

Eclipsing variables: Catalogue and classification

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A new version of the Catalogue of Eclipsing Variables is presented. The catalogue contains parameters and morphological types of light curves for some 7200 stars. Spectral classification is also given when available. Recently published information about classification of 1352 systems is also included in the catalogue. Thus, the catalogue represents the largest list of eclipsing binaries classified from observations. The analysis of stellar parameter distributions of catalogued eclipsing systems has been performed, and an algorithm of eclipsing-variable classification has been developed. Classification of some systems is troublesome or contradictory due to lack of modern observational data or their possible rare evolutionary class.

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1 Introduction

Eclipsing binaries represent an invaluable source for the determination of fundamental properties of stars: masses, radii, temperatures, and luminosities. They also provide critical tests of stellar physics, stellar evolution and stellar structure theories. However, to properly estimate the orbital and components' parameters of a given system, one needs to know its class, since the process of estimating mass and other astrophysical parameters differs for different evolutionary classes of systems.

Various procedures for determination of the evolutionary class from observational data were proposed by Svechnikov & Snezhko (1974), Giuricin et al. (1983), and other authors. The procedures were based on a restricted number of systems with known classes contained in old catalogues and were not accurate enough.

In 2006, a Catalogue of Eclipsing Variables (CEV) was compiled by Malkov et al. (2006). It contains 6330 eclipsing systems and represents the largest list to date of eclipsing binaries classified from observations.

The CEV was used to develop the most comprehensive set of rules for the classification of eclipsing binaries to date (Malkov et al. 2007). We investigated the distribution of the catalogued systems in various observational planes and thus suggested a number of rules that permit classification of a given system based on a set of observational parameters,

even if the set is incomplete. The developed procedure was applied to large catalogues and lists of eclipsing variables. Altogether, some 5300 systems were classified for the first time. The classified systems can be used for the determination of astrophysical parameters of their components.

New eclipsing systems were discovered, studied, and classified, and new data for some of known systems were obtained in the course of five years.

On the other hand, thousands of unclassified eclipsing binaries are found as by-products of microlensing surveys (e.g., OGLE, MACHO, EROS, MOA) and discovered in all-sky photometric surveys (e.g., ASAS). Data on eclipsing variables generated from acting and future space observatories (COROT, *Kepler*, *Gaia*) also need a modern classification procedure to be processed. Thus, renovation of the Catalogue of eclipsing variables, which can be used for construction of a modern classification procedure, remains a challenging task.

The scheme of eclipsing-binary classification adopted in this study is presented in Sect. 2. The catalogue compilation procedure is described in Sect. 3. The description of the catalogue is also given there. A method of eclipsing-binary classification based on catalogued data is discussed in Sect. 4. We draw our conclusions in Sect. 5.

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2 Evolutionary classes of eclipsing binaries

The study supplies data with independently determined evolutionary classes of systems. According to well-known schemes, we divided all binaries into three classes: detached (denoted as D), semidetached (denoted as S) and contact (denoted as C). Moreover, in each of these types, sub-classes can be distinguished as listed below. We use the second letter for sub-class designation. In some cases, a third letter is used to denote the sub-class.

The detached main-sequence systems in the catalogue were classified according to two main sources, namely the catalogues of Perevozkina & Svechnikov (1999) and Svechnikov & Perevozkina (1999). For other types of detached systems, we used the Svechnikov (1969) catalogue, the study by Popper & Ulrich (1977) (detached systems with two subgiants), as well as lists in Popper (1980) and Malkov (1993). Catalogues of Surkova & Svechnikov (2004) and Budding et al. (2004) served as main sources for semidetached systems. To distinguish between different sub-classes of contact systems, we used catalogues of Shaw (1994), Pribulla et al. (2003), Dryomova et al. (2005) (near-contact binaries), and Csizmadia & Klagyivik (2004).

2.1 Detached systems

Main sequence systems (DM). Here both components are main sequence stars that do not fill their inner Roche lobes. There are a few binaries at the pre-main-sequence evolutionary stage in the catalogue (e.g., EK Cep). Such stars are usually included in the sample of substantially unevolved detached systems with nearly main-sequence components (see, e.g., Giuricin et al. 1983). Due to their extreme paucity, we also do not segregate them into a separate class, but consider them DM systems.

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. Systems show stronger emission lines in the spectrum outside eclipses. Typically they are expected to have negligible mass exchange, though the majority of RS CVn systems are classified as detached in Samus et al. (2009).

Giant and supergiant systems (DG). In such systems, at least one member has evolved away from the main sequence. Based on value of period and spectral type we have divided the DG systems on two subclasses: E (early-type) and L (late-type). Primaries of the E-subclass systems are hot and evolved stars (WR, giant or supergiant). Secondaries of such systems are MS early type star or hot giants. Orbital periods of DGE systems are not longer than 35 days. Primaries of the L-subclass systems are MS, giant or supergiant stars of spectral type from late-B to mid-F. Secondaries of L-subclass systems are always late type (from

late-G to M) evolved stars. Orbital periods of such systems are about 100 days and longer.

White dwarf systems (DW). The hotter and more evolved component of such systems is a white dwarf or subdwarf, and the secondary is usually a low-mass (main-sequence or subgiant) star.

Symbiotic detached systems (D2S). These systems consist of a red giant or supergiant and a degenerate star (white dwarf or neutron star). There is no observational proof for mass exchange in D2S systems. The CEV contains only five such systems.

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 for its spectral type and to be not over-luminous compared to main sequence stars in the mass-luminosity plane (Giuricin et al. 1983), hence it can be considered a main sequence star. Note that the primary can have a larger (if it is a donor) or smaller (if it is an accretor) radius than the secondary. Statistics of semidetached systems in Surkova & Svechnikov (2004) and Budding et al. (2004) catalogues gives a ratio of such systems as about 3:7. The secondary (cooler, overluminous, and oversized) component is assumed to fill its Roche lobe.

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

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

Cataclysmic semidetached systems (S2C). These systems contain a white-dwarf (or a white-dwarf-precursor) primary and a low-mass secondary that fills its critical Roche lobe. The secondary is not necessarily unevolved. It may even be a highly evolved star as, for example, in the case of AM CVn-type stars. We use catalogues by Ritter & Kolb (2003) and Downes et al. (2001) to classify this type of objects.

Massive X-ray semidetached systems (S2H). Such systems comprise a compact object orbiting a massive OB star (supergiant or a Be star). The compact object should be either a neutron star or a black hole; it is a strong X-ray emitter due to accretion of matter from the OB companion. We use the catalogue of Liu et al. (2006) to add this type of systems to the CEV. There are only three such systems in the CEV: GP Vel, V0779 Cen, V1343 Aql.

Low-mass X-ray semidetached systems (S2L). These binaries consist of either a neutron star or a black-hole primary and a low-mass secondary that fills its critical Roche lobe. This type of systems was added to the CEV according to Ritter & Kolb (2003). These systems are V1341 Cyg, V1727 Cyg, V0691 CrA.

Double-contact (β Lyr) systems. According to Wilson (1979), both components in such a binary fill their critical lobes exactly but do not touch each other due to asynchronous rotation of at least one of them. Svechnikov (1969) considered β Lyr to be “on its way to a detached system with a subgiant”. However, this system might not represent a subclass because more recent investigations of Linnell (2002) confirm the uniqueness of β Lyr.

Undermassive (RCMa) systems. Both components in such a system are overluminous, oversized, and hotter with respect to their masses, and neither component can be considered a main sequence star (see Sarma et al. 1996, study of the prototype).

Systems in early stages of mass transfer. In these early-type detached systems, the more massive component is evolving off the main sequence. It almost fills its Roche lobe, thereby initiating mass transfer (see, e.g., Kallrath & Strassmeier 2000, study of BF Aur). A very rapid mass transfer takes place from the primary to the secondary, proceeding on a thermal time scale. Examples of such systems are TT Her (Milano et al. 1989), which is classified as a contact system in the CEV, and AB Cru (Lorenz et al. 1994) classified as hot semidetached in the CEV. The latter has already undergone a reversal of its mass ratio, so mass transfer from the (formally more massive) secondary towards the primary is observed. In these cases, a period change or/and a mass ratio reversal support the assumption that mass exchange has started or is about to start.

Broken-contact systems. If the energy transfer in a close binary is insufficiently effective, a cycle consists of a long quiet phase in a good contact and a short violent phase with rapid changes between contact, semidetached and detached configurations (Kähler 2002). One such system observed in a semidetached stage is CN And (van Hamme et al. 2001). Broken-contact systems exhibit orbital periods in the 0.3–0.7-day range, and their spectral type is around F–G.

The four last groups consist of a relatively small number of binaries. Due to this fact, we do not separate them from other semidetached pairs. Some of them were classified as contact or detached binaries in the CEV.

2.3 Contact systems

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

Near-contact systems (CB). This class was introduced by Svechnikov (1969) as being similar to W UMa systems but where both components did not fill their critical lobes and their physical characteristics were similar to those of late-type contact systems (see later). They are also called short-period RS CVn-type binaries or W UMa-similar non-contact systems. Formally they can be referred to as de-

tached or semidetached systems, but their light curves are peculiar and distorted by gaseous streams, and the brightness of the components is slightly variable, which makes them similar to contact systems. Pribulla et al. (2003) designate them as B-type contact 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. The secondary is located below and to the left of the main sequence in the HR diagram.

Following Shaw (1994), we distinguish F-type (CBF, FO Vir is the prototype) and V-type (CBV, V1010 Oph is the prototype) near-contact binaries. In V1010 Oph-type systems, the primary (hotter) component is at or near the Roche lobe, while the secondary (cooler) one is inside the critical lobe and light curves are usually asymmetric, with Maximum I higher than Maximum II. 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 spectral types, with both components close to their Roche lobes. The spectrum of the more massive component is usually not later than A0 (Pribulla et al. 2003).

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

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 Catalogue of eclipsing variables

In this section, we describe the procedure of catalogue compilation and present the format of the catalogue.

3.1 Catalogue compilation

For compilation of the first version of catalogue (see Sect. 2.1 in Malkov et al. 2007), we used data from the GCVS (version 2004) and its textual remarks. A lot of new eclipsing variables were discovered since 2004, and currently the GCVS contains about 7000 eclipsing binaries. We have added the new stars in the second version of CEV. Some twelve of them turned out to be non-eclipsing variables. The current version of the CEV contains data for 7179 eclipsing binaries.

We have also used additional sources to update data in the CEV. Photometric V-band data and periods for a lot of southern systems were obtained in the ASAS-3 project and published by Pojmański (2002) or in the VSX data

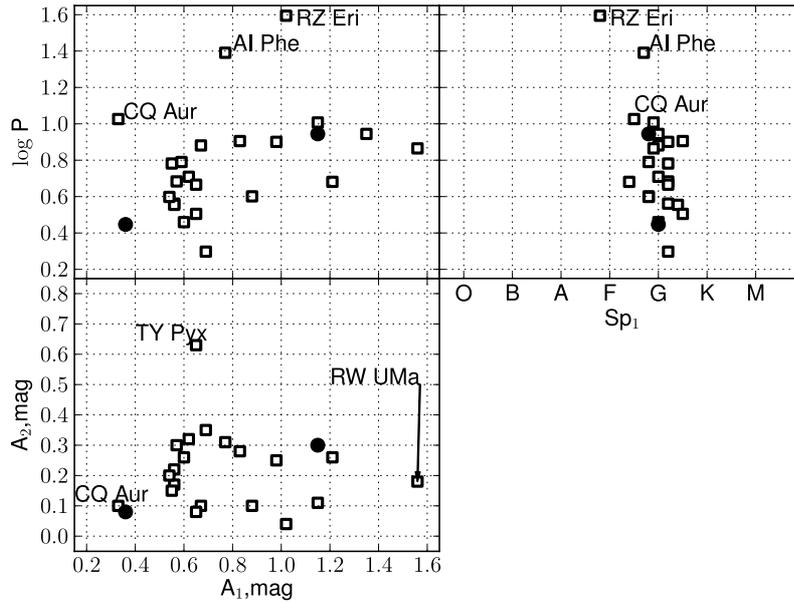


Fig. 1 The distribution of detached systems with subgiants (DR systems) on the A_1 - A_2 - $\log P$ - Sp_1 planes. Catalogued DR systems are plotted as squares. Filled circles denote two systems that have been classified as DR with our classification algorithm.

base (<http://www.aavso.org/vsx/>). These data were especially useful when the depth of the secondary minimum was unknown or/and only photographic photometry was given in the GCVS. Additional sources of photometric data were from Dvorak (2004), Hooegeven (2005), and the catalogue of Bulut & Demircan (2007). Periods were checked with Kreiner (2004), and data on period variability were taken from Liao & Qian (2010) and Lanza & Rodonò (1999). Spectral types of WR binaries were updated according to van der Hucht (2001), while Bilir et al. (2008) was used as a source for detached systems. We have used also catalogues of Pourbaix et al. (2004), Skiff (2012), and Wright et al. (2003) to update spectral types.

In the current version of the CEV, we have added information about chromospheric activity of binaries, taken from Karataş et al. (2004) and Strassmeier et al. (1993). Systems with chromospheric activity may belong to different evolutionary classes, namely: most of DR systems; short-period RS CVn systems (belong to CB class in the CEV); components of cool semidetached systems (denoted as SC in the CEV; examples are RZ Cnc, AD Cap, etc.); cooler components of subdwarf systems (DW class, e.g., FF Aqr); some of DM systems (e.g., CM Dra, YY Gem, HP Aur).

Thus, data about chromospheric activity can be used as indicator of some evolutionary classes for late-type systems.

Altogether, information on 1783 binaries was updated. However, while updating the catalogue, we have found a number of systems whose parameters contradict each other or/and are too unusual for the system's evolutionary class (concerning evolutionary classes, see item 2 in the list in Sect. 3.3). In most 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 such systems. The list of these systems contains 238 eclipsing binaries. In particular, it contains systems with too large depth of the primary minimum A_1 . It also contains contact and semi-detached systems, exhibiting evidence of orbital eccentricity: the phase of secondary minimum differs from 0.5 or the durations of primary and secondary eclipses are not equal.

3.2 Format of the catalogue

Beside the README file and the main table (see its description in the next section), the CEV contains a number of auxiliary files.

As it was mentioned in the previous section, data for 1691 GCVS systems were updated with a number of modern sources. These systems are listed in the REF file, together with references to the literature. The BIB file contains corresponding bibliographic information. Finally, the NON-EB file contains a list of systems erroneously classified as eclipsing binaries in the GCVS. They are not included in the main table of the CEV. The first fifteen lines of the catalogue are presented in Table 1.

4 Parameter analysis and system classifications

The resulting catalogue can be used for construction of rules for classification of eclipsing binaries. 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 vs. A_2), (A_1 vs.

Table 1 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)	(17)
RT And	CB	EA	RS	8.97	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		—	
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					—	
AN And	DM	EB		6.00	0.16	0.09	p	3.2196			0		0		A7Vm	

Identification and classification: (Col. 1) name of the star (as listed in the GCVS); (Col. 2) class of the system (the abbreviations are given according to sections 2.1–2.3); (Col. 3) morphological type of the light curve (EA, EB, EW; as in the GCVS); (Col. 4) additional variability type from the GCVS. *Photometry:* (Col. 5) magnitude at maximum brightness; (Col. 6) depth of primary minimum, A_1 , mag; (Col. 7) depth of secondary minimum (if known), A_2 , mag; (Col. 8) the photometric system for magnitudes as in the GCVS. *Period:* (Col. 9) period of the variable star, P , days; (Col. 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* (units in phase $\times 1000$): (Col. 11) duration of primary eclipse, DI; (Col. 12) duration of totality in primary eclipse, dI; (Col. 13) duration of secondary eclipse, DII; (Col. 14) duration of totality in secondary eclipse, dII; (Col. 15) phase of secondary minimum, MinII–MinI. *Spectra:* (Col. 16) spectral types and luminosity classes of the primary and secondary (if known); (Col. 17) information on chromospheric activity (a: chromospherically active system).

log P), (Sp_1 vs Sp_2) etc. An example of such analysis for detached systems with subgiants (denoted as DR in the catalogue, most of them belong to RS CVn systems) is shown in Fig. 1.

