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CATACLYSMIC VARIABLES AND RELATED OBJECTS

Edited by Mario Livio and Giora Shaviv

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PROCEEDINGS OF THE 72nd COLLOQUIUM
OF THE INTERNATIONAL ASTRONOMICAL UNION
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EDITORS' FOREWORD

Colloquium No. 72 of the International Astronomical Union covered many observations and theoretical developments in the field of cataclysmic variables and related objects. Much time was devoted to discussions and we made an effort to include as much of the discussions material as possible in the proceedings.

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THE PERIODS OF CATACLYSMIC VARIABLE STARS

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I. INTRODUCTION

To understand the structure and evolution of the cataclysmic variables, we will need accurate values for their masses, dimensions, mass transfer rates, and other physical properties. Unfortunately, despite an abundance of observational data on these systems, there is a severe dearth of reliable, quantitative information about their fundamental physical properties. Only two cataclysmic variables, U Gem and EM Cyg, are simultaneously eclipsing binaries and double-lined spectroscopic binaries, and only for these two systems can masses and dimensions be determined with a minimum of assumptions (Stover 1981a; Stover, Robinson, and Nather 1981). Even if there were more systems like U Gem and EM Cyg, it is not obvious that our information would be any more reliable, because observers are often unable to agree on the values of the directly measured quantities used to determine physical properties. Thus, the radial velocity curve of the brightest dwarf nova, SS Cyg, has been measured independently 5 times in the last 30 years. The agreement among the measurements is unsatisfactory, and the reasons for the disagreement are not completely understood (Joy 1956; Kiplinger 1979; Stover et al. 1980; Cowley, Crampton, and Hutchings 1980; Walker 1981). The physical properties may still be unreliable when the disagreements are understood and eliminated, because there is considerable uncertainty about the proper way to extract physical properties from observational data. For example, the observed radial velocity curves of cataclysmic variables are believed to be different from the true radial velocity curves of their component stars, but the amount of difference and ways to correct for the difference are unknown.

There is only one physical property known accurately for a large number of cataclysmic variables: the orbital period. The orbital periods have, therefore, an importance out of proportion to their immediate information content. The purpose of the present paper is to gather together into one place the data on the orbital periods of cataclysmic variables; to discuss the selection effects distorting

