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Research Note

Catalogue of Algol type binary stars⋆

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Abstract. A catalogue of (411) Algol-type (semi-detached) binary stars is presented in the form of five separate tables of information. The catalogue has developed from an earlier version by including more recent information and an improved layout. A sixth table lists (1872) candidate Algols, about which fewer details are known at present. Some issues relating to the classification and interpretation of Algol-like binaries are also discussed.

Key words. stars: eclipsing: binaries – catalogs

1. Introduction

This catalogue represents a newer, fuller edition of that of Budding (1984), to which reference may be made for earlier background. What follows here should help the reader use the catalogue and understand the reasons for producing it.

The main peculiarity of stellar structure of eclipsing binary systems with properties like those of β Per was noticed in the *spezielle Algolsterne* of Walter (1931). Algols consist of two stars of comparable size in close proximity, but of quite different mass. Most of the more obvious peculiarity is confined to the less massive and less bright component. The more massive star is apparently much like a normal Main Sequence (MS) star, though very frequently in the limited spectral range mid-B to mid-F. The relatively large depth of primary eclipse in many cases directly indicates that the fainter companion is large; usually larger than its companion, while the low scale of proximity effects shows up its relatively low mass. Clearly some oddity or "paradox" is implied. Otto Struve (1948) called attention to the "amazing discrepancy" more than half a century ago. The general explanation is by now, of course, well-known: Algol systems like β Per testify to interactive evolution with mass loss or transfer between the components. They are perhaps the simplest examples of steller pairs having this interactive history.

The "classical" Algol is associated with an "Algol-type light curve", but not every time. Ambiguity arises, corresponding to the two types of eclipsing binary with roughly similar light curves (EA type, in the General Catalogue of Variable Stars, GCVS). The physical difference lies in whether there has been interactive evolution. Of particular relevance is the "semi-detached" (sd) configuration, where one of the components is close to a structural stability limit, further expansion beyond which entails mass loss. Early recognition of the significance of this sd property can be seen in the work of Wood (1950), Kopal (1954), Crawford (1955) and Hoyle (1955).

Advances in classification and the classical mechanics of close binaries were given by Kopal (1959), though a clearer picture of binary evolution and the mass transfer mechanism had to wait for the computer-based studies that started in the sixties (cf. Morton 1960). By the time of the reviews of Paczyǹski (1971), Plavec (1973) and Batten (1973), most scientists were in agreement about the essential solution of Struve's paradox, though the general problem of binary evolution still supports much investigation. In more recent years, a lot of attention has gone toward the challenge of more extreme physical conditions (e.g. cataclysmics, X-ray sources, pairs containing collapsed stars; cf. Pringle & Wade 1985). While the more familiar kinds of eclipsing binary appear generally agreed on, there are still gaps in knowledge, e.g.: how many Algols are there and in what conditions are they? How do they all compare with each other and possibly relatable types of binary? How can we usefully deal with the wealth of accumulated observational data?

The physical situation can often be directly inferred from the light curve. Here the empirical division of EA light curves into EAD and EAS types is significant. The EAS light curve, with its deep eclipse of an early type star, normally provides a clear indication of Algol evolution. The earlier list of EAS ("EA2") candidates (Budding 1984) proved a useful

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⋆ Catalogue is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/417/263

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pointer to new Algols among previously little-known binaries (cf. Polidan & Wade 1992). As with many classification systems, however, one can make a central group sharing similar attributes, while peripheral candidates exist whose placing is awkward. Thus, although most Algols have an EAS light curve, there are cases where photometry alone does not allow a clear decision (e.g. TT Aur; Özdemir et al. 2001), and other evidence is then required.

In order to establish a detailed model, there should be two clear radial velocity curves (one for each component), to confirm the photometry regarding the sd status. Mass ratios and absolute parameters began to be determined in this way for some bright stars by the late seventies (Tomkin & Lambert 1978; Popper 1980). In the eighties and nineties, this has developed into detailed analysis of high dispersion spectrograms of bright Algols, particularly with the tomographic work of the Charlottesville group (cf. Richards et al. 1995). The familiar single-line radial velocity variation, complicated by "spurious eccentricity", the "s-wave" or other effects, may remain for still some time with the fainter objects.

