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Eclipsing binaries in ASAS and NSVS databases: Fourier analysis

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Abstract. We present a statistical investigation of eclipsing binaries presented in the ASAS and compared with the same investigation of the light curves from an NSVS survey. Applying Fourier analysis on the light curves, we used the relations between coefficients to infer principal properties of eclipsing binaries. Subsequently, detached, semi-detached and contact systems were separated and the light curves with different Fourier coefficients were compared.

Key words: ASAS database – Fourier coefficients

1. Introduction

The amount of photometric data for eclipsing binaries (and variable stars in general) has substantially increased with a number of sky surveys and dedicated observational projects. Ground-based observational programs have various goals: e.g., OGLE monitors the Galactic bulge to detect optical lensing events (Szymański et al., 1996), ASAS monitors the sky to detect primarily variable stars (Udalski et al., 2002; Pojmański, 1997, Pojmański et al., 2001), NSVS is a database of ground-based observations of the northern sky (Woźniak et al., 2004), SuperWASP (Kane et al., 2004) and the HAT network (Bakos et al., 2004) focus on the detection of transiting extrasolar planets. The satellite observations are aimed at detection of transiting exoplanets and asteroseismology (e.g. Kepler, see Borucki et al., 2010; CoRoT (Baglin et al., 2002) and MOST, (Walker et al., 2003; Pribulla et al., 2010)).

These observational programs produced large databases containing a huge number of LCs of eclipsing binary systems. Characterization and analysis of the data is therefore daunting and can hardly be carried out "curve by curve". Therefore, it is necessary to write codes for an automatic classification, determination of the orbital period, and a preliminary photometric analysis. A rather fast and straightforward way is to use the Fourier analysis.

To illustrate the methodology we used the database resulting from the ASAS (All Sky Automated Survey)[1] observational program and the NSVS (Northern

[1] http://www.astrouw.edu.pl/asas/?page=download

Sky Variability Survey)[2] survey. Preliminary ephemerides, the variability type, and the photometric amplitude for the objects were adopted from the ACVS (ASAS catalogue of Variable Stars). Original LCs for eclipsing binaries can still be used to classify the LC type (EA, EB, EW).

This topic was discussed before from various aspects. Rucinsky (1993, 1997) performed Fourier analysis for the contact binaries and searched for dependence between Fourier coefficients and some physical properties of eclipsing systems, Eyer & Blake (2005) made a classification of 1700 variable stars using Fourier analysis, Deb & Singh (2011) presented a detailed light curve analysis of 62 binary stars, mostly contact binaries, from ASAS-3, and Hoffman et al. (2008, 2009) classified eclipsing binaries within the NSVS database.

The present paper is organized as follows: In Section 2 ASAS and NSVS database are described. The main goal of this paper is to show how the Fourier coefficients are related to the properties of the light curve. Fourier analysis of the ASAS and NSVS LCs and relationships between Fourier coefficients and geometric properties of the LCs are described in Section 3. The results are discussed and summarized in Section 4.

2. ASAS and NSVS databases

The project ASAS consists of two observing stations: Las Campanas in Chile (since 1997), and Haleakala in Hawaii (since 2006). Only data from the Las Campanas station are available online at present. The ASAS-3 database (V passband data)[3] contains $\approx 10^7$ stars brighter than 14 magnitude, fully covering the southern skies reaching declinations $< +28°$. ACVS resulting from the ASAS data contains ~ 50 thousand variable stars (of those ~ 10 thousand are eclipsing binaries, see Tab. 1 and 2).

Table 1. The basic information about the ASAS database. Only candidates for eclipsing binaries were taken into account. The number in parenthesis at eclipsing binaries is the total number of all files referring to eclipsing systems (classification of eclipsing binaries is ambiguous, which means one system can have more than one identified type of eclipsing binaries).

No. of all systems	∼ 15 000 000
No. of all variable systems	∼ 50 000
No. of eclipsing binaries	∼ 10 000 (totally 12 779)
No. of pulsating variables	∼ 8 000
No. of irregular variables	∼ 31 000

[2] http://skydot.lanl.gov/

[3] I-band data from ASAS-2 are available only for the selected fields, will not be considered in this paper

For most of the systems, ACVS gives a linear ephemeris for the primary minimum. The ACVS ephemerides are, however, preliminary and often incorrect. Pilecki (2009) determined new ephemerides for $\sim 5\ 500$ LCs[4]. These improved ephemerides were used to phase the ASAS photometry for the following analysis.

