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Eclipsing binaries in the All Sky Automated Survey catalogue

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ABSTRACT

The All Sky Automated Survey (ASAS) is a long-term project to monitor bright variable stars over the whole sky. It has discovered 50 099 variables brighter than $V < 14$ mag south of declination $+28^{\circ}$, and among them 11 076 eclipsing binaries. We present a preliminary analysis of 5384 contact, 2949 semi-detached, and 2743 detached systems. The statistics of the distribution provides a qualitative confirmation of decades old idea of Flannery and Lucy that the W UMa-type binaries evolve through a series of relaxation oscillations: the ASAS finds comparable number of contact and semi-detached systems.

The most surprising result is a very small number of detached eclipsing binaries with periods $P < 1$ d, the systems believed to be the progenitors of the W UMa stars. As many (perhaps all) contact binaries have companions, there is a possibility that some were formed in a Kozai cycle, as suggested by Eggleton and his associates.

Key words: binaries: eclipsing – stars: evolution.

1 INTRODUCTION TO THE ASAS

The ASAS – All Sky Automated Survey – is a long-term project dedicated to the detection and monitoring of the variability of bright stars. This paper presents the results of several years of observations carried out at the Las Campanas Observatory with a single instrument: a telescope with an aperture of 7 cm, a focal length of 20 cm, done through a standard V-band filter and a $2\,\mathrm{K} \times 2\,\mathrm{K}$ CCD camera with 15-μm pixels from Apogee (Pojmański 1997, 1998, 2000, 2002, 2003; Pojmański & Maciejewski 2004, 2005, Pojmański, Pilecki and Szczygieł 2005). More information about the ASAS is provided on the WWW:

http://www.astrouw.edu.pl/∼gp/asas/asas.html

http://archive.princeton.edu/∼asas/

The variable stars were discovered quasi-uniformly for declination $< +28^{\circ}$, covering almost three quarters of the full sky. Fig. 1 shows the distribution of the ASAS variables in the sky in Galactic coordinates. The Milky Way is clearly visible, together with the dust lanes. The distribution of the ASAS stars as a function of V magnitude is shown in Fig. 2, for all stars (17 000 000), all variable stars (50 099), and all eclipsing binaries; the latter are divided into eclipsing contact binaries (EC, 5384), eclipsing semi-detached binaries (ESD, 2949), and eclipsing detached binaries (ED, 2743). The statistics for stars with $8 < V < 12$ mag appears to be approximately complete, but the efficiency falls rapidly within the range $12 < V < 14$ mag as the detection limit is approached. Also, the statistics deteriorate for $V < 8$, because of saturation effects.

All stars were observed for about 5 yr, with a small subset observed for 8 yr. The typical number of photometric measurements was several hundred. The distribution of this number is shown in Fig. 3. The total number of photometric measurements was 2916 000. As the ASAS continues its operation, the number of measurements will increase, by approximately 100 V-band photometric measurements per year per variable. We intend to continue the project indefinitely, with some upgrades. While only the V-band results are reported here, the I-band photometry was accumulated, and several years of data are already stored on a RAID-5 disc system. However, it will take another year to process the I-band data, totalling well over a terabyte. There are more stars detectable in the I-band, so we expect that the number of variables will more than double. We are also planning an expansion of ASAS to the Northern hemisphere, to fully cover the whole sky.

The results presented in this paper are not final in any sense. Please note that all data are in the public domain. A different classification of binaries can readily be done by whoever feels like verifying and/or correcting our presentation.

This is an observational paper, but Section 2 gives a short introduction to the main ideas about the structure and evolution of contact binaries. Section 3 gives the information about the ASAS data, the classification scheme, and some examples of a diversity of light curves. Section 4 provides simple statistics of the ASAS binaries. Finally, in Section 5 we make a somewhat speculative discussion based on this observational paper.

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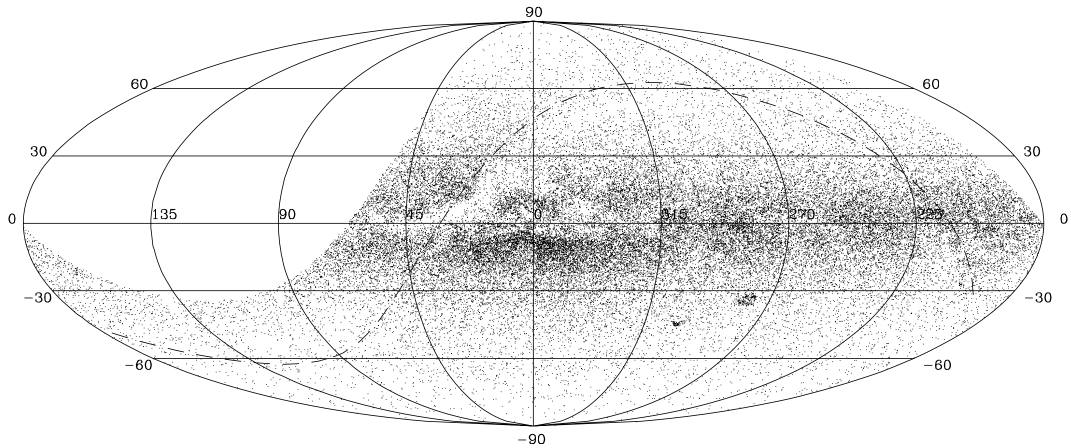

