CLASSIFICATION OF ECLIPSING BINARIES: ATTRACTIVE SYSTEMS

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Abstract. We have compiled a catalogue of eclipsing variable stars, the largest catalogue, containing classified eclipsing binaries. A procedure for the classification of eclipsing binaries, based on the catalogued data, is also developed. It was applied to unclassified eclipsing binaries. In this paper we discuss eclipsing binaries, which can not be classified with the procedure. Some of them belong to marginal evolutionary classes. Observational data for others are too contradictory, and additional observations are needed to attribute them to one or another evolutionary class.

Key words: binaries: eclipsing – catalogues

1. Introduction

Eclipsing binaries represent one of the most numerous type of binaries and serve as an invaluable source for determination of the fundamental properties of stars: masses, radii, temperatures and luminosities.

Catalogue of Eclipsing Variables (CEV) was compiled by Malkov et al.\textsuperscript{(2006)}. CEV has been used to develop the most comprehensive set of rules for the classification of eclipsing binaries to date (Malkov et al.\textsuperscript{2007}).

For compilation of the first version of catalogue (see Malkov et al.\textsuperscript{2007, sec. 2.1}) we used data from General Catalogue of Variable Stars, GCVS (version 2004) and its textual remarks (Samus et al.\textsuperscript{2009}). A lot of new eclipsing variables were discovered since 2004, and currently GCVS contains about 7000 eclipsing binaries. We have added the new stars in the second version of CEV. The current version of CEV contains data for 7179 eclipsing binaries and represents the largest list to date of eclipsing binaries classified from observations. Catalogue is described in detail by Avvakumova et al.
Table I: Catalogue of eclipsing variables, main table, first fifteen lines.

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) | (16) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RT And | CB | EA | RS | 8.99 | 0.41 | 0.31 | V | 0.6289 | v | 170 | 0 | 170 | 0 | F8V+K1 | a |
| SY And | EA | 10.70 | 1.50 | 0.00 | V | 34.9085 | 60 | 27 | A0+K1 |
| TT And | SA | EA | 11.50 | 1.50 | 0.10 | V | 2.7651 | v | 140 | 0 | A+G7IV |
| TW And | SA | EA | 8.98 | 2.06 | 0.15 | V | 4.1228 | v | 130 | 20 | F0V+K0 |
| DK And | EW | 12.50 | 0.60 | 0.60 | p | 0.4892 | 0 | 0 | 0 |
| UU And | SA | EA | 11.20 | 3.00 | 0.20 | V | 1.4863 | v | 170 | 0 | A8IV/V |
| WW And | SA | EA | 10.92 | 0.67 | 0.16 | V | 23.2852 | 50 | 12 | A0+G5-K0III |
| WX And | EA | 12.10 | 1.70 | 0.00 | V | 3.0011 | d | 120 | 30 | F5IV |
| WZ And | CB | EB | 11.60 | 0.40 | 0.01 | V | 0.6957 | v | 0 | 0 | F5 |
| XZ And | SA | EA | 9.91 | 2.54 | 0.25 | V | 1.3573 | v | 160 | 0 | 260 | A1V+G5IV |
| AA And | CB | EA | 10.30 | 0.90 | 0.30 | p | 0.9351 | 210 | 0 | B8V |
| AB And | CWW | EW | 9.49 | 0.97 | 0.83 | V | 0.3319 | v | 0 | 0 | G5+G5V |
| AD And | EB | 11.20 | 0.62 | 0.58 | V | 0.9862 | v | 0 | 0 | 494 | A0V |
| AM And | EA | 12.50 | 1.20 | 0.00 | p | 8.8505 | 80 | 0 | 0 | A7Vm |

Identification, classification: (1) name of the star (as listed in GCVS); (2) class of the system (the abbreviations are given according to sections 2.2.1–2.2.3); (3) morphological type of the light curve (EA, EB, EW; as in the GCVS); (4) additional variability type from the GCVS. Photometry: (5) magnitude at maximum brightness; (6) depth of primary minimum, \( A_1 \), mag; (7) depth of secondary minimum, \( A_2 \), mag; (8) the photometric system for magnitudes as in the GCVS. Period: (9) period of the variable star, \( P \), day; (10) information on the sign of period variability (d: derivative is negative and period decreases, i: derivative is positive and period increases, v: derivative is non-zero and the sign varies thus period increases and decreases, u: derivative is non-zero, but the sign is unknown thus period increases or/and decreases). Eclipses: (11) duration of primary eclipse, \( D_I \); (12) duration of totality in primary eclipse, \( d_I \); (13) duration of secondary eclipse, \( D_{II} \); (14) duration of totality in secondary eclipse, \( d_{II} \); (15) phase of secondary minimum, Min\( II \)-Min\( I \). Spectra: (16) spectral types and luminosity classes of the primary and secondary; (17) information on chromospherical activity (a: chromospherically active system).