All data were obtained from the official website of the ASAS project[5]. There is a single ASCII file with the photometry for each target. It contains a header (the number of datapoints, coordinates, apertures used, etc.) and the data (HJD, magnitudes and errors for all apertures, a flag giving the quality of the CCD). The data file contains more columns with magnitude referring to different aperture used during the observations. In this paper we decided to use the first aperture.

Table 2. The statistic overview of the limit values of the basic characteristics (period P, amplitude of changes V_{max}, magnitude in the V-filter V_{mag} and color indices) taken from the ACVS catalogue. The real limit values (the lowest and highest possible value) for color indices were taken from Tokunaga (2000) (in parenthesis at min and max value of the color index). Many of these color indices are out of bounds, which means that they are determined incorrectly.

	max	ID	mean	min	ID
Period	822.00	082051−3759.0	5.78352	0.04048	070621+2024.7
V_{amp}	4.20	155042+1508.0	0.43706	0.01000	070523+0215.7
V_{mag}	14.80	050645−1534.1	11.56674	5.74000	043238−0312.5
$V-J$	6.32 (6.33)	064005+1506.7	1.10296	-1.10 (-1.11)	073109−2816.4
$V-H$	6.29 (6.99)	064520−4210.1	1.37638	-1.04 (-0.87)	115115−6313.7
$V-K$	7.32 (7.37)	082419−2001.3	1.48123	-0.90 (-0.91)	093623−5959.2
$J-H$	0.66 (0.96)	many	0.28499	-0.15 (-0.16)	075749−0850.2
$H-K$	0.38 (0.38)	many	0.08983	-0.13 (-0.13)	081631−1150.5

The Northern Sky Variability Survey[6] is a database of ground-based observations of variable stars (Woźniak et al., 2004). The observations cover the whole northern sky (plus the southern sky to -38 deg) and were performed from Los Alamos in New Mexico (USA).

The NSVS is the most extensive available database of variable stars with the time base of one year and typically with $100 - 500$ observations per object.

All measurements are available on the website Sky Database for Objects in Time-Domain (SkyDOT[7]) and all technical details can be found in the paper of Woźniak et al. (2004). Hoffman et al. (2008) analyzed the light curves

[4]http://www.astrouw.edu.pl/asas/i_eclipsing/data/t_linephem.tab
[5]http://www.astrouw.edu.pl/asas/
[6]http://skydot.lanl.gov/
[7]http://skydot.lanl.gov/

from the NSVS database and they published a catalogue of 409 eclipsing binaries of an Algol- and β Lyr-type. Using automated Fourier analysis and other additional methods they computed ephemeris and minima depths. They discovered 37 candidates having low-mass components on the main sequence ($M_{1,2} < 1M_{\odot}, T_{eff} < 5\,500$ K).

3. Fourier analysis

An effective way to quickly classify an eclipsing binary star is to perform the Fourier decomposition of its phase LC (see Rucinski, 1993). In general, one can represent the phase dependence of intensity by the following trigonometric polynomial:

$$I(\varphi) = \frac{a_0}{2} + \sum_{n=1}^{6} [a_n \cos(2\pi n\varphi) + b_n \sin(2\pi n\varphi)], \tag{1}$$

where φ is the orbital phase.

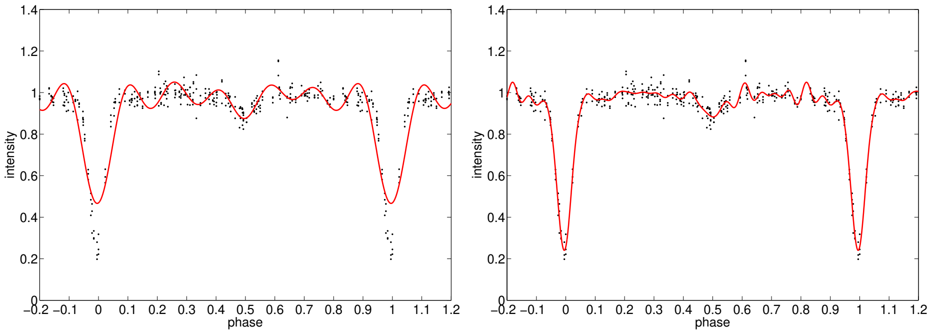

Figure 1. Comparison of two decompositions in the presented light curve (the system with catalogue ID 000030-3937.5 from the ASAS database). Left: the fit where we used the Fourier polynomial of the 6^{th} degree. Right: the 20^{th} degree of a polynomial is used.