Figure 1. The distribution of the 50 099 ASAS variables in the sky in the Galactic coordinates. The Milky Way is clearly seen, as well as the patches of interstellar extinction. The celestial equator is shown with a dashed line. The distribution is limited to declination $< +28°$.

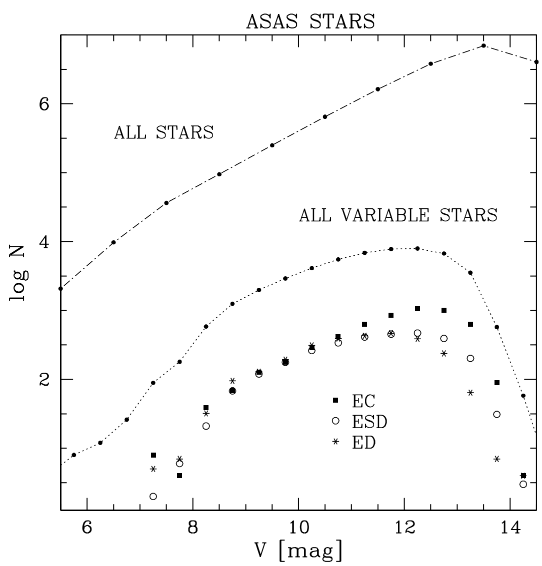

Figure 2. The distribution of the ASAS stars as a function of V-band magnitude. The total number of stars is about 17 000 000. The total number of variable stars is 50 099. The total number of eclipsing binaries is 5384 for contact systems (EC), 2949 for semi-detached systems (ESD), and 2743 for detached systems (ED). Note, that the efficiency of discovering variable stars declines for $V > 12$, because the detection limit is approached, and for $V < 8$, because of saturation effects.

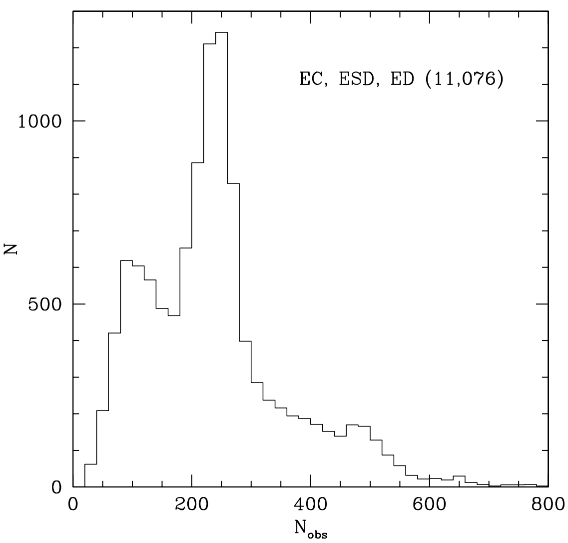

Figure 3. The histogram of the number of photometric measurements obtained during 5 yr of the ASAS life. A small subset of data extends back to 8 yr.

2 INTRODUCTION TO CONTACT BINARIES

Contact binaries, also known as the W UMa stars, are in a physical contact, with continuously changing brightness because of large tidal distortion of the two components.

The first theoretical milestone in the understanding of contact binaries was due to Lucy (1968a,b), who proposed that the two components share a common envelope with the same entropy, thereby making the effective temperature almost constant over the surface of the two stars. As contact binaries have a mass ratio distinctly different from 1, most nuclear energy is generated in the more massive component and it is redistributed around the whole surface through a moderately thick convective envelope.

The second theoretical milestone was the recognition of the consequences of the fact that the mass–radius relation for the zero-age main-sequence (ZAMS) stars is much steeper than for the two Roche lobes. There can be no stable equilibrium between the two stars with a common envelope. The system evolves through a sequence of relaxation oscillations, with the mass flowing from star A to B, next from B to A, etc. (Flannery 1976; Lucy 1976; Robertson & Eggleton 1977). The cycle repeats on a thermal (Kelvin–Helmholtz) timescale. According to the thermal relaxation model, the binary oscillates between thermal contact, with two eclipses of almost equal depth, and a semi-detached phase in which one eclipse is much deeper than another.

Hazlehurst (1970) suggested that the nuclear evolution of the primary component of a contact binary affects its structure. Stępień (2003, 2005) suggested that the currently more massive primary was originally the less massive of the two. The nuclear burning formed a small helium core, the star expanded and transferred mass to the original secondary. In analogy with the Algol systems, the currently more-massive component is the less evolved, while the present secondary has a small helium core, and it is more advanced in its nuclear evolution.