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Table 1

The Orbital Periods of Cataclysmic Variable Stars

Star	Class	Normal Mag (V)	Orbital Period (hr)	References
RX And	UG	13.7	5.08	Hutchings and Thomas (1982)
AE Aqr	MV	11.5	9.88	Chincarini and Walker (1981)
V603 Aql	N	11.9	3.48	Haefner (1981)
TT Ari	NL	10.6	3.2	Smak and Stepien (1975)
T Aur	N	15.4	4.91	Mumford (1976)
SS Aur	UG	14.8	4.33	Kraft and Luyten (1965)
KR Aur	NL	13.5	3.91	Shafter (1982)
Z Cam	UG	14.5	6.96	Kraft, Krzeminski, Mumford (1969)
YZ Cnc	SU	14.6	2.21(S)	Patterson (1979a)
AC Cnc	NL	13.8	7.21	Kurochkin and Shugarov (1981)
OY Car	SU	16	1.51	Vogt *et al.* (1981)
QU Car	NL	11.6	10.9	Gilliland and Phillips (1982)
HT Cas	UG	16.5	1.77	Patterson (1981)
BV Cen	UG	13.2	14.66	Gilliland (1983)
V436 Cen	SU	15.5	1.50	Gilliland (1982a)
WW Cet	NL	14.5	3.8	Kraft and Luyten (1965)
Z Cha	SU	15.2	1.79	Cook and Warner (1981)
T CrB	RN	10.8	227.5 d	Paczynski (1965)
SS Cyg	UG	12.2	6.60	Stover *et al.* (1980)
EM Cyg	UG	14.0	6.98	Mumford (1980)
V1500 Cyg	N	>20	3.35	Patterson (1979b)
V1668 Cyg	N		10.54?	Campolonghi *et al.* (1980)
HR Del	N	12.5	4.10	Hutchings (1979)
EF Eri	AM	15.3	1.35	Schneider and Young (1980a)
U Gem	UG	14.5	4.25	Arnold, Berg, Duthie (1976)
AM Her	AM	12.9	3.09	Young and Schneider (1979)
DQ Her	N	14.6	4.65	Africano and Olson (1981)
EX Hya	NL	13.5	1.64	Gilliland (1982b)
VW Hyi	SU	13.9	1.78	Vogt (1974)
WX Hyi	SU	14.9	1.80	Schoembs and Vogt (1981)
AY Lyr	SU	18.3	1.81(S)	Patterson (1979a)
MV Lyr	NL	12.5	3.21	Schneider, Young, Shectman (1981)
TU Men	SU	17	2.82	Stolz and Schoembs (1981)
BT Mon	N	15.4	8.01	Robinson, Nather, Kepler (1982)
V2051 Oph	NL	14	1.50	Bond (1977)
CN Ori	UG	14.8	3.91?	Schoembs (1982)
BD Pav	N	>16.4	4.30	Barwig and Schoembs (1981)
RU Peg	UG	13.1	8.99	Stover (1981b)
GK Per	N	14.0	1.99d	Crampton (1982)
RR Pic	N	12.3	3.48	Vogt (1975)
VV Pup	AM	15	1.67	Schneider and Young (1980b)
RZ Sge	SU	17.4	1.68(S)	Bond, Kemper, Mattei (1982)
WY Sge	N	19	3.69	Shara *et al.* (1982)
WZ Sge	SU?	15.3	1.36	Robinson, Nather, Patterson (1978)
V3885 Sgr	NL	10.4	4.94	Cowley, Crampton, Hesser (1977a)
VZ Scl	NL	15.6	3.47	Warner and Thackeray (1975)
LX Ser	NL	14.0	3.80	Africano and Klimke (1981)
RW Sex	NL	10.6	5.93	Cowley, Crampton, Hesser (1977b)
RW Tri	NL	12.8	5.57	Longmore *et al.* (1981)
EK TrA	SU	>17	1.56(S)	Vogt and Semeniuk (1980)
UX UMa	NL	13.5	4.72	Kukarkin (1977)
AN UMa	AM	16.5	1.91	Liebert *et al.* (1982)
0139-68	AM	15.6	1.83	Visvanathan and Pickles (1982)
0526-328	MV?	13.5	5.49	Hutchings *et al.* (1981b)
0643-1648	UG	13.2	4.3 or 5.3	Hutchings *et al.* (1981a)
1012-03	NL	14.5	3.23	Williams and Ferguson (1982)
1013-477	AM	17	1.72	Mason *et al.* (1982a)
1103+254	AM	16.2	1.90	Stockman *et al.* (1982)
1115+18	AM	18.2	1.50	Biermann *et al.* (1982)
1148+719	NL?	16	3.9	Patterson *et al.* (1982)
1405-451	AM	15.5	1.69	Mason *et al.* (1982b); Tapia (1982)
1550+191	AM	15.4	1.89	Liebert *et al.* (1981)
2129+47	NL	16.9	5.24	Thorstensen *et al.* (1979)
2215-086	MV	13.5	4.85	Shafter and Targon (1981)
2252-035	MV	13.3	3.59	Warner *et al.* (1981)
Lanning 10	NL	14.2	7.71	Horne *et al.* (1982)

the sample of orbital periods; and to determine the properties of the period distribution.

II. OBSERVATIONAL DATA

a) The Known Orbital Periods

The cataclysmic variables whose orbital periods are known with reasonable certainty are listed in Table 1 along with their class, their normal V magnitude, their orbital period, and a reference to the source of the orbital period. Binary systems that probably contain neutron stars instead of white dwarfs, such as 2A1822-371, have been excluded from the table. The two binary white dwarfs AM CVn and G61-29 (= GP Com), the peculiar variable V Sge, and binary systems without mass transfer such as V471 Tau have also been excluded. Orbital periods are now known for 66 cataclysmic variables.

The dwarf novae have been divided into two classes in Table 1: the normal dwarf novae (UG), and the SU UMa stars (SU) (for a description of the SU UMa stars, see Vogt 1980). The other sub-classes of the dwarf novae have been put into one or the other of these two classes; the Z Cam stars, for example, have been included in the UG class. The novae (N) have not been further subdivided, nor have the recurrent novae (RN). The remaining variables have been classified as nova-like variables (NL) except for the nova-like variables with magnetized white dwarfs, which have been placed in the AM Her class (AM) if the white dwarf rotates synchronously, and in the magnetic variable class (MV) if it does not.

We have used the quantity "Normal" V magnitude in Table 1 instead of the minimum magnitude or magnitude range. Neither the minimum nor the maximum magnitudes are appropriate quantities for discussing the statistics of orbital periods of cataclysmic variables because cataclysmic variables usually spend most of their time at some intermediate magnitude. Thus, the dwarf nova Z Cha fades to near magnitude 17 at the bottom of its deep eclipse and can reach magnitude 11.9 during its eruptions. These are the minimum and maximum magnitudes given by the General Catalogue of Variable Stars. However, Z Cha spends most of its time between eruptions near magnitude 15.2. I have defined the normal magnitude of Z Cha to be 15.2, and have entered that value in Table 1. Defining appropriate normal magnitudes for the cataclysmic variables requires some subjective interpretation of their light curves, so the normal magnitudes I give in Table 1 could differ by perhaps 1/2 magnitude from estimates for the same quantity made by others.