A distribution of DR systems on the “depth of primary minimum A_1 – depth of secondary minimum A_2 ” plane is presented in the bottom panel of Fig. 1. As can be seen from the figure, the depth of primary minimum A_1 for most DR systems lies between 0.5 mag and 1.2 mag. The three exceptional cases are CQ Aur ($A_1 = 0.33$ mag), RW UMa ($A_1 = 1.56$ mag), and TY Pyx ($A_2 > 0.6$ mag). Data for one of them, RW UMa, are obsolete, and the system needs a further study.

The location of DR systems on the (A_1 –log P) plane is shown in the left top panel of Fig. 1. Most of DR systems have periods shorter than 10 days, except RZ Eri and AI Phe. These two systems are long-period RS CVn systems. The lower period limit is about 1.5 days.

The relation between the period of DR systems and the spectral type of the hotter component is presented in the right top panel of Fig. 1. The spectral type of the hotter component of the majority of catalogued DR systems is F–G. Only RZ Eri, with its spectral type of the hotter component A8–F0IV, does not satisfy this rule. We have also found that secondary spectral types of such systems are G to mid-K. All of DR systems are chromospherically active stars.

Also, our analysis of parameters of DR systems has shown that all of them exhibit EA-type light curves (i. e.

the light of the binary remains almost constant between eclipses). So we can specify a set of rules to classify detached systems with subgiants. 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 as black circles in Fig. 1. We have examined these systems using Simbad. One of them, RS Ari, is included in catalogue of Brancewicz & 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 (Dogru et al. 2009). Thus, our classification of these two binaries as detached systems with subgiants is confirmed. Using a restricted list of parameters (e.g., the secondary’s spectral type is unknown) allows us to find some 20 more candidates to DR systems in our catalogue.

After comprehensive analysis of our catalogue, we have developed similar sets of rules for the classification of other types of binaries in our catalogue. Beside that, we have compiled a large list of systems that are attractive for additional observations and further investigations. The first part of this list contains systems with unusual values of parameters and lacking observations (an example is RW UMa in Fig. 1). The total number of such systems is 238. Some other systems are found to belong to a “marginal” (rare) type, they are collected in the second part of the list. All of these systems have (reliably known) values of parameters that dis-

tinguish them from other classified systems (examples are CQ Aur and RZ Eri in Fig. 1). The total number of such systems in the second part of the list is 93. Some of them belong to unusual stages of evolution (for example, pre-MS systems) and are rare. But for the majority of binaries listed there, we could not find any explanation of peculiar values of their parameters. New comprehensive investigations are advised for these systems. This list of systems is available upon request.

5 Conclusions

A new version of the Catalogue of Eclipsing Variables contains 7179 stars. The following data are available in the catalogue: morphological type of light curve, depth and duration of minima, duration of totality (if present), phase of secondary minimum, orbital period and information on period variability, spectral classification and indication of chromospheric activity. Furthermore, the catalogue contains recently published information about classification of 1364 systems and therefore represents the largest list of eclipsing binaries classified from observations. The catalogue can be used for classification and parametrization of known objects, characterization of new populations, and discoveries of unusual objects.

We have performed a comprehensive analysis of the distribution of observable stellar parameters of eclipsing systems in our catalogue and have developed an algorithm for classification of eclipsing variables. We have also compiled a list of systems with unusual values of their observational parameters. For some of such systems, a discrepancy in observational data can be explained with lacking modern observations. However, other systems were thoroughly studied by different authors for a long time, but there is still no satisfactory explanation of unusual values of their observable parameters.

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