It is interesting that there is a controversy about thermal relaxation oscillations in the W UMa systems. Some authors claim there are no such oscillations (Webbink 2003), while others claim that such oscillations exist (Quin 2003; Li, Han & Zhang 2004; Yakut & Eggleton 2005, and references therein). The controversy seems to be rooted in the popular conviction that there are only very few eclipsing binaries in the period range $0.2 < P < 1.3$ d which are not in a thermal contact, while the theory of relaxation oscillations requires them to be common. We do not try to understand the origin of this conviction, but we point out that the ASAS statistics resolve this controversy on purely observational grounds: we demonstrate there are approximately as many W UMa systems which are in thermal contact, that is, systems with the two eclipses of about the same depth, and the W UMa-like binaries with different depths of the two eclipses, as theoretically expected (cf. Figs 8 and 9).

3 ASAS DATA

Close binaries with a deep common envelope are in thermal contact and they have eclipses of almost equal depth. If the contact is shallow, or if there is no physical contact, then the effective temperatures of the two stars are different, and the two eclipses have different depths.

Theoretical models of relaxation oscillations indicate that the radii of the two components change relatively little throughout the cycle (Flannery 1976; Lucy 1976; Robertson & Eggleton 1977; Yakut & Eggleton 2005, and references therein). With the geometry of the two stars almost unchanged, tidal distortions due to the geometry remain almost the same, and the most profound difference in the light curve is the relative depth of the two eclipses.

For the purpose of this paper, the classification of eclipsing binaries was achieved by decomposing their light curves into Fourier coefficients: a_1, a_2, a_3, a_4, following Ruciński (1997a,b, 1998, 2002) and Pojmański (2002). The classification is shown in Fig. 4 in the a_2–a_4 plane, with the EC, ESD and ED binaries shown with different symbols: ESD stars have smaller marks than EC and ED. Some examples of bright binaries of the EC, ESD and ED types are shown in Fig. 5. The parameters of these 15 binaries are listed in Table 1. The type of an eclipsing binary, EC, ESD or ED, is indicated at the upper right-hand corner of the light curve. The complete version of Table 1, for all eclipsing binaries used in this paper, and with all eight Fourier parameters, is in the file Fourier. E on the following webpages:

http://www.astrouw.edu.pl/∼gp/asas/asas_paper_data.html

http://archive.princeton.edu/∼asas/asas_paper_data.html

where all the data on which this paper is based are available electronically. These include all photometric measurements in compressed files: ec.tgz (49 MB), esd.tgz (27 MB), ed.tgz (27 MB).

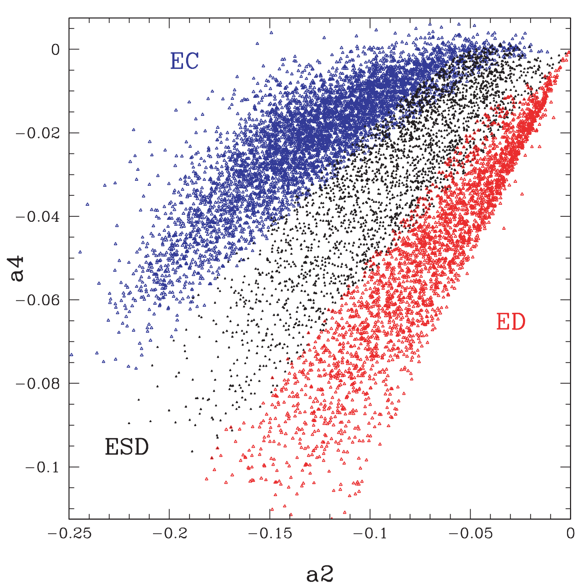

Figure 4. Classification of eclipsing binaries in the Fourier coefficients plane a_2–a_4. The three symbols refer to contact (EC), semi-detached (ESD), and detached (ED) binaries, following Pojmański (2002). Note: when the amplitude of variability is very small, the classification is very uncertain, as in the upper right-hand corner.

Some investigators (e.g. P. Eggleton) strongly prefer the classification of close binaries into EW, EB and EA types, on the grounds that photometry alone cannot provide unique geometry. Our classification into EC, ESD and ED types should be considered preliminary, as we have only single-band photometry and no spectroscopic information for thousands of our binaries.

A sample of the catalogue of ASAS eclipsing binaries is shown in Table 2. The full table has the information for all the 11 076 binaries, and can be found on our webpage, in the file ‘Vars. E.’

A subset of all the ASAS results related to binary stars was ‘frozen’ for the epoch of this paper. The ASAS is an on-going project, with more data added every clear night. Therefore, as time goes on, the volume of data related to eclipsing binaries will increase, and the quality will improve. To make the results presented in this paper reproducible, we decided to provide ‘frozen’ data.

Note: all light curves presented in Fig. 5 are for bright variables discovered with the ASAS. They were not known before. Just as expected, the majority of the ASAS variables are new discoveries (Paczyński 1997).

4 STATISTICS OF CONTACT BINARIES

All the statistics of this section is based on the data provided in the file ‘Vars.E’, which can be found on our webpage. Table 2 is a sample of this file. In particular, the classification of the ASAS binaries is given there.

The Galactic distribution of the ASAS eclipsing binaries shows a significant difference, with detached binaries most strongly concentrated to the Galactic plane, while the short-period contact binaries have almost isotropic distribution. It is well known that there is a period–luminosity relation for the W UMa stars (Ruciński 1996; Klagyivik & Csizmadia 2004), and the Galactic distribution of those stars is not surprising. The strong concentration of detached binaries to the Galactic plane implies that these are even more luminous and massive, on average.

The binary period distribution is shown in Fig. 6 for stars with the Galactic latitude $|b| > 30°$ to reduce the luminosity bias. The distribution of contact systems (EC) peaks near 0.37 d, it has a sharp cut-off at 0.2 d, and a long tail extending beyond 1 d. In fact, the tail extends to more than 100 d, as it is apparent in Figs 8 and 10. Also shown is the distribution of orbital periods of semi-detached (ESD) and detached (ED) binaries.

The important topic of this paper is the presentation of eclipse depth of EC binaries, as this is directly related to the issue of relaxation oscillations. For contact binaries, the depth of both the eclipses is directly related to the Fourier coefficients of the light curve. The following analytical formulae approximate these relations with

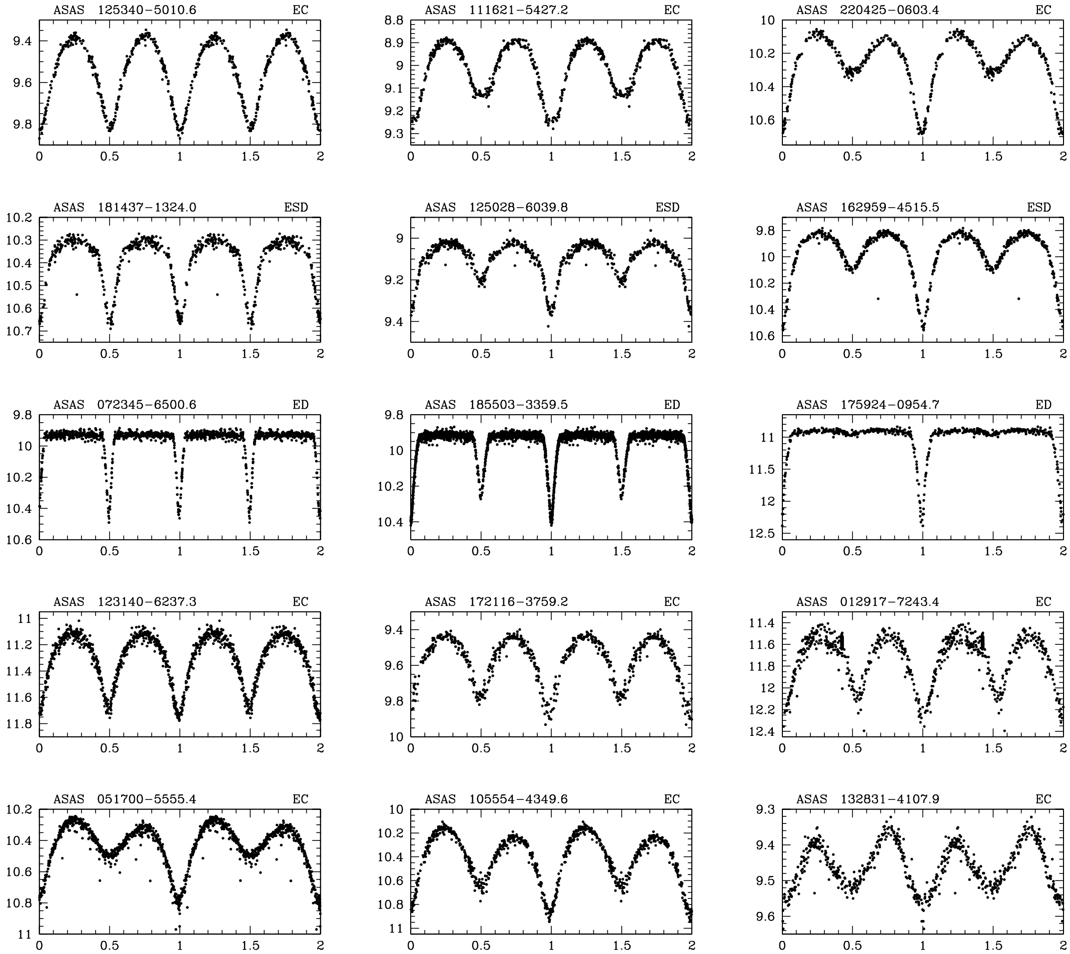

Figure 5. Examples of light curves of nine contact (EC), three semi-detached (ESD) and three detached binaries (ED) are shown. All these are the ASAS discoveries, even though all of them are very bright. Note, a distinct difference in the light curve shapes between contact and semi-detached binaries. The first three rows are sorted by minimum depth difference, the fourth row presents contact binaries with long and exceptionally long periods, and the fifth with the distinct maximum height difference. See Table 1 for details.