To compute the Fourier coefficients, we used the code FOURIER written by Nedoroščík (2012). As we can see in Fig. 1, we have to be careful with the selection of the polynomial degree. A low degree results in an inaccurate representation of the LC (Fig. 1, left), while a high degree of decomposition is strongly affected by deviating data points resulting in a wave-like behavior of the fit[8]. The highest acceptable degree is given by the number of observational points

[8]Standard errors of ASAS photometry were not taken into account

(for uniformly-spaced data by the Nyquist frequency). The Fourier coefficients for all studied ASAS eclipsing binaries are available online[9].

A trigonometric polynomial (Eq. 1) is an orthonormal base of functions for uniformly distributed data. In the case of the ASAS data the polynomial is not orthonormal and the values of the Fourier coefficients slightly depend on the degree of the polynomial. In our analysis we always used the 6th degree of the polynomial. This is because if you want to describe the light curve you need at least 12 parameters. Thus we have 13 coefficients: the absolute coefficient a_0, six cosine terms with Fourier coefficients a_1 to a_6, and six sine terms with b_1 to b_6.

Some of these coefficients represent physical or geometrical properties of the eclipsing binary (see Selam, 2004):

a_0	mean brightness level
$a_1 \leq 0$	difference between depths of primary and secondary minima (for $a_1 > 0$ the ephemeris is incorrect: primary and secondary minima are swapped)
$a_2 < 0$	amplitude of LC changes
$a_4 < 0$	degree of filling of the Roche lobe
b_1	magnitude of the O'Connell effect
b_2	system eccentricity estimate

In this paper we focused on showing that Fourier coefficients really correspond to expected properties (shown in the overview above, the system eccentricity will be discussed in the next paper).

Fig. 2 shows that the lower the Fourier coefficient a_1, the smaller the difference between the depths of the primary and secondary minima. This comparison is listed in Table 3. The Fourier coefficient a_2 should show an amplitude of light curve changes. As we can see, this comparison is shown in Fig. 2 and the values are collected in Tab. 3. The smaller the value of this Fourier coefficient a_2, the greater the amplitude of the light curve changes.

Fourier coefficients $a_{1,2,4}$ enable a quick but reliable classification of the LC type (ED, ESD, EC) of eclipsing binaries (see Fig. 3 and 4).

Fig. 3 shows the relation between Fourier coefficients $a_2 - a_4$ for all studied eclipsing binaries in ASAS (top) and NSVS (bottom). Semi-detached and detached binaries can be separated from contact binaries using the following relation (Rucinski, 1993)

$$a_4 \leq a_2(0.125 - a_2). \tag{2}$$

Fig. 4 (top) shows the relation between $a_1 - a_2$. In the case of contact systems, the coefficient a_1 is located in the range of $-0.02 \leq a_1 \leq 0$, because