A lot of additional bibliographic sources were used to update data in CEV. The list of the sources with the comments is also given in the Avvakumova et al. (2013). Altogether information on 1783 binaries was updated. First fifteen lines of the catalogue are presented in table I. The catalogue will be available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr or via http://vizier.u-strasbg.fr/viz-bin/VizieR.

We have investigated the distribution of the catalogued systems in various observational planes and extracted from them a number of rules that allows us to make classification of catalogued systems based on a set of observational parameters, even if the set is incomplete.

When procedure of classification has been applied to previously unclassified CEV systems, we have found a number of eclipsing binaries, which can not be classified with the procedure. Some of them, apparently, belong to marginal evolutionary classes. Observational data for others are too contradictory, and additional observations are needed to attribute them to one or another class.

The scheme of eclipsing binaries classification, adopted in the present study, is described briefly in Section 2. Our method of eclipsing binaries classification, based on catalogued data, and principal results, including...
unclassified binaries, are discussed in Section 3. Finally, in Section 4 we draw conclusions.

2. Evolutionary classes of eclipsing binaries

The catalogue CEV supplies data with independently determined evolutionary classes of systems. The list of the original catalogues and data sources we used have been listed in Avvakumova et al. (2013).

According to well known schemes, we have divided all binaries into three classes: detached, semidetached and contact (denoted as D, S, C, respectively) systems. Moreover, in each of these classes, sub-classes can be distinguished.

2.1. Detached systems

Main sequence systems (DM)
Both components are main sequence stars which do not fill their inner Roche lobes.

Systems with two subgiants (DR)
In these systems, both stars are subgiants, they do not fill their Roche lobes (alternative names: AR Lac systems, RS CVn systems or long-period RS CVn systems). The hotter component in such systems is usually less massive and smaller and has a spectral type of either F or G.

Giant and supergiant systems (DG)
Based on value of period and spectral type we have devided DG systems on two subclasses: E (early-type) and L (late-type). Binaries of the E-subclass systems consist of two hot stars: well evolved primary (WR, giant or supergiant) and MS early type or hot giant secondary. Orbital periods of DGE systems are shorter than 35 days. L-subclass systems include two stars with large temperature difference. Primaries of such systems are MS, giant or supergiant stars of spectral type from late-B to mid-F while secondaries are always late type (from late-G to M) evolved stars. Orbital periods of L-subclass systems are about 100 days and longer.

White dwarf systems (DW)
Detached systems with white dwarf (or subdwarf) as a primary. The secondary usually is a low-mass star (main sequence or subgiant).
Symbiotic detached systems (D2S)
According to Belczyński et al. (2000) there are five detached symbiotic binaries which comprise a red giant transferring material to a white dwarf via a stellar wind.

2.2. Semidetached systems

Classical algols (SA)
Here the more massive component lies in the range from middle B to early F, and the other component is of type F or later. The primary (hotter, brighter and more massive) component is assumed to have a normal mass, radius and luminosity for its spectral type. Also the primary can have larger (if it is a donor) or smaller (if it is an accretor) radius than the secondary. The secondary (cooler, overluminous and oversized) component is assumed to fill its Roche lobe.

Cool semidetached systems (SC)
Based on the definition of Popper (1980), both components are late type subgiants or giants.

Hot semidetached systems (SH)
According to Popper (1980) the hotter component of these systems is an early B-type star and the cooler is of type B or an early A.

Cataclysmic semidetached systems (S2C)
These systems contain a white dwarf (or a white dwarf precursor) primary and a low-mass secondary, which fills its critical Roche lobe. The secondary is not necessarily unevolved. We use catalogues of Ritter and Kolb (2003) and Downes et al. (2001) to classify this type of objects.