Some of the periods given for the SU UMa stars are superhump periods, not true orbital periods. There is an (S) appended to these periods in Table 1. If there is any doubt about the reliability of the period, a question mark has been appended. Finally, the references given in Table 1 are the most recent careful determinations of the orbital periods, not necessarily the most complete studies of the general properties of the systems.

b) Selection Effects

The distribution of cataclysmic variables as a function of orbital period is shown in Figure 1, where the orbital periods have been grouped together into one hour bins. Although there are some striking features to the distribution, the selection effects at work in Figure 1 are significant and must be dealt with before the distribution can be interpreted properly.

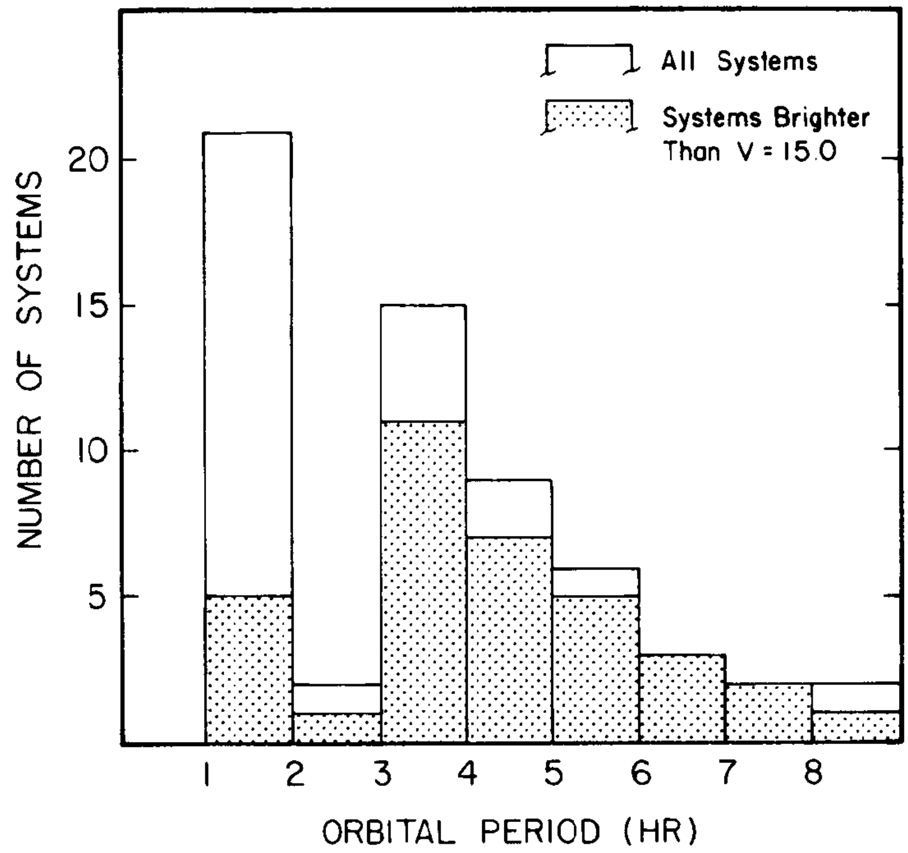

Figure 1 - The distribution of cataclysmic variables as a function of orbital period. Two samples of the known orbital periods have been graphed: the sample of all periods, and the sample of periods for cataclysmic variables brighter than magnitude 15. The latter sample is 70 percent complete.

The most serious selection effects fall into three groups. (1) Because different classes of cataclysmic variables have different light curves and luminosities, lists of cataclysmic variables are more complete for some classes than for others. For example, dwarf novae are easy to discover because of their frequent eruptions, but the nova-like variables are difficult to discover unless they have magnetized white dwarfs and are strong X-ray sources. As a result, dwarf novae and systems with magnetized white dwarfs are probably over-represented in Table 1, whereas nova-like variables without magnetized white dwarfs are under-represented. (2) Information is more complete for those classes of cataclysmic variables that have attracted the attention of the observers than for those that have not. The AM Her class is an example of this selection effect: the orbital period of every AM Her star has been measured. (3) The specific technique used to observe a cataclysmic variable will be more effective at detecting orbital modulation at some orbital periods than at others. Thus, photometry will detect orbital light variations more readily if the orbital period is near 2 hours than if it is near 10 hours.