Table 1. A sample of the most important Fourier parameters for the light curves from Fig. 5 are listed along with orbital periods. Each row of the light curves is here separated by a blank line. The a_2 parameter can be easily translated to the amplitude, a_1 and a_3 determine the difference between the two eclipses, and b_1 is related to the difference between the two maxima. The full table is available as supplementary material in the online version of this paper.

ASAS ID	P (d)	a_1	a_2	a_3	a_4	b_1
125340−5010.6	0.4047	−0.003	−0.158	−0.003	−0.028	−0.003
111621−5427.2	0.4971	−0.026	−0.123	−0.012	−0.020	−0.000
220425−0603.4	0.7273	−0.062	−0.139	−0.034	−0.027	0.021
181437−1324.0	1.3992	−0.001	−0.110	−0.004	−0.054	0.004
125028−6039.8	2.0439	−0.030	−0.085	−0.010	−0.031	−0.001
162959−4515.5	1.1376	−0.068	−0.155	−0.032	−0.049	0.001
072345−6500.6	3.1240	−0.006	−0.066	−0.003	−0.060	−0.001
185503−3359.5	1.1678	−0.019	−0.070	−0.015	−0.060	0.002
175924−0954.7	2.3438	−0.115	−0.119	−0.090	−0.088	0.006
123140−6237.3	1.9307	−0.009	−0.184	−0.004	−0.051	0.001
172116−3759.2	5.2056	−0.021	−0.135	−0.005	−0.033	0.007
012917−7243.4	180.60	−0.050	−0.190	0.016	−0.052	0.041
051700−5555.4	0.7904	−0.059	−0.126	−0.028	−0.021	0.020
105554−4349.6	1.1541	−0.034	−0.185	−0.019	−0.030	0.037
132831−4107.9	16.515	−0.010	−0.069	−0.011	0.003	−0.015

Table 2. A sample of the catalogue of the ASAS eclipsing binaries is presented here. Each star has its own ASAS designation (ID), equatorial coordinates (RA and Dec.), orbital period, epoch of minimum light (T_0), and the ASAS classification. Additional information of other designation and classification is also given, when available. The full table is available as supplementary material in the online version of this paper.

ID –	RA (2000)	Dec. (2000)	P (d)	T_0 245 0000+	V (mag)	A (mag)	Class –	Other ID	Other class
065819+1028.4	06:58:19	+10:28:24	0.447 763	2387.63	11.04	0.28	EC		
070017+0202.2	07:00:17	+02:02:12	1.397 550	1873.07	10.53	0.57	EC	V0460 Mon	EB/KE
211201−2003.2	21:12:01	−20:03:12	0.352 202	1872.84	13.22	0.34	EC/ESD		
025535−0219.9	02:55:35	−02:19:54	0.792 74	1920.00	11.59	0.54	ESD		
095930−6440.1	09:59:30	−64:40:06	2.2428	1869.42	11.48	1.12	ESD		
202110−4333.9	20:21:10	−43:33:54	1.002 18	1876.053	12.08	0.71	ESD/ED	V2265 Sgr	EA
001855−7954.9	00:18:55	−79:54:54	0.903 10	1870.45	11.28	0.77	ED		
114500−7247.6	11:45:00	−72:47:36	22.230 37	1895.60	11.15	0.09	ED		
235052−2316.7	23:50:52	−23:16:42	1.4023	1871.06	9.42	0.29	ED		

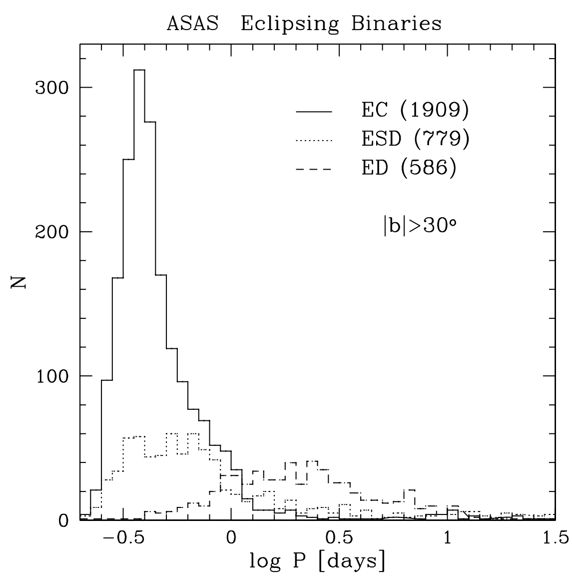

Figure 6. The distribution of periods of the ASAS contact binaries (EC) at high Galactic latitude $|b| > 30°$ is plotted. The distribution peaks near 0.37 d, it has a sharp cut-off at 0.2 d, and a tail extending far beyond 1 d. Also shown is the distribution of orbital periods of semi-detached (ESD) and detached (ED) binaries. Contact binaries outnumber other binaries for binary periods shorter than 1 d.

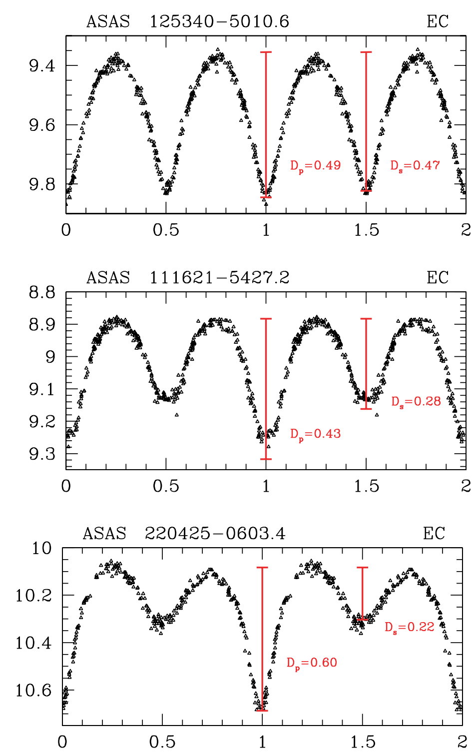

Figure 7. The first row of EC stars from Fig. 5 is shown. Vertical lines represent depth of a primary (D_p) and a secondary (D_s) eclipse calculated with equations (1) and (2), respectively. Flat bottom eclipses may result in a significant error, which is somewhat reduced in the $D_\mathrm{s}/D_\mathrm{p}$ ratio.

better than 5 per cent accuracy for the majority of stars:

$$D_\mathrm{p} = -2\left[1.2a_2 - 2a_2^2 + (a_1 + a_3)\right] \quad \text{(mag)}, \tag{1}$$

$$D_\mathrm{s} = -2\left[1.2a_2 - 2a_2^2 - (a_1 + a_3)\right] \quad \text{(mag)}, \tag{2}$$

where D_p and D_s correspond to the depth of the primary and secondary minimum, respectively. Three examples are presented in Fig. 7.

The eclipse depth ratio is shown in Fig. 8 for EC binaries, and in Fig. 9 for EC and ESD binaries. These are important figures. They demonstrate that some EC binaries are in good thermal contact, as the depth of secondary eclipse is almost the same as the primary. However, many other EC binaries have two eclipses that are very unequal, implying that they are not in thermal contact, yet their geometry is close to that expected for a contact system. Finally, there are ESD binaries, in which the geometry is very different and, of course, the two eclipses usually have different depths. Qualitatively, this is just what was expected in the models with relaxation oscillations (cf. Flannery 1976; Lucy 1976; Robertson & Eggleton 1977; Yakut & Eggleton 2005). There is no shortage of stars without thermal contact. Combining ASAS data with models of relaxation oscillations should provide quantitative verification of the theory, but this task is beyond the scope of this paper.

The distribution of the primary eclipse depth with binary period is shown in Fig. 10. A histogram of the primary eclipse depth integrated over the binary period is shown in Fig. 11. Note that while the vast majority of the W UMa binaries have periods in the range $0.2 < P < 1.2$ d, there are contact binaries with periods over 100 d, as is apparent in Figs 5 and 10.

Contact binaries often have maxima of different heights, with the maximum following the primary (i.e. deeper) eclipse being either higher or lower than the maximum following the secondary

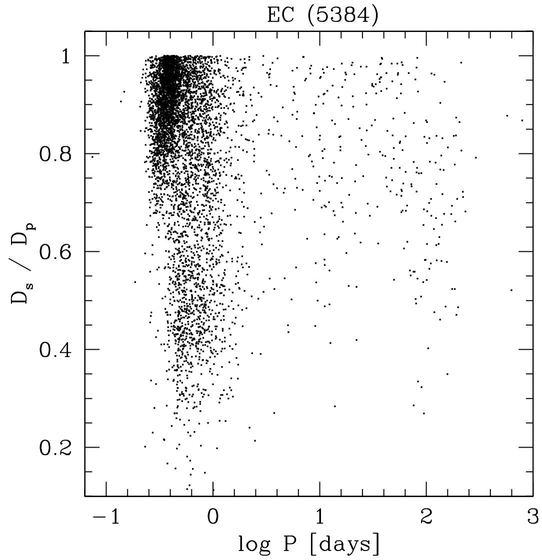

Figure 8. The ratio of eclipse depth is shown for contact binaries as a function of their period. Stars in thermal contact have the eclipse depth ratio close to 1.

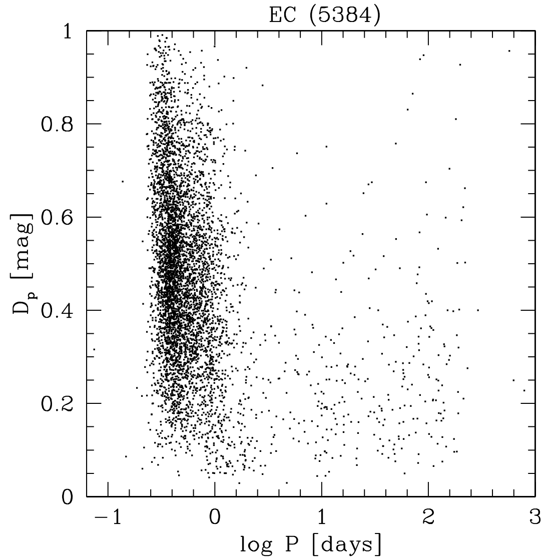

Figure 10. The distribution of the primary eclipse depth as a function of orbital period for contact binaries. D_p is the fraction of light obscured in the primary eclipse.

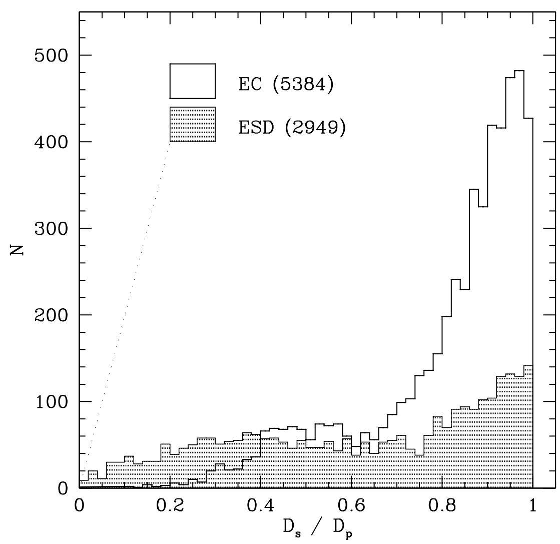

Figure 9. The ratio of the eclipse depths, integrated over binary periods, is shown for contact (EC) and semi-detached (ESD) systems. Stars in a thermal contact have the eclipse depth ratio close to 1. Note, the step in the histogram at $D_\mathrm{s}/D_\mathrm{p} \approx 0.7$. The same feature is also apparent in Fig. 8 at $\log P \approx -0.4$.

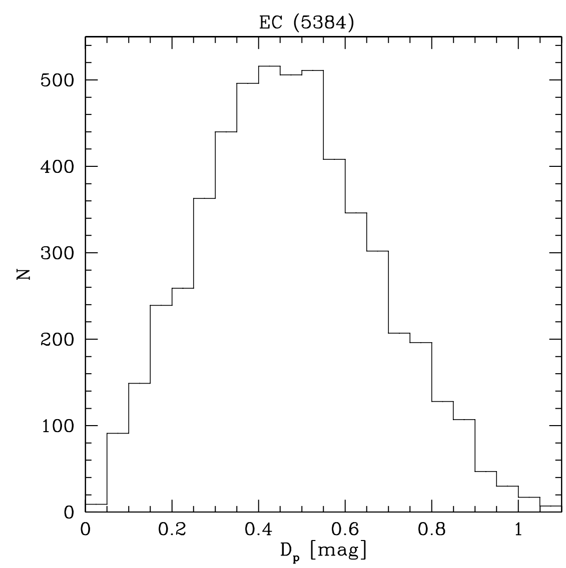

Figure 11. The distribution of the primary eclipse depth integrated over all periods.

eclipse. The distribution of the difference is shown in Fig. 12. The positive value of the $b1/|a2|$ parameter indicates that the maximum following the primary eclipse is brighter of the two. The asymmetry in distribution, i.e. the excess of the positive values of $b1/|a2|$, is known as the O'Connell (1951) effect (cf. also Ruciński 1997b): the maximum following the primary eclipse is on average brighter, presumably due to the stream of gas flowing between the two stars. An extreme case of this phenomenon is shown in V361 Lyr (Kaluzny 1991).

5 DISCUSSION

Our conclusion, based on the distribution of eclipse depths (Figs 8 and 9), is that the relaxation oscillations, first proposed by Lucy and Flannery, are real. There is no shortage of binaries corresponding to no thermal contact, with a very different depth of the two eclipses. Model calculations of the type recently carried out by Yakut & Eggleton (2005), when combined with the ASAS data, should allow a quantitative verification of the theory.