X-ray semidetached systems (S2H, S2L)
According to Liu et al. (2006) and Ritter and Kolb (2003) there are two subclasses of X-ray semidetached binaries: massive (denoted as S2H) and low-mass (denoted as S2L) systems. Massive X-ray binaries comprise a compact object orbiting a massive OB star (supergiant or Be star). Low-mass X-ray systems consist of either a neutron star or a black hole primary and a low-mass secondary which fills its critical Roche lobe.
2.3. Contact systems

According to Wilson (1979), these systems are all in fact overcontact systems with both components having surfaces larger than their critical Roche lobes. They are synchronous, circular orbit systems with common envelope. Besides overcontact systems, in this section we also consider near-contact systems.

Near-contact systems (CB)

Pribulla et al. (2003) designate near-contact binaries as B-type systems whose components are in physical but not in thermal contact. They usually consist of two stars of very different effective temperature enclosed in a common envelope. According to Shaw (1994) we distinguish F-type (CBF, FO Vir is a prototype) and V-type (CBV, V1010 Oph is a prototype) near-contact binaries. In V1010 Oph type systems the primary component (hotter) is at or near the Roche lobe, while the secondary (cooler) is inside the critical lobe and light curves are usually asymmetric. In FO Vir type binaries, the secondary is at or near its Roche lobe and the primary is inside the Roche lobe. Light curves for these systems are always symmetric. In both cases the primary has normal size but the secondary is oversized.

Early-type systems (CE)

They are contact systems of early spectra (not later than A0) with both components close to their Roche lobes.

Late-type systems (CW)

They are contact systems with spectrum of primary usually later than about A-F (also known as W UMa systems). According to Binnendijk (1977), classical CW systems were divided into A-type (CWA, the larger star is hotter and primary minimum is the transit) and W-type (CWW, the smaller star is hotter, the primary minimum is the occultation).

Giant systems (CG)

Both components of these systems are early-type very luminous giants or supergiants close to their critical lobes. Orbital periods of CG systems are longer than those of CE binaries.

3. Classification of eclipsing variables

To develop the method of classification we have performed analysis of the distribution of observable stellar parameters of eclipsing systems on various
diagrams such as \((A_1 \text{ vs } A_2), (A_1 \text{ vs } \log P), (Sp_1 \text{ vs } Sp_2)\) etc. An example of such analysis for detached systems with subgiants (denoted as DR in the catalogue, most of them belongs to RS CVn systems) is shown in Fig. 1.

As can be seen from the figure (bottom panel), the depth of primary minimum \(A_1\) for the most DR systems lies between 0.5 mag and 1.2 mag, while the depth of secondary minimum \(A_2\) is not greater than 0.6 mag. Three exceptional cases are CQ Aur \((A_1 = 0.33 \text{ mag})\), RW UMa \((A_1 = 1.56 \text{ mag})\) and TY Pyx \((A_2 > 0.6 \text{ mag})\). Data for one of them, RW UMa, are obsolete and the system needs a further study.

Most of DR systems have value of period (left top panel of Fig. 1) less than 10 days, except of RZ Eri and AI Phe. Both systems are long-period RS CVn systems. Lower limit for period value equals to about 1.5 days.

The spectral type of the hotter component (on the right top panel of Fig. 1) of the most of catalogued DR systems is F-G with luminosity class IV or V. Only RZ Eri with spectral type of the hotter component A8-F0IV does not satisfy this rule. We have found also that secondary spectrum of such systems are G to mid-K with luminosity class IV or V. All of DR systems are chromospherically active stars.

Also, all of DR systems exhibit EA-type light curves (i.e. the light of binary remains almost constant between eclipses).

We have used all conditions listed above to classify systems with unknown evolutionary type in our catalogue and have found two additional detached systems with subgiants. These two systems are shown with filled circles in Fig. 1. We have examined these systems with SIMBAD. One of them, RS Ari, is included in the catalogue of Brancewicz and Dworak (1980) as a detached system and in the catalogue of chromospherically active binaries of Eker et al. (2008). The other system, CF Tuc, is a detached and well studied RS CVn binary star (Doğru et al., 2009). So our classification of these two binaries as detached systems with subgiants is confirmed.

After comprehensive analysis of our catalogue we have developed similar sets of rules for the classification of other types of binaries in our catalogue.