More recent approaches have extended the wavelength range, for example into the infrared, where the subgiant's contribution becomes more noticeable (cf. e.g. Varricatt et al. 1998; Lazaro et al. 2002), while Algols also proved interesting candidates for ultraviolet observations (e.g. Peters & Polidan 1997). High-energy mechanisms are revealed through light curves from X-ray wavelengths (Stelzer et al. 1999). Radioastronomy too has seen remarkable advances in both sensitivity and resolution capability, permitting fuller geometrical insights into the Algol configuration (Mutel et al. 1998; Richards et al. 1998; Lestrade et al. 1999; Gunn et al. 1999). Optical astrometry (e.g. Ribas et al. 2002) and polarimetry (e.g. Lynch et al. 1996; Coleman et al. 1998) also have roles in dealing with Algols. With the relatively nearby and bright prototype of β Per itself, the whole picture was undoubtedly better substantiated by a fuller combination of all such information (Söderhjelm 1980; Mutel et al. 1998).

2. Absolute parameters

Analysis of the light curve of eclipsing binaries yields radii of the component stars $r_{1,2}$ expressed in units of the mean stellar separation. Such radii can be combined with Kepler's law to give:

$$3\log R_{1,2} - \log(M_1 + M_2) = 2\log P + 3\log r_{1,2} + 1.871, \qquad (1)$$

where P is the orbital period (in days), $M_{1,2}$ are the masses and $R_{1,2}$ the radii in solar units. The quantities on the right-hand side of Eq. (1) are known – the aim for physical studies, is to evaluate those on the left. A number of different ways (8) of doing these were given by Budding (1984). The most direct way uses two radial velocity curves. If there is only one radial velocity curve, normally that of the primary, then it is commonly assumed that this star is close enough to the MS to permit standard correlations to be used. Absolute parameters may be thus determined, and the initially assumed Main Sequence character of the primary then checked.

Another route, not making MS presuppositions, would require assumption of the semi-detached configuration, thereby allowing the mass ratio ($q = M_2/M_1$) to be derived from the Roche model property, i.e. $q = q(r_2)$ (Kopal 1979). The appropriate formula is:

$$\log M_1 = 2\log(1+q) - 3\log q + \log f - 3\log(\sin i), \qquad (2)$$

where f is the mass function obtained from the single radial velocity curve (cf. e.g. Batten 1973), and i is the inclination. It can be seen by differentiating this, however, that the derived mass will have appreciable errors for relatively small errors of the small quantities q and f. These are difficult to estimate with a precision better than a few percent. In fact, the relatively few double line sd binaries indicate that their primaries conform reasonably well to the same mass:luminosity relation as those of reliably determined detached binaries (Popper 1980), so that assumption should allow the derivation of absolute parameters more confidently than using Eq. (2) alone.

Conformity of primaries to the mass:luminosity law should not be exact, due to interactive binary evolution; though there have been different views on how this works out in practice (cf. the references given by Budding 1984). A more recent study (García 1990) has shown differences in a $T_{\rm eff}$, L diagram to be small.

3. Catalogue of Algol candidate stars

The catalogue is arranged in the following way:

Table I: Identification

1. Serial number of entry;

2. Name of star, arranged in alphabetical order of constellation listing (as in the GCVS, Kholopov 1985–87);

3. Durchmusterung listing;

4. Henry Draper Catalogue listing;

5. Hipparcos and Tycho Catalogues (ESA SP-1200 1997) listing. The Hipparcos Catalogue is preferred. If it doesn't include the star, the Tycho Catalogue is used;

6. Right ascension (2000);

7. Declination (2000);

8. Semi-detached (sd) status. This was a crude probability indicator used by Budding (1984). It took the five values from 0.1 up to 0.9 in steps of 0.2: 0.9 for well-known examples; 0.7 for binaries of apparently similar properties to the 0.9 cases, but generally less well known; 0.5 for binaries for which an EAS or EAD designation was about equally likely; 0.3 meaning rather unlikely; 0.1 would be definitely unlikely to be a classical Algol, but such examples were included because of historical or previous references, or related interest. Some of the 0.7 candidates have moved to a 0.9 status since 1984 (cf. e.g. Hartman et al. 1995; Lynch et al. 1996). The present catalogue then retains only 0.9, 0.7 and 0.5 candidates for most of its information. Lesser probability examples are occasionally listed in Table I for completeness;

9. Catalogue reference. This identifies the source of the listed information via a letter identifying generally the most recent of such catalogues: thus HIP refers to Hipparcos catalogue (ESA SP-1200 1997), GCVS to the General Catalogue

of Variable Stars (Kholopov 1985–87), and so on (see later abbreviations list).

Table II: Basic photometric information

1. Serial number of entry;

2. Name of star, arranged in alphabetical order of constellation listing (as before);

3. M_{max} gives the magnitude at maximum brightness;

4. Δm gives the depth of the primary minimum. The importance of depth of primary minimum as a salient datum, by means of which likely sd candidates can be identified, was stressed in Shapiro's (1973) thesis. It was utilized by Budding (1981) to select light curves of EAS type. Inspection of the candidate list will show that most of the well known Algol systems have light curves of this type;

5. Colour. Where possible, we list $B-V$ values for both components $(B-V)_1$ and $(B-V)_2$, otherwise a single value would reflect the predominating effect of the primary;

6. Wavelength of the light curve to be associated with the photometric solutions provided in the following section. Standard designations of photometric systems (e.g. Johnson *UBV*) are given here;

7. Epoch of primary minimum of reference;

8. Orbital period of the binary;

9. Reference. Sources are indicated by appropriate letters (see below).

Table III: Photometric elements

1. Serial number of entry;

2. Name of star, arranged in alphabetical order of constellation listing (as before);

3. Fractional luminosity of primary component L_1 (i.e. the star eclipsed at primary minimum);

4. Fractional luminosity of secondary component L_2;

5. Relative radius of the primary component r_1, which is the mean spherical radius divided by the mean orbital separation. This quantity is calculated from analysis of photometric data, and though published analysis often quote values to three or more significant decimal digits, a two-digit value is already rather optimistic for the likely light curve information content of the majority of less well-known stars. The extent of disagreement between different sources for even the more well-known examples suggests two significant figures is realistic here, though a third digit is sometimes included;

6. Relative mean radius of the secondary component r_2;

7. Orbital inclination i;

8. q_{LC} is a mass ratio obtained by the light curve solution;

9. q_{MS} is a mass ratio calculated so as to make the parameters of the primary star fit in with MS correlations (see Sect. 2). The quantity q_{SD} is the mass ratio calculated by using r_2 and the assumption of sd status (cf. Kopal 1959 Table **3-2);

10. Wavelength of the light curve associated with the photometric solution;

11. Reference. Sources are again indicated by appropriate letters.

Table IV: Spectroscopic information

1. Serial number of entry;

2. Name of star, arranged in alphabetical order of constellation listing (as before);

3. The MK spectral type(s) (when available). These have been mainly adopted from the SIMBAD database;

4. Half-amplitude (in km s^{-1}) of the radial velocity of the primary component;

5. Half-amplitude (in km s^{-1}) of the radial velocity of the secondary component;

6. Radial velocity of the mass center of the system;

7. Mass function *f(m)* (above), given by:

$$f(m) = m_2^3 \sin^3 i/(m_1+m_2)^2 = 1.0385\times10^{-7}(1-e^2)^{3/2}K_1^3P. \quad (3)$$

Individual spectroscopic masses, when available, follow from

$$m_{1,2}\sin^3 i = 1.0385\times10^{-7}(1-e^2)^{3/2}(K_1+K_2)^2K_{1,2}P; \quad (4)$$

8. Reference, indicated by appropriate letters.

Table V: Absolute parameters

1. Serial number of entry;

2. Name of star, arranged in alphabetical order of constellation listing (as before);

3. Primary mass M_1;

4. Secondary mass M_2;

5. Primary radius R_1;

6. Secondary radius R_2;

7. Primary luminosity L_1;

8. Secondary luminosity L_2;

9. Distance (pc);

10. Remarks;

11. Reference, indicated by appropriate letters.

This latter column, as with the reference columns of the earlier tables, contains various abbreviations, as follows:

EA Algol type light curve as defined by Kukarkin et al. (1969).

EB β Lyrae type light curve as defined by Kukarkin et al. (1969).

EAD, EAS Subdivisions of the EA type designation, Budding (1981).

B Budding (1984).

B&D The catalogue of Brancewicz & Dworak (1980).

S&K The catalogue of Svechnikov & Kuznetsova (1990).

KKN Kreiner et al. (2002).

GCVS Kholopov (1985–87).

HIP ESA SP-1200 (1997).