The last two selection effects can be reduced or eliminated by taking a magnitude-limited, complete sample of the orbital periods. It is possible to achieve a good approximation to a magnitude-limited, complete sample by taking a subset of the periods given in Table 1. The upper half of Table 2 gives both the total number of cataclysmics known and the number with measured orbital periods in 1 magnitude intervals from magnitude 10.0 to 15.0. The sample is highly incomplete for cataclysmic variables fainter than magnitude 15.0, but even for the relatively faint variables with magnitudes between 14.0 and 15.0 the sample is now more than 50 percent complete. The sample is 70 percent complete for all variables brighter than magnitude 15.0, so by restricting ourselves to the variables brighter than magnitude 15.0 we obtain nearly the magnitude-limited, complete sample we need. This limited sample still has 40 systems, enough to give reasonable reliability to our results. The lower half of Table 2 lists the bright cataclysmic variables whose orbital periods have not yet been determined.

Figure 1 compares the distribution of orbital periods in the magnitude-limited sample to the distribution of periods in the entire sample. At orbital periods longer than about 3 hours the shapes of the two distributions are similar, but in the period range from 1 to 2 hours the distributions are markedly different. The difference is caused by the absence from the magnitude-limited sample of many SU UMa stars and AM Her stars that appear in the entire sample. These two groups have attracted considerable attention from observers in the past few years, so they are over-represented in the entire sample.

Table 2

The Completeness of the Orbital Period Sample

Magnitude Range	Systems With Known Orbital Periods	Total Number of Systems Known	Cumulative Percent With Periods
<10.0	0	0	
10.1 - 11.0	6	6	100
11.1 - 12.0	2	2	100
12.1 - 13.0	5	7	87
13.1 - 14.0	14	20	77
14.1 - 15.0	13	22	70

Bright Cataclysmic Variables Without Orbital Periods:

AE Ara	T Pyz
SY Cnc	V426 Oph
V751 Cyg	V841 Oph
DN Gem	V630 Oph
AH Her	V1016 Sgr
DI Lac	V2562 Sgr
TU Leo	VY Scl
RS Oph	SU UMa
KT Per	

Although use of the magnitude-limited sample reduces the importance of the last two selection effects, the selection effects in the first group are still acting, and are distorting the distribution, perhaps severely. For example, novae, which have mean absolute visual magnitudes near +4.5, are much brighter than dwarf novae, which have mean absolute visual magnitudes near +7.5 (McLaughlin 1960; Kraft and Luyten 1965). Because of the 3 magnitude difference in their absolute magnitudes, the volume of space included in a magnitude-limited sample is 60 times larger for novae than for dwarf novae. If all other selection effects were the same for the two groups (they are not), the classical novae would be over-represented in the magnitude-limited sample by a factor of 60 compared to the dwarf novae. All novae have orbital periods longer than 3 hours and most novae have orbital periods between 3 and 5 hours, so there is an excess or novae in the magnitude-limited sample in this period range. If they were removed from the sample, the large peak in the period distribution at these periods would be reduced.

There is another, even larger selection effect acting on the novae. No nova has ever been recognized to be a cataclysmic variable before its eruption; and even if a pre-nova were to appear in a list of cataclysmic variables, it is unlikely it would be recognized as a nova. Therefore, a nova only appears in Table 1 if it has erupted within the past few hundred years. As the eruptions of novae are thought to recur every 10^5 years or so, only 1 out of every 10^3 novae in the solar neighborhood has been found, and the novae are under-represented in Table 1 by this large factor.

There may be enough information available to estimate the true space density of dwarf novae and correct all the selection effects acting on their period distribution, but the necessary information is not available for the other classes. Thus, calculation of the true space density of novae requires knowledge of their mean recurrence time, but their recurrence time can only be estimated from theoretical arguments and could easily be in error by more than a factor of 10. Except for the dwarf novae, the selection effects involve such large and uncertain factors that any attempt to correct for them would risk introducing other even larger biases into the period distribution. Therefore, we will not correct for the remaining selection effects; and therefore, we must refrain from interpreting the fine details in the distribution of orbital periods.

III. RESULTS

a) The 80 Minute Period Limit

The period distribution has several features too strong to be caused by selection effects. Perhaps the most important of them is that the distribution terminates at an orbital period near 80 minutes. There are excellent reasons for believing that the 80 minute limit is not due to an observational selection effect, and that cataclysmic variables with orