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Cataclysmic Variables: A 'SWOT' Analysis

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Abstract. A brief review of the nature and subtypes of cataclysmic variables (CVs) is given. The catalogue of CVs is still very incomplete. All-sky surveys should add large numbers of CVs, which will improve knowledge of the space density of these systems. It is pointed out that the nova-like variables, which are the most difficult to discover, are the subtype having the highest space density. Their discovery is therefore the highest priority – they fix the frequency of CVs, which is important in population syntheses of binary stars.

1. Introduction

The cataclysmic variables (CVs) will feature prominently in any All-Sky monitoring programs, both as transient events and as periodic phenomena. The amplitudes of the largest nova eruptions rival those of supernovae but reach much brighter apparent magnitudes (e.g., Nova Cygni 1975 which had been fainter than 21st magnitude until a week before its eruption, when it rose to 13.5 mag, then erupted to 2.2 mag, and has settled back at 16.3 mag). Dwarf novae erupt on time scales from days to years, with most being in the region of months, and ranges of two to eight magnitudes. Thanks largely to the sterling efforts of amateur astronomers over the past century, continuous light curves are available for a few dozen dwarf novae. Ideally, many more should be available in order to assist theoreticians to understand the accretion disc instabilities that cause the dwarf nova outbursts. Ironically, the most frequent outbursters, exemplified by V1193 Ori and ER UMa, have been recognised only in recent years, and so far only about 5 are known; this was a result of undersampling in earlier All-Sky photographic surveys. Many CVs do not have outbursts, but many of these non-eruptive CVs have irregularly spaced low states, often many magnitudes deep. More challenging to find are the nova-like variables without either outbursts or low states; these CVs in stable states nevertheless may have brightness variations of a few tenths of a magnitude and should be readily discoverable from their photometric unsteadiness alone in repeated All-Sky surveys. As with all unreddened CVs, they should also have UV excesses or distinctive colours.

All CVs are close binaries, transferring mass from a companion to a white dwarf, with orbital periods from tens of minutes to hundreds of days. Only 7 of the shortest period systems, the AM CVn stars, have been so far found, but it is likely that very many more brighter than 17th magnitude remain to be discovered; more than a hundred CVs with orbital periods in the range 1.5 hours

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to a few days are known; but only a few with giant secondaries and periods of hundreds of days have been found, and there are hundreds of CVs and suspected CVs that still have no certain classification or known orbital periods. Many CVs have brightness modulations at the orbital period - with amplitudes ranging from a fraction of a magnitude to eclipses many magnitudes deep. The SU UMa class of dwarf novae during superoutbursts have superhumps with slightly varying periods that are a few percent longer than the orbital periods. There is extensive evidence for precession of the accretion discs in many CVs, with periods of days. On shorter time scales, there are Dwarf Nova Oscillations and Quasi Periodic Oscillations in many dwarf novae during outbursts and in nova-like variables, on time scales of seconds to tens of minutes. These vary their periods rapidly and await really comprehensive monitoring, with round-the-Earth coverage. The problem has been the unpredictability of their appearance in any chosen CV, so collaborative monitoring has been difficult (for example, despite having been known for nearly 30 years, only recently have Dwarf Nova Oscillations in the optical and X-ray been observed simultaneously - in SS Cyg - and that was achieved by arranging Target of Opportunity time).

Turning to the 'SWOT' aspects. The strengths of CVs are that they are some of the most rapidly varying close binaries - several orbits of data may be collected in a night. They are also the objects in which accretion discs can best be studied - with a wide range of mass transfer rates ($\dot{M}$) and transitions between them. Accretion discs appear around young stars, in close binaries containing neutron stars and black holes, and in Active Galactic Nuclei, but it is in the CVs that much of the physics can most readily be seen in action. There are many other valuable aspects to CVs - a list is given in Warner (2000). The Weaknesses and Threats aspects probably can be combined into one category - that, CVs being stars, it is becoming more difficult to get observing time on large telescopes, and to get grant funding, to follow up the discoveries made with small telescopes: the extragalactic and extra-terrestrial planet bandwagons have strong lobbyists.

It is the Opportunities provided by All-Sky monitoring and by global co-operation among smaller telescopes that can provide a major step forward in understanding of CVs. Many of the brighter CVs are still being overlooked or are inadequately studied. The asymmetry between the numbers of CVs known in the northern and southern celestial hemispheres, and the large number of quite bright CVs for which orbital periods are unknown, illustrates this clearly. Even novae that reach apparent magnitudes 4 to 6 are being missed (Duerbeck 1990). The nova-like CVs, which do not have large outbursts to draw attention to themselves, are the most difficult to discover. They have been found mostly in surveys of ultraviolet-rich stars at higher galactic latitudes - these are still incomplete, especially in the southern hemisphere. Large numbers of nova-likes should be found in the all-sky photometric surveys (e.g. the Sloan Digital Survey) that are underway or planned. They have distinctive colours, but large amounts of small telescope time will be needed to classify all the CVs found this way. Detailed studies of the brighter nova-likes will provide the opportunity to have worked on a CV prior to its becoming a nova - many of the novae of the twentieth century were found (retrospectively from archived photographic plates) to have developed from relatively bright nova-likes that had been previously overlooked (e.g., V603 Aql 1918, pre-eruption magnitude 11.4; RR Pic

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1925, 12.0; HR Del 1967, 11.9). Sometime soon a known nova-like is going to become a nova. Only by having studied all the bright nova-likes comprehensively will we be able to make a comparison of before and after (e.g., a small orbital period change, which shows how much mass and angular momentum are carried away by a nova eruption).

The opportunity for discovering CVs in All-Sky surveys is of considerable importance. A full inventory of CVs to some well-defined magnitude limit is necessary if we are to have reliable statistics on space densities of the various subtypes. This is important for population and evolution studies of binary systems in general. The CVs and their detached precursors are a significant channel of evolution for the shorter period (less than about 1 year) binaries. Getting agreement between observation and theory will involve better understanding of common envelope evolution and of the processes of angular momentum loss from binary orbits. This knowledge will spill over into other important studies, including, for example, the precursors of Type Ia supernovae.

Below I give an illustration of approximate space densities of some of the more common subtypes of CVs. Missing from any such estimates are the CVs that have temporarily stopped transferring mass, i.e., that are currently detached systems, being as a result only as bright as the sum of the luminosities of the stellar components. These, and systems with extremely low mass transfer rates that are both intrinsically faint and are very infrequent outbursters, may appear in large numbers at twentieth magnitude or fainter. To complete our picture of CV evolution the numbers of such objects must be known, and their orbital period distribution determined.

2. The Space Density of Cataclysmic Variables

Eventually, with a complete inventory of CVs and their distances, it will be possible to make accurate determinations of their space density. This is likely to progress in several stages. At present we are probably missing a large fraction of CVs - especially those currently in a low or zero state of mass transfer - so we can only provide lower limits to the density. Current or near future surveys should find all the active CVs to at least 20th magnitude. At present we must continue to use statistical methods to determine space densities. Here I will apply a method that I used 27 years ago (Warner 1974) which uses the concept of statistical robustness of the tenth brightest object in a group. This technique, introduced by Allen (1954) to deal with All-Sky Statistics of stars of selected types, in principle gives a good estimate of space density, but requires knowledge of the absolute magnitude and dispersion of the group, and involves allowance for interstellar absorption.

Knowledge of the absolute magnitudes of CVs has improved greatly in the past decade. There are period–absolute magnitude relations for dwarf novae at maximum, and better absolute magnitude–rate of decline relationships for erupting novae (e.g. Warner 1987, 1995). There are, however, selection effects in operation that must be evaluated with some care. First, I briefly describe the requirements for Allen's method. The space density D is given by

$$\log_{10} D = -2.62 - 0.6m_v(10) + 0.6M_v + 1.38(q - 0.6)\sigma^2 - \log_{10} S \qquad (1)$$

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where $m_v(10)$ is the (smoothed) magnitude of the tenth brightest object, M_v is the mean absolute magnitude of the class, q is the slope of the accumulative distribution (the graph of $\log N$ versus m_v, where N is the rank of the object), σ is the dispersion about M_v, and S is the interstellar extinction correction (obtainable from Allen's tables and graphs). The latter depends on the average galactic latitude and the average distance modulus (with allowance for dispersion) of the brightest stars of the group.

The values of $m_v(10)$ and q are found by plotting $\log N$ versus m_v for the brightest 20 or so objects and then fitting a straight line whose slope provides q and whose intercept with $m_v = 10$ gives the smoothed value for $m_v(10)$. For a sample uniformly distributed in transparent space, q takes the value 0.6.

In performing the analysis I have used the catalogue of CVs prepared by Downes, Webbink and Shara (1997; hereafter DWS). I have segregated CVs into the various subclasses, and have treated CVs at maximum and in quiescence separately. These are slightly different samples because, e.g., the ten dwarf novae that are brightest at maximum are not exactly the same as the ten that are brightest at minimum. For the most populous of the subclasses I discuss below the names of the stars selected. The state of CV classification and observation is such that even the choice of the brightest ten members of a subclass has some subjectivity in it.

Some comments on selection effects that influence the choice of sigma are required. At quiescence the accretion disc dominates the luminosity of almost all CVs. For all high $\dot{M}$ CVs (i.e., nova-likes and dwarf novae in outburst) the accretion disc certainly dominates. But the brightness of a disc depends strongly on the angle at which it is viewed, and the absolute magnitude–orbital period relation is provided only for discs viewed at a standard orbital inclination of 57° (Warner 1987). A disc viewed face on is 1.0 mag brighter than at 57°, and a disc viewed at 74° is 1.0 magnitude fainter than at 57°. There is therefore a strong selection effect against larger inclinations, which have much fainter magnitudes. This is seen in the lists of the ten brightest objects given below: only one of the nova-likes is an eclipsing system and only two of the U Gem stars and two of the SU UMa stars are eclipsing. Therefore, although high inclination is statistically more probable than low inclination, this is offset by the much greater brightness of the low inclination systems. By keeping U Gem stars and SU UMa stars separate the intrinsic spread of M_v caused by different disc radii (at different orbital periods) is greatly reduced. I assume, therefore, that the range in M_v for high $\dot{M}$ disc systems is probably quite small - a total range of M_v of 1.5 mag, or a sigma of 0.4 mag seems appropriate. At quiescence, however, all CVs show considerable spread in M_v (Warner 1995) and twice the dispersion at maximum is more appropriate. For novae at maximum there is a spread in magnitude caused by the grouping together of novae of different speed classes, and a sigma of 1.5 mag is adopted (Warner 1974).

The absolute magnitudes have been taken from the evidence presented in Warner (1995 - Figures 3.5, 3.10, 4.16, 5.3), and the assumption that the brightest magnitudes for SU UMa stars are those for superoutbursts, which are on average 1.0 mag brighter than normal outbursts. Care has to be taken with the nova-likes: the absolute magnitudes given in Warner (1987) and Warner (1995) are for average high state brightnesses, whereas the brightest magnitudes in the

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DWS catalogue (and listed below for the top ten) are extrema. This only affects the adopted absolute magnitude by a few tenths. Before presenting the results of the application of Allen's technique I will discuss the choice of the brightest CVs in the three subclasses that contribute most to the space density.

3. The Brightest U Gem Stars

There are about 20 U Gem stars that reach brighter than magnitude 11.0 at maximum of outburst. Not unexpectedly, almost all of these have been known for half a century or more. It is possible, however, that a few infrequent outbursters may remain to be found. The most recent suspected bright candidates are Lib4 (in the DWS Catalogue), 10.0 at maximum (Debehogne 1990), which has been shown not to be a CV (Liu, Hu, Li & Cao, 1999) and there are two candidates in the Catalogue of Suspected variables: NSV 11280 (Aql), 10.4 at maximum, and NSV 7956 (UMi), 9: at maximum. Neither of the latter has been confirmed to be a U Gem star, even though discovered several decades ago.

Omitting these uncertain candidates, the ten brightest U Gem stars are:

SS Cyg (8.2 at max), U Gem (8.2), RU Peg (9.0), WW Cet (9.3), HL CMa (10.0), HP And (10.5), SS Aur (10.5), Z Cam (10.5), BV Cen (10.5) and YY Dra (10.6).

Of these, only HL CMa, which is very close to Sirius, has been discovered in relatively recent times.

4. The Brightest SU UMa Stars

As with the U Gem stars, we may expect that the majority of the brightest SU UMa stars are known, except for a few with WZ Sge characteristics - i.e. superoutbursts on time scales of decades. The ten brightest SU UMa types are:

WZ Sge (7.1 at max), VW Hyi (8.5), SW UMa (9.4), WX Cet (9.5), T Leo (10.0:), VY Aqr (10.3), EK TrA (10.4), YZ Cnc (10.5), BZ UMa (10.5) and CU Vel (10.7).

