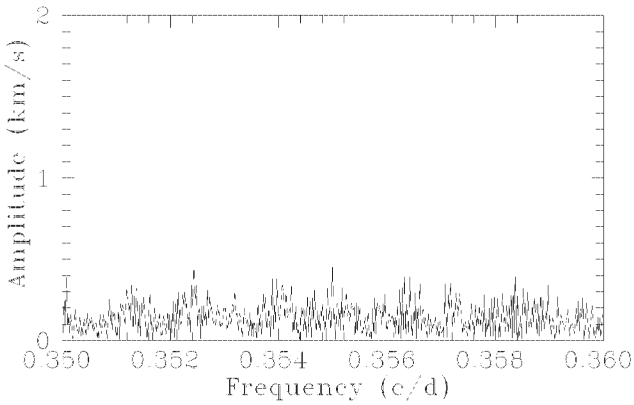

Figure 3: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to pulsational period in fundamental tone.

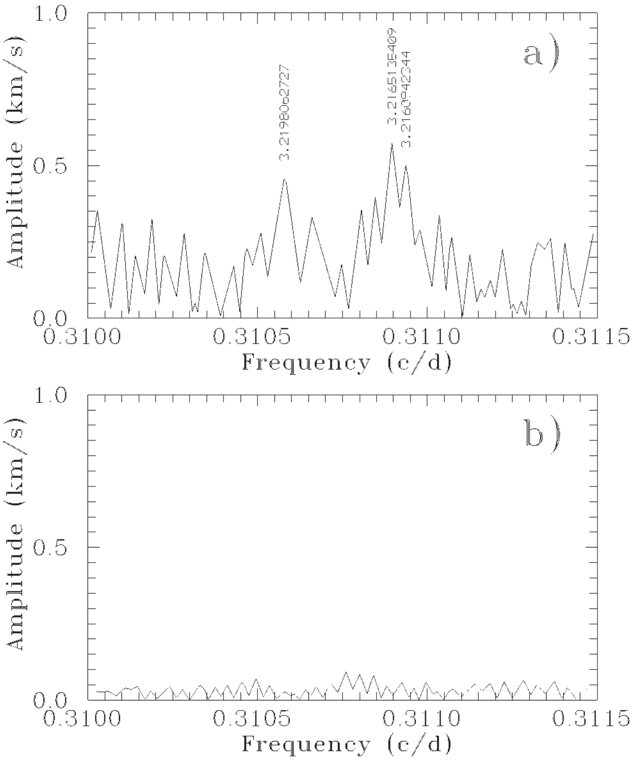

Figure 4: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to pulsational period in second overtone (a) and to its spectral window (b).

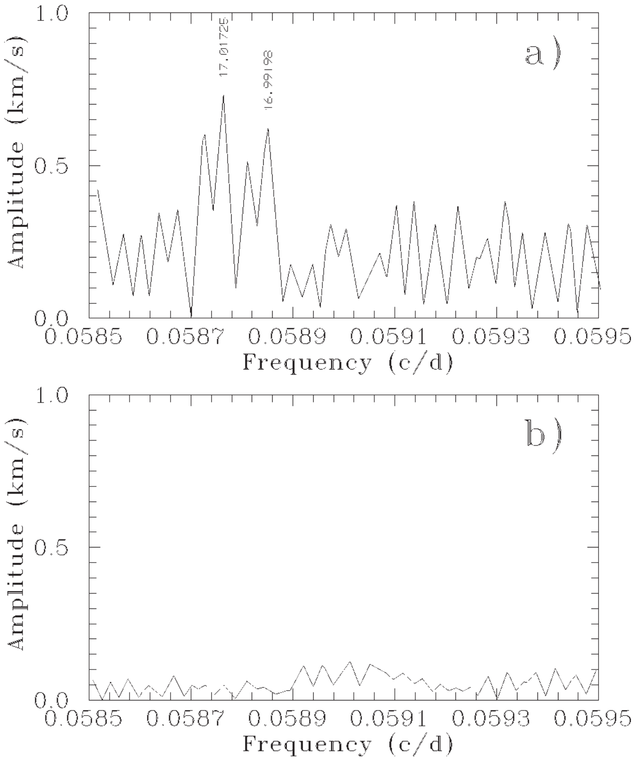

Figure 5: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to beat pulsational period between the first and second overtones (a) and to its spectral window (b).

frequences are 0.251930991 c/d and 0.251846727 c/d, respectively. They have a good agreement with observed ones of f_{P3} and f_{P1} from Table 3. A presence of frequence f_{P5} is still unaccounted.

Next but very important step in our investigations was to determine the mode of observed pulsational period. Usenko et al. (2005) have founded that radii and distances obtained from interferometry and HIPPARCOS parallaxes correspond well to pulsational in *first overtone*. Having a plenty of radial velocity values we could be try to found the presence of different modes in our Fourier amplitude spectrum. On the assumption of observed period of 3.968453520 day is *fundamental* one and $P_1/P_0 = 0.71$, an espected frequency lies near 0.3549 d^{-1}. As seen from Figure 3, there are not any so significant frequences, whose could be correspond to value, mentioned above.

If this observed period corresponds still to *first overtone* pulsation and $P_2/P_1 = 0.81$ then we would make an attempt to search for the traces of frequences, corresponded to *second overtone*, - near 0.311 d^{-1}. And these traces were detected (see Figure 4).

Judging from Figure 4 there are three noticeable peacks with the highest amplitudes, - f_{P6}, f_{P7} and f_{P8} (see Table 3). If we take the highest amplitude period of 3.216513541 day (corresponds to frequency f_{P7}) and divide it by 0.81, we obtain the period of 3.96845 day, i.e. f_{P4} from Table 3. The same operation for frequency f_{P8} gives the period of 3.97013 day, - f_{P1} from Table 3. Therefore, frequences f_{P7} and f_{P8} correspond to *second overtone* pulsations, and like in the previous case there are mode splitting caused by companions presence. At that the period of 3.216513541 day is conventional due to posiible Jovian-like body, mentioned above, with period of 19.44 yr. Frequence f_{P6} is very unusial, because its presence does not connect with any of observed orbital periods.

In order to confirm the fact of existence for pulsations in second overtone, it is enough to detect the *beat period* between it and first one. An expected period lies in the ranges of 16.5 - 17 days. As seen from Figure 5 there are two highest peaks with frequences f_{P9} and f_{P10} (see Table 3), which correspond to periods of 16.99 and 17.02 days, respectively. It is marvellously, but last value agrees with 17.03 days one, founded by Hatzes & Cochran (2000)! Although these authors have supposed this period corresponds to the beat period between *fundamental* and *first overtone* modes and inasmuch as the fundamental one of 5.6 day did not detected, they considered 17.02 days period as a false one.

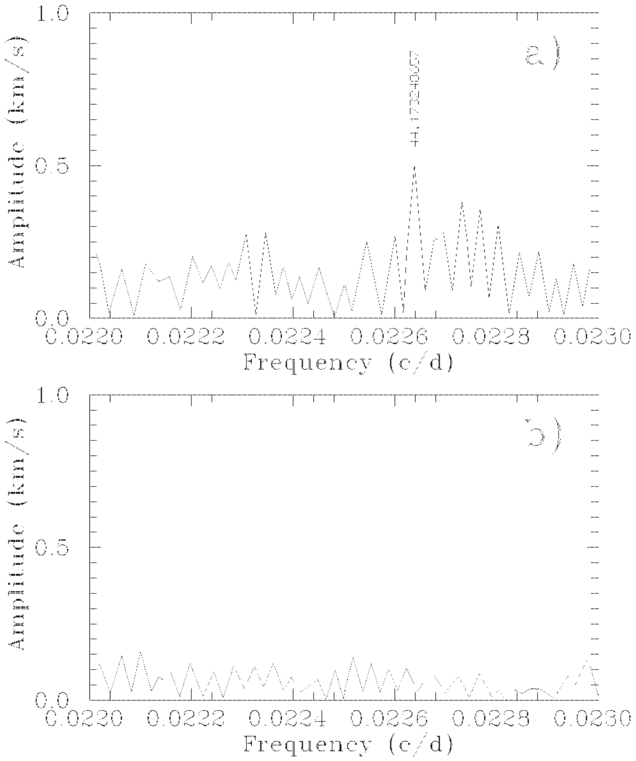

Figure 6: Fragment of Fourier amplitude spectrum of Polaris over a narrow frequency range corresponding to 45-days period (a) and to its spectral window (b).

2.3 45-days period

An existence of this unusual period was announced firstly by Dinshaw et al. (1989). An application of Fourier analysis for residual velocities displayed a strong peak on the periodogram at a frequency of 0.022 d^{-1} and amplitude near 0.4 $km\,s^{-1}$. This result corresponded to the period of 45.3±0.2 days. Later Hutzes & Cochran (2000) confirmed this one, but the result was 40.2±0.7 days with the same amplitude. To check these results we have applied the same procedure for residual velocities. The resulting Fourier periodogram is given in Figure 6.

As seen, the highest peak corresponds to frequency of 0.022638136 d^{-1} with amplitude 0.5 $km\,s^{-1}$, or period of 44.173249 days that has an exellent coincidence with the result of Dinshaw et al. (1989). There are any traces of 34.3 days (0.02915 d^{-1}) period's presence, detected earlier by Hatzes & Cochran (2000).

3. Summary

1. Changes of pulsational period for Polaris both periodical and spasmodic, can be explained by presence at the least of three companions;
2. Suspected orbital periods of 18.6 and 19.44 yrs are quite reliable.
3. Polaris belongs to double-mode Cepheids (DMC), at that its pulsation in fundamental tone is absent and there are pulsations in *first* and *second overtones* only with $P_2/P_1 = 0.81$ that agrees well with results of theory for classical Cepheids.
4. The presence of second overtone to be confirmed by the existence of *beat period* between it and *first* one.
5. Polaris modes splitting for pulsations in first and second overtones caused by the presence of three companions at the least.
6. The period of 44.173 days closed to 45-days one detected by Dinshaw et al. (1989) is quite reliable.

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