The full set of rules can be applied only for systems with all known parameters, i.e. amplitudes, periods and spectra. In this case our procedure has allowed us to classify about 77% of systems. Therefore there is a number of systems in CEV that we could not classify for some reason. Three main reasons are discussed below.
Figure 1: The distribution of detached systems with subgiants (DR systems) on $A_1 - A_2 - \log P - Sp_1$ planes. Catalogued DR systems are shown with squares. Filled circles denote two systems which have been classified as DR with our classification algorithm (see text for details).
3.1. Lack of observations

In the case of incomplete set of parameters (for example period or/and spectra are unknown) a lot of systems have been classified ambiguously.

For example we have found a number of “candidates” to CE or CG classes, and they are shown on Fig. 2. On the left panel of Fig. 2 the distribution of classified CE (contact early type binaries) and CG (giant and supergiant contact binaries) on the plane “primary spectrum — period” is shown with circles and crosses, respectively. On the right panel, classified CE and CG systems on the plane “primary spectrum — secondary spectrum” are shown. The “candidates” to both CE and CG classes are shown with filled circles. Information about secondary spectrum is available only for three “candidates”. As one can see, CG systems have longer periods as compared with CE and it will be possible to divide CE binaries and CG binaries if only primary (hotter) spectrum and period are known. But without secondary spectrum all these “candidates” may be classified as DM (detached main sequence), DG (giant and supergiant systems) or SH (hot semidetached algols)! So information about secondary spectrum is necessary for a lot of systems in CEV to classify them properly.

Another problem that we can refer as “lack of observations” is an old photographic data about amplitudes of primary and secondary minima. One such system RW UMa have been mentioned earlier (see Fig. 1). RW UMa were classified as DR by Popper (1990) and values of $A_2$, period and spectra are normal as compared to other DR binaries. But value of depth of the primary minima is equal to $1.56\,m$ and is larger than typical values for other DR. It may be assumed that new photometric observations will help us to determine new value of $A_1$ and it will be lower than $1.2\,m$.

While updating the catalogue we have found a number of systems, whose parameters contradict each other or/and too unusual for the system’s evolutionary class. In the majority of cases such parameters are based on photographic (probably, outdated) photometry, and we could not find confirmation (or refutation) of that data in the literature. Consequently, new observations and further investigations are required for these systems. The list of these systems contains 238 eclipsing binaries. In particular, it contains systems with too large depth of primary minimum $A_1$. It also contains contact and semi-detached systems, exhibiting evidence of orbital eccentricity (which is strange for such close systems): phase of secondary minimum
Figure 2: The distribution of contact early-type systems (CE and CG systems) on logP – Sp₁ – Sp₂ planes. Catalogued CE systems are shown with empty circles, catalogued CG systems are shown with crosses, filled circles denote “candidates” to CE or CG class (see text for details).
differs from 0.5 or duration of primary and secondary eclipses are not equal.

3.2. Contradictory classification

One of the result of our classification is that a number of systems have turned out to belong simultaneously to several classes. Observed parameters (periods, spectra, depth of minima, etc) are inconsistent with each other. All of such systems were checked with the literature. For a lot of them we have found contradictory classifications. Several examples are listed below.

RT Lac

This system is one of the most "peculiar" in our list. Its period is as for classical semidetached algols (denoted as SA) and detached systems with subgiants (DR), but spectrum of the hotter primary component corresponds to typical spectra of cool algols (SC in our notation) and DR. Additionally we can use the relation between spectra of primary and secondary. Such a relation for RT Lac points out to SC and DR classes. Moreover the depth of the secondary is greater than for other SA, SC and DR systems! We could include it in the DR class because of its RS CVn type of variability (Strassmeier et al., 1993), but most of DR type systems have depth of secondary minima $A_2$ not greater than 0.4", while $A_2$ of RT Lac equals to 0.83". According to İbanoğlu et al. (2001) the brightness of the system at three phases, i.e., mid-primary and quadratures, shows quasi-periodic changes. The brightness at the primary eclipse (phase 0.0) shows the largest variation with a maximum amplitude of about 0.3 mag in the B and V filter. The light variations at the secondary maximum (phase 0.75) resemble those at primary eclipse but with a maximum amplitude of about 0.2 mag, while the variations at primary maximum (phase 0.25) are generally in the opposite sense, but with a lower amplitude (about 0.1 mag). Thus the significant out-of-eclipse variations may lead to a large $A_2$ value. Again İbanoğlu et al. (1997) have pointed out to semidetached configuration of RT Lac, so why it is not SA or SC? As it was mentioned above we could not classify this system as SA because of its spectra, and its period is some lower than typical values for SC systems.