TYC ESA SP-1200 (1997).

GM Giuricin & Mardirossian (1981) (Sect. 4 above).

RS A system containing an "undersize" subgiant. Attention was called to these systems by Kopal (1959) and also (using the same designation, though with a slightly more restricted meaning, by Svechnikov 1969). Many systems of this type have since been found to conform to the RS CVn type designation (Hall 1976; Morgan & Eggleton 1979). Svechnikov (1969) described these as AR systems.

k Ratio of relative radii (usually r_2 / r_1).

q Ratio of masses (i.e. $M_{lesser}/M_{greater} = M_2/M_1$).

sd Semi-detached (cf. Kopal 1955).

Table VI: New candidates

Apart from the relatively well-known binaries in the main part of this catalogue, there are still large numbers of Algols among those known (or suspected) variables, about which data is scanty, or that come from newer surveys (Hipparcos (ESA 1997); OGLE (Udalski et al. 1992); MACHO (2002)), where supporting information, e.g. light curve plots or spectroscopy, may be still incomplete. The same photometric EAS criterion has been used, where possible, in selecting Algol candidates from the surveys. They are listed in this sixth section of the catalogue. As well, Svechnikov & Kuznetsova's (1990) catalogue listed a large number of candidate Algol binaries, on the basis of preliminary analyses of older, incomplete, or lower quality data. We have included almost all such cases, that were not already among more well-studied examples, in this section.

At present, all these (1872) stars have sd-status (see above) 0.7 or 0.5: in time, many of them can be expected to move to the main part of the catalogue with sd-status 0.9.

VIa: Hipparcos

1. Serial number of entry;
2. Name of star, arranged in alphabetical order of constellation listing (as before);
3. Durchmüsterung identification;
4. Henry Draper identification;
5. Hipparcos identification;
6. Right ascension (2000);
7. Declination (2000);
8. Spectral type;
9. SD-status.

VIb: OGLE

1. Serial number of entry;
2. OGLE identification;
3. Right ascension (2000);
4. Declination (2000);
5. Magnitude (I-filter);
6. Period;
7. SD-status;
8. Spectral type.

VIc: MACHO

1. Serial number of entry;
2. MACHO identification;
3. Right ascension (2000);
4. Declination (2000);
5. Magnitude (V-filter);
6. Period;
7. SD-status.

VId: Svechnikov & Kuznetsova (1990)

1. Serial number of entry;
2. Name of star;
3. Right ascension (2000);
4. Declination (2000);
5. Period;
6. Spectral type;
7. Mass-ratio;
8. Primary relative radius;
9. Orbital inclination;
10. SD-status.

4. Additional points

In many of the more well-known (sd status 0.9), trouble-free cases, the general agreement between the different sources is good. There are, however, a number of problematic examples. In a few cases, difficulties may have come from a poorer quality of older data, though often there are inherent complications due to real effects in the stars. Differences in the method of analysis of the data should not account for very significant changes in derived parameters for Algols, where proximity effects are relatively small. There may, however, be interpretive problems affecting the analyses in certain examples (cf. next section).

We also note here the *information limit* determining the number of separate parameters that can be reliably obtained from a curve-fitting. Modern methods of analysis have facilities for specifying light curves in terms of detailed models, involving a number of parameters that could become quite large. They cannot increase the information content of the data, however, and ambiguity arises about parameters when this content is low (Budding & Najim 1980).

The present catalogue has drawn substantially from other catalogues e.g. (more recently) Svechnikov & Kuznetsova (1990), Duquennoy & Mayer (1991), as well as many individual papers. The information originally selected by Budding (1984) leaned to the photometric side. This naturally arose from the EAS selection principle. The present updating includes newer and more comprehensive information on Algols than photometry alone can deliver.

5. Non-conforming cases

The classical Algol has an early type Main Sequence primary and a late type semi-detached secondary of mass usually less than half that of the primary. Kopal (1959) considered systems not quite matching this picture by comparing results from different applications of Eqs. (1) and (2) (cf. Budding 1984).

One situation is when the Roche lobe in which the secondary is located has a signifcantly larger mean radius than the derived r_2. This is the undersize or RS (Svechnikov 1969) case, which usually corresponds to an RS CVn type system (Hall 1976). For genuine RS CVn stars the mass ratio is shown (spectroscopically) to be greater than corresponds to a semi-detached condition, and is usually around unity (Popper & Ulrich 1977), i.e. inherently different to the Algols. Such systems often satisfy EAS selection criteria, however (cf. e.g. V788 Cyg).