5. The Brightest Nova-likes.

Among the ten brightest nova-likes in the DWS catalogue are three from the Catalogue of Suspected Variables - namely NSV 2872 (mag 11.2 at maximum), NSV 3432 (mag 10.6), and NSV 13022 (mag 10.5). Of these, only one, NSV 2872, has been inspected spectroscopically and has been found not to be a nova-like (Liu & Hu 2000). I am reluctant to admit the other two NSV stars as nova-likes on the basis of their poorly recorded photometric behaviour alone. HM Aur, which is in the DWS catalogue as a nova-like, has been shown by Liu & Hu not to be a CV. This leaves the following as the brightest currently known:

IX Vel (9.1, 1985), TT Ari (9.5, 1975), UU Aqr (9.6, 1986), V3885 Sgr (9.6, 1972), RW Sex (10.4, 1972), QU Car (11.1, 1972), KR Aur (11.3, 1980:), RZ Gru (11.5, 1981), EC 04224-2014 (11.5, 1997) and V747 Cyg (11.7, 1993:).

The dates in brackets show the year in which the star was recognised as being a thick disc CV. As can be seen, many of the brightest nova-likes have

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been found in the past 20 years. No doubt there are many more, brighter than 12th magnitude, that will be found in ongoing and forthcoming All-Sky surveys. The magnitude of the tenth brightest nova-like was 12.5 in 1974, but is now 11.7 in the DWS catalogue; as pointed out above, these are extrema magnitudes, although this doesn't affect the ranking of the nova-likes.

We will see below that U Gem stars, SU UMa stars and nova-likes contribute about equally, and are the dominant suppliers of CV space density. Unlike the dwarf novae, therefore, further discovery of nova-likes is the area that will probably contribute to higher CV space densities. It is interesting that although many nova-likes (the intermediate polars) have been found from X-ray surveys, and are bright in the X-ray sky, none of them make it into the optical top ten; so it is unlikely that further bright nova-likes will be found from future X-ray surveys.

6. Results

The results of the analysis of the brightest members of the most populous CV subclasses are given in Table 1. Dwarf novae of the U Gem and SU UMa subclasses contribute about equally, with the U Gem class only slightly outnumbering the SU UMa class. The latter subclass is probably less completely sampled than the former - all of the dwarf novae with very long outburst intervals are SU UMa stars, and it is conceivable that a few more that reach 11th magnitude or brighter are still to be found. The nova-likes are about as populous as the U Gem stars and, as pointed out above, are probably still quite poorly sampled. It is with the nova-likes that we can expect the estimate of space density to be pushed up further. The space densities found here for the U Gem and SU UMa stars are about twice those given previously (Warner 1995); that for the nova-likes is similar to what was found before. The current estimate of the space density of optically active CVs, from Table 1, is $\sim 1.9 \times 10^{-6}$ pc^{-3}. To this must be added the space density of the strongly magnetic CVs (polars) found largely from X-ray surveys, which is $\sim 5 \times 10^{-7}$ pc^{-3} (Beuermann & Burwitz 1995). The other, minor contributors (novae, and the recurrent novae and intermediate polars not considered here), add at most about 20 percent to this value, so the total amounts to $\sim 3 \times 10^{-6}$ pc^{-3}.

This may be a considerable underestimate of the true CV space density, as has long been known (e.g., Patterson 1984). Although densities from the most comprehensive optical survey (the Palomar-Green Survey) also arrive at $3-6 \times 10^{-6}$ pc^{-3}, X-ray All-Sky surveys, which are particularly good at detecting the hard X-rays from systems of low $\dot{M}$, give densities $\sim 1 \times 10^{-5}$ pc^{-3} (Patterson 1984, 1998) or even a factor of two higher (Warner 1995). Patterson (1998) discusses this problem, and the further one that for short period CVs there is an order of magnitude disagreement with the predictions of population synthesis. He concludes that there is a need for an intensive search for the faint CVs predicted by population synthesis with orbital periods around 80 - 100 minutes that have passed through the 'orbital period minimum' at about 80 min and have increasing orbital periods. If large numbers of these can be found (and these would be among the low $\dot{M}$ systems detected by X-ray surveys) it would go some way to reconciling the observed and predicted space densities and frequency of

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short orbital period systems. Such a program can only be carried out with the kinds of small telescope collaborations under consideration in this symposium.