AO Cas

AO Cas has been classified as contact early type binary (CE) according to Polushina (2011), but its period ($3^d.52$) is larger than upper limit for CE systems ($1^d.89$). Such a large period is typical for contact systems with gi-
ants and supergiant (denoted as CG in CEV), but for this class the lower limit for $A_1$ equals to $0.32^m$ while $A_1$ for AO Cas is $0.17^m$. According to Gies and Wiggs (1991) and Bagno and Gies (1991) the system is semidetached, less massive secondary is subgiant which fills its Roche lobe and more massive primary is a MS star and does not fill its Roche lobe. With using depth of minima, period and primary spectrum we could classify AO Cas as hot semidetached algol (SH), but secondary spectrum $S_p_2$ is somewhat earlier as compared with other SH systems.

**AD Cap**
This system was classified as cold semidetached binary (SC). But according to data of Pojmanski (2002) depth of the primary and secondary minima equal to $0^m.33$. However the lower limit of $A_1$ is larger than $0^m.5$ for SC systems. Also the value of period of AD Cap is smaller as compared with other SC. Antonopoulou (1987) have pointed out that AD Cap is chromospheric active system of RS CVn type. The depth of both minima and period are appropriate to DR class, but spectra are not. The spectra of AD Cap is later than upper limit for DR class.

As a result we have compiled a list of about 39 such systems, which are attractive for additional observations and further investigations. All of these systems have (reliably known) values of parameters that distinguish them from other classified systems and lead to contradictory classification.

### 3.3. Extreme and unusual systems

When our algorithm have been applied to CEV, we found a number of systems with unusual parameters: periods, spectra, depth of minima, eccentricity. These systems do not fall at any of the classes that we use. Such systems belong to unusual stages of evolution (for example pre-MS systems) and are rare. Some of them are listed below, the full list of unusual systems contains 54 binaries.

**Post common envelope binaries**
We have found that several detached systems with white dwarf have very large depth of the primary minimum: UU Sge, RR Cae, GK Vir, QS Vir. They are all turned out to be post common envelope systems (also known as pre-cataclysmic binaries).

**BY Dra variables**
We have found also three detached chromospherically active systems with
late-type subdwarf spectra (dK–dM): YY Gem, CM Dra and BB Scl. They all have been classified as DM (detached main sequence binaries) but their periods are shorter as compared to other DM systems. They all are well known variables of BY Dra type.

**OW Gem**

OW Gem consists of two supergiants and was classified as DG system but, according to GCVS data and ASAS-3 light curve, it has an extreme value of the phase of secondary minima (0.23P) which points to the high eccentricity of the orbit. We have found it incredible and have checked OW Gem with literature. We have found that system consists of two stars with quite different masses. [Terrell *et al.* (2003)] have noted that if the two stars were formed together both cannot possibly be in the red giant stage. Also significant mass transfer is ruled out by very small relative radii of stars and the very large orbital eccentricity. [Eggleton (2002)] proposed a suggestion that OW Gem is a former triple system with the primary having formed from the merger of a close binary. But the merger product might be expected to have rapid rotation, and although the primary star does appear to be rotating faster than the pseudosynchronous rate, it is not unusually rapid. Primary could have undergone a G/K supergiant stage just after the merger and had substantial angular momentum removed by stellar wind and magnetic braking during a period of enhanced activity. This hypothesis needs to be tested.

4. Conclusions

A new version of the Catalogue of Eclipsing Variables (CEV) is constructed. The catalogue contains parameters for some 7200 stars. Also we have included to CEV recently published information about classification of 1352 systems, and, therefore, it represents the largest list of eclipsing binaries classified from observations. The catalogue can be used for classification and parameterization of known objects, characterization of new populations and discoveries of unusual objects. We have performed the comprehensive analysis of the distribution of observable stellar parameters of eclipsing systems of our catalogue and have developed an algorithm for the classification of eclipsing variables.

The procedure was applied to all catalogued EBs, and some systems remain unclassified. Part of them belong to marginal evolutionary classes.
Observational data for others are too contradictory, and additional observations are needed to attribute them to one or another evolutionary class (lists of unclassified systems are available upon request).

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