If $q_{\rm MS}$ is only slightly greater than $q_{\rm SD}$, we must be cautious about the real explanation. A genuine undersize Algol phase has been theoretically modelled (e.g. Refsdal & Weigert 1969); however there are several sources of errors in the evaluations and peculiar results must occasionally occur. The effects of errors in q and f in Eq. (2), particularly when they are small, on the determined value of M_1 were mentioned before. For Algols, both of these quantities decline with increasing period, often to quite low values ($q \sim 10^{-1}, f \sim 10^{-2}$), although q is not sensitive to r_2 when its value is small ($q_{\rm SD} < 0.2$). The error of the radius r_1 affects the absolute radius R_1, not insensitively, through Eq. (1), again more particularly when r_1 is small (i.e. P large). Hence, if the RS condition is associated with parameter inaccuracy, we should expect an increase in numbers of such systems at longer periods. This might happen anyway, for genuine physical reasons: the foregoing point merely reinforces the need for careful study of long period systems sometimes listed as undersize (e.g. S Cnc).

If a derived primary mass is too low for the Main Sequence (e.g. AE Cyg) the effects of errors are looked at more credulously, since a corresponding "oversize" condition is not permitted physically. Kopal called these cases "R CMa type systems". Most, if not all, of the original candidates for this type turned out to be sd binaries when the evidence was critically reexamined (Hall & Neff 1979). There does remain, however, a real grouping of Algols with low periods and unexpectedly low mass ratio (like R CMa itself). This must be a pointer to angular momentum loss, so that some of the basic physical conditions or evolutionary background may well be different for this group (Budding 1989).

The possibility of misidentification of eclipse type occurs with both of these anomalies. Since r_2 is greater on the occultation than the transit hypothesis and $q_{\rm SD}$ is a monotonic function of r_2, for example, $q_{\rm SD}$ could be reduced if the eclipse type was wrongly identified as an occultation. Deep minimum transits would be very unlikely for Algols with periods larger than about ~1−2 days. This error is therefore more likely to occur at short period. Cases where $q_{\rm SD}$ seems extreme ($q_{\rm SD} > 0.75$ or $q_{\rm SD} < 0.05$) may be better modelled by adopting alternative eclipse type solutions (Mancuso et al. 1981).

Algol candidates of low mass, in general, turn out less likely to be regular Algols than those with primaries of A or B spectral type. This may be just some indirect support of the mass transfer hypothesis (cf. Plavec & Polidan 1976); however low primary mass Algols may perhaps occur, though observational selection effects greatly reduce their chance of discovery. The relatively few candidates (e.g. EX Car) should be studied in more detail, to check for a cut-off effect in primary mass (cf. also Svechnikov & Kuznetsova 1990).

With high mass candidates peculiarities of a different kind appear. As we move from the prototype β Per to systems of earlier type, such as DM Per, Z Vul or U Her, there is an increasingly significant ellipticity effect in the optical light curves. This can be associated with the general correlation (Svechnikov 1969) between primary and secondary masses in Algol systems. By the time we reach systems like V Pup or TT Aur there has been a qualitative change of light curve from EA to EB type, so that the photometric selection principle referred to for the majority of Algols, with relatively cool secondaries, is no longer clear. There has been ambivalence in the literature about the classification of high mass systems of this kind. The situation is not helped by a tendency in the secondaries of unevolved early type detached binaries towards over-luminosity, and increased difficulties for accurate radial velocities (Popper 1980). Such systems may have followed a different evolution scheme (Case A) from that of the great majority of Algols (Case B). Some of these candidates were retained in the present catalogue where the evidence appears interesting. With the complicated system β Lyr, though, while a physical connection with the Algol condition is not unlikely, (Plavec 1984), it is hardly a "classical" example.

Also among the exceptional Algols are a few cases where the primary has already evolved into a giant (e.g. RZ Cnc – see Popper 1976), or other exceptionally large, long period or massive systems (e.g. BL Tel) with a generally similar physical situation. Stars like RZ Cnc have been considered alongside more typical Algols for various purposes, however, and following Popper's (1976) discussion and comparisons, we include the small number of giant Algols in the present catalogue with an appropriate remark.

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