[9]http://www.ta3.sk/~jnedoroscik/ASAS

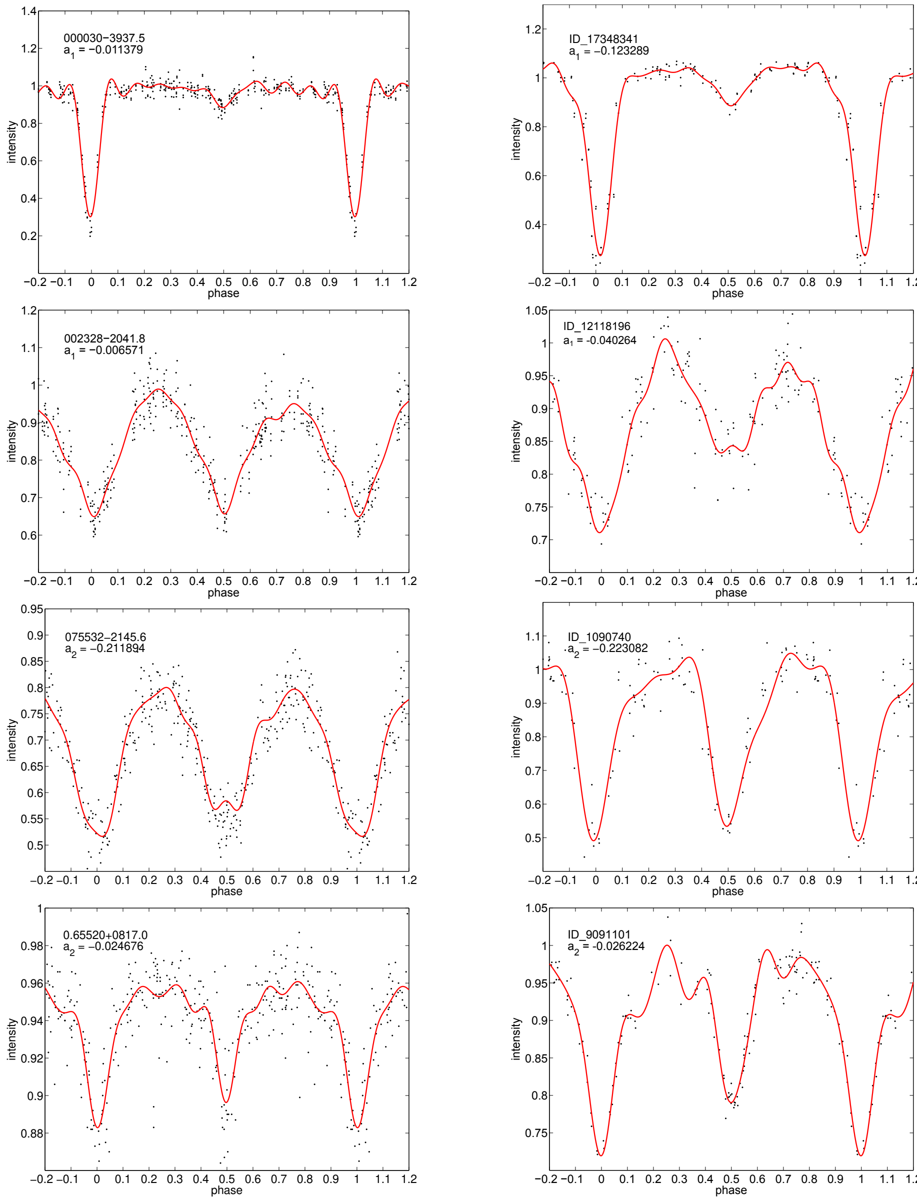

Figure 2. The light curves from the ASAS and NSVS databases focus on the difference between depths of primary and secondary minima represented by the Fourier coefficient a_1 (top two rows). The smaller value of this coefficient, the greater difference between depths of primary and secondary minima. The light curves from the ASAS and NSVS databases focus on the amplitude of the light curve changes represented by the Fourier coefficient a_2 (last two rows). The smaller the value of this coefficient, the greater the amplitude of the light curve changes.