A very large number of contact or near-contact systems reveal features never noted before: the distribution of eclipse-depth ratios as shown in Figs 8 and 9 has a distinct break around $\log P \approx -0.4$ and $D_\mathrm{s}/D_\mathrm{p} \approx 0.7$. We do not speculate on the origin of this feature, but we bring this break to the attention of our readers. This break is best seen in systems with the most robust classification.

The most surprising result of this paper is presented in Fig. 6. A traditional view for the origin of the W UMa contact binaries is to assume that they come from detached binaries of comparable

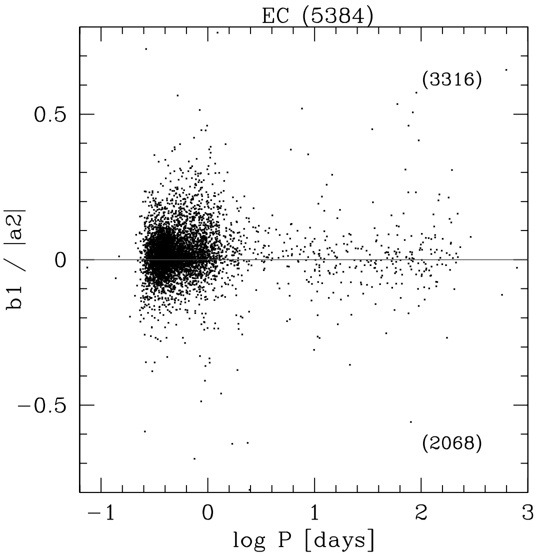

Figure 12. The distribution of light curve asymmetry of contact binaries is shown – this is known as the O'Connell (1951) effect. Most stars have their light maxima of approximately equal height, but there is an asymmetry in the distribution: the maxima that follow the primary minimum are on average higher than the maxima preceding the primary eclipse. The O'Connell effect is likely a consequence of the gas streams in these binaries.

periods. For the first time we have approximately complete statistics for binaries of all types with orbital periods shorter than 1 d, and there are very few detached binaries. Obviously, they are more difficult to find than either contact or semi-detached systems. As time goes on, the statistics of the ASAS detached binaries will improve, and a statistical analysis will tell us if there is a problem with the origin of the W UMa stars. At this time the contact systems seem to appear 'out of nowhere'.

In about a year, we will have I-band data for our eclipsing binaries. This will make it possible to be more quantitative about the distribution properties, including the distribution in our Galaxy. Also, it will be much easier to quantify the impression about a shortage of detached binaries and the space density of systems of different types: EC, ESD and ED. At this time, it is premature for us to speculate about the outcome of binary statistics while we wait for the I-band data.

While this is an observational paper, written to promote the usefulness of the ASAS catalogue of variable stars, we are tempted to speculate about the possible interpretation of Fig. 6, which was so surprising to us. We are not consistent with the previous paragraph, but the temptation is hard to resist. The following is a speculative hypothesis.

There has been a gradual emergence of the notion that contact systems have companions (Ruciński & Kaluzny 1982; Chambliss 1992; Hendry & Mochnacki 1998, also Tokovinin 2004). Recently, Pribulla & Ruciński (2006) found that up to 50 per cent of the W UMa binaries have companions. This opens up a possibility that the Kozai (1962) cycle operates in some such triples, as suggested by Kiseleva, Eggleton & Mikkola (1998), and Eggleton & Kiseleva (2001). The mechanical three-body orbital evolution, with a large range of inclinations of the two orbits, inner and outer, may induce large variations in the eccentricity of the inner binary. In time the eccentricity may become large enough to make a contact system out of the inner binary.

In this scenario, the inner binary has the initial period that is relatively long, and in most cases no eclipses would be detectable. During a Kozai cycle, the inner binary occasionally has a chance to reach a physical contact: it may either merge forming a single star, or it may become a W UMa star. This process is somewhat similar to the model of formation of close binaries in globular clusters (Pooley et al. 2003, and references therein).

Recent papers (D'Angelo, van Kerkwijk & Ruciński 2006; Tokovinin et al. 2006) brought up a similar issue: the commonality of tertiary (and higher) components among close binaries and a possible role of a Kozai (1962) cycle in their origin. The surprisingly small number of short-period detached eclipsing binaries, as seen in Fig. 6, may indicate that the Kozai cycle is not just a curiosity, but it may be an important channel for forming the W UMa stars. This possibility cannot be rejected without careful analysis. After all, the W UMa stars are rare, with the local space density of just 0.2 per cent of the main-sequence stars (Ruciński 2002, 2006, and references therein). The relative importance of the traditional origin of the W UMa binaries through angular momentum loss, and through the Kozai cycle, will require further study.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online:

Table 1. The most important Fourier parameters for light curves from Fig. 5 are listed along with orbital periods.

Table 2. The catalogue of the ASAS eclipsing binaries.

This material is available as part of the online article from http://www.blackwell-synergy.com.

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