Table 1. Space Densities D for Cataclysmic Variable Subtypes

Class	M_v	q	σ	$m_v(10)$	b	$\log S$	$\log D$
Dwarf Novae (max)	4.4	0.36	0.4	10.6	27	-0.4	-6.0
Dwarf Novae (min)	8.0	0.36	0.8	14.2	25	-0.4	-6.2
SU UMa(max)	4.2	0.57	0.4	10.8	28	-0.3	-6.2
SU UMa(min)	9.2	0.35	0.8	16.2	28	-0.5	-6.5
Nova-likes	4.5	0.32	0.4	11.6	26	-0.7	-6.2
Na (max)	-8.8	0.25	1.5	2.8	10	-2.0:	-8.7:
Na (min)	4.3	0.27	0.4	15.6	10	-2.0:	-7.5:
Nb (max)	-6.0:	0.19	1.5	7.4	7	-2.5:	-9.4:
Nb (min)	4.3	0.18	0.4	17.6	7	-2.5:	-8.2:

7. Concluding remarks

The Cataclysmic Variables provide exciting and extensive opportunities for All-Sky surveys and for small telescope collaborations on a variety of time scales. Large telescopes will not be used for these studies, which are more time consuming than photon limited. The importance of CVs for the investigation of the shorter period binary stars, and for stellar evolution in general, is enormous. The understanding that is emerging from the observation and modelling of mass transfer, accretion discs and their instabilities, accretion onto the primary, and nuclear runaways, has miscellaneous applications in areas as wide ranging as black hole and neutron star binaries, supernova explosions, and active galactic nuclei.

References

Allen, C.W. 1954, MNRAS, 114, 387

Beuermann, K. & Burwitz, V. 1995, ASP Conf.Ser. 85, 99

Debehogne, H. 1990, IAU Circ.No. 5131

Downes, R, Webbink, R.F. & Shara, M.M. 1997, PASP, 109, 345

Duerbeck, H.W. 1990, IAU Colloq.No. 122, p. 134

Liu, W. & Hu, J.Y. 2000, ApJS, 128, 387

Liu, W., Hu, J.Y., Li, Z.Y. & Cao, L. 1999, ApJS, 122, 257

Patterson, J. 1984, ApJS, 54, 443

Patterson, J. 1998, PASP, 110, 1132

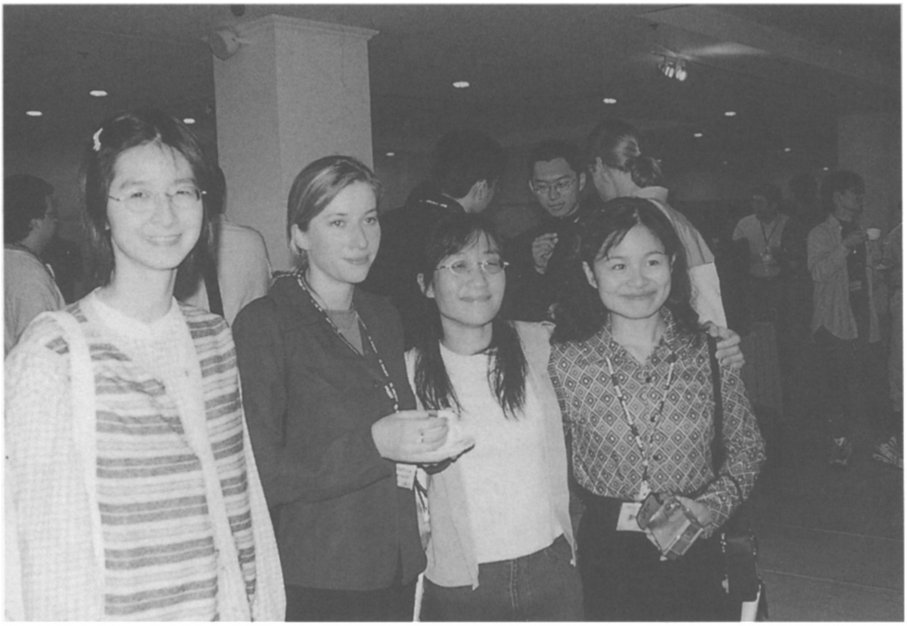
Warner, B. 1974, MNASSA, 33, 21

Warner, B. 1987, MNRAS, 227, 23

Warner, B. 1995, Cataclysmic Variable Stars, Cambridge University Press

Warner, B. 2000, PASP, 112, 1523

https://doi.org/10.1017/S0252921100078799 Published online by Cambridge University Press



(Top, from left) Lai, Meiszel, M. Y. Tsai, and S. I. Lin;
(bottom, from left) Gaustad, Jassur, and Saucedo

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