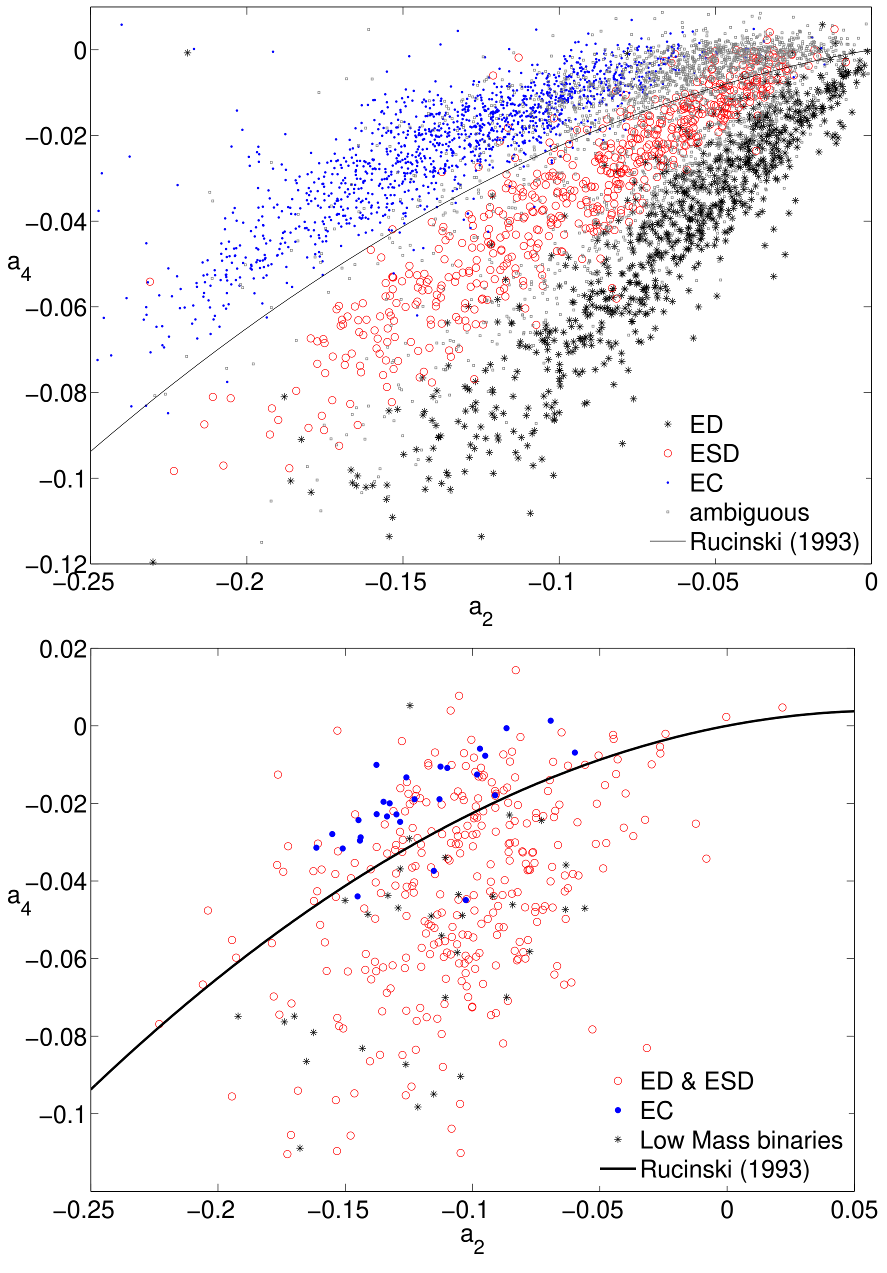

Figure 3. The relationship between Fourier coefficients a_2 and a_4 and comparison of this relationship with the data from the NSVS database. The solid line represents the border separating contact systems from semi-detached and detached ones (Rucinski, 1993). The grey squares represent systems with an ambiguous classification from the ACVS catalogue.

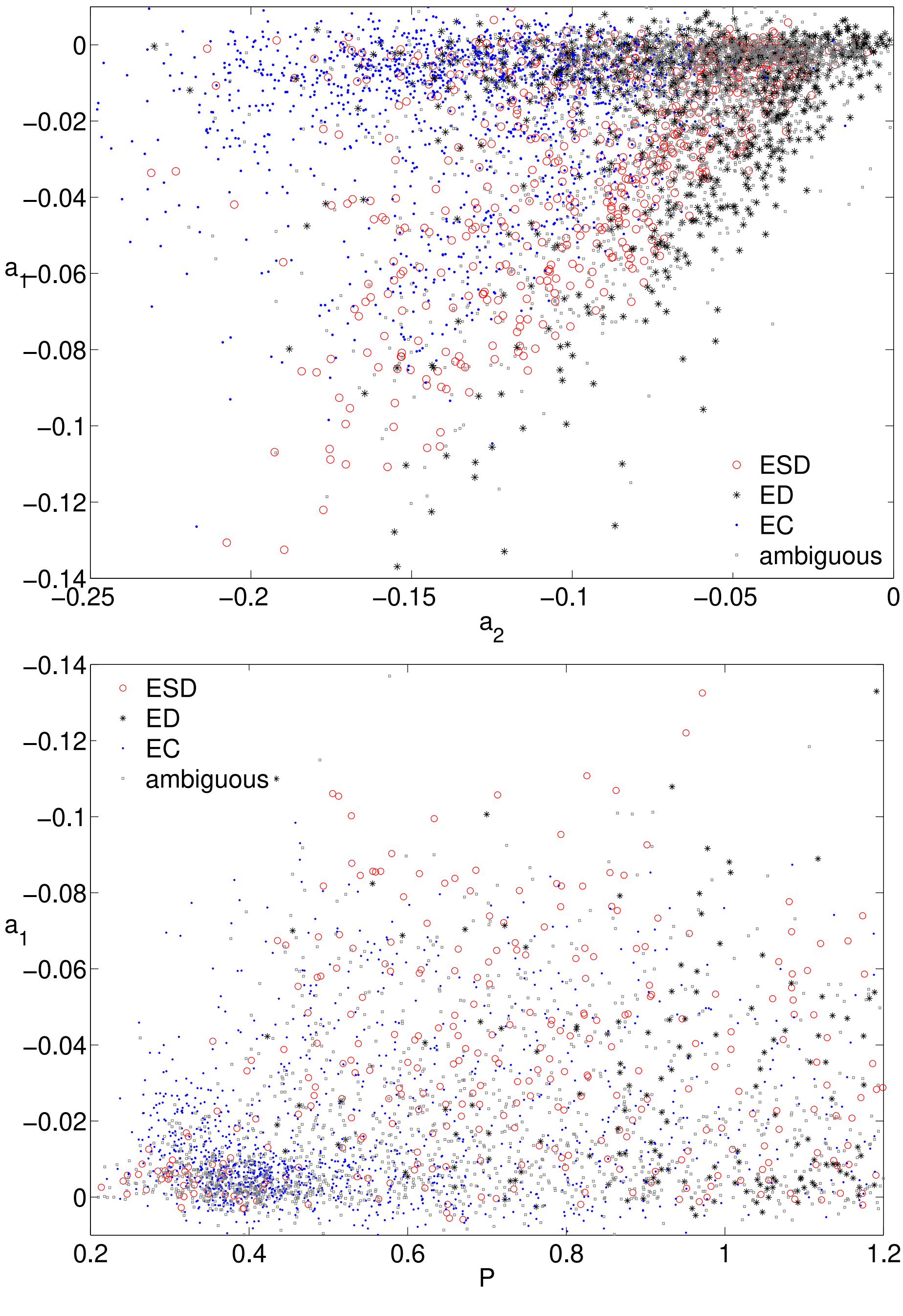

Figure 4. Dependences between coefficients $a_1 - a_2$ and $a_1 - P$, where P is the orbital period.

Table 3. A comparison of the values of Fourier coefficient a_1 and a_2 for the systems from ASAS and NSVS databases where d is the difference between the depths of the primary and secondary minima and *ampl* is the amplitude of the light curve changes (difference between maxima and primary minima magnitudes). The left part of this table is aimed to compare values of the Fourier coefficient a_1 with the difference d for two chosen systems from ASAS and NSVS databases and in the right part of this table there are compared the Fourier coefficient a_2 and the amplitude of the light curve.

ASAS	a_1	d	a_2	*ampl*
000030−3937.5	-0.011379 ± 0.001839	0.6450	-	-
002328−2041.8	-0.006571 ± 0.002709	0.0300	-	-
075532−2145.6	-	-	-0.211894 ± 0.020888	0.5252
065520+0817.0	-	-	-0.024676 ± 0.001484	0.1041
NSVS	a_1	d	a_2	*ampl*
17348341	-0.123289 ± 0.008618	0.6274	-	-
12118196	-0.040264 ± 0.004689	0.1106	-	-
1090740	-	-	-0.223082 ± 0.015957	0.7973
9091101	-	-	-0.087780 ± 0.003810	0.2620

of small differences between the depths of minima. This is caused by a thermal and physical contact of the components embedded in a common envelope equalizing the surface temperature. Unfortunately, some of detached and semi-detached binaries also show similar surface temperatures of the components. Thus $-0.02 \leq a_1 \leq 0$ is the necessary, but not sufficient condition for the contact nature of an eclipsing binary.

Fig. 4 (bottom) shows the relation of the orbital period and the Fourier coefficient a_1. Most short-period eclipsing binaries with $0.2 \leq P \leq 0.5$ are contact binaries. It is known that contact binaries have the shortest periods. Those are visible as clustering of points with $a_1 \sim 0$.

4. Conclusions

In this paper we investigate Fourier coefficients of the light curves from the ASAS and NSVS databases. We used $\sim$ 5500 light curves with proper ephemerides (Pilecki, 2009) from the ASAS database and 378 systems with well known ephemerides (Hoffman, 2008). We have shown that the Fourier coefficients correspond to the preliminary (expected) properties of the LCs (Selam, 2004). In Fig. 2 and Tab. 3 we can see the relationship between the Fourier coefficient a_1 and differences between depths of primary and secondary minima. The closer to zero the coefficients a_1, the smaller the difference between the depths of the minima. Fig. 2 depicts the relationship of the coefficient a_2 and the amplitude of light curve changes. We can see the same condition: The closer to zero the coefficients a_2, the smaller the amplitude of the LC (Tab. 3). We have described some relations between Fourier coefficients (Fig. 3 and Fig. 4) and demonstrated that the border calculated by Rucinski (1993) can be used for the NSVS data as well.

This information is very useful for a preliminary classification of the binary stars. A Fourier decomposition and computation of the Fourier coefficients is a fast way how to find specific types of binaries. Using these properties of the Fourier coefficient a_1, one can easy determine the difference between the depths of minima and find detached eclipsing binaries or, in case of a_2, one can investigate the amplitude of the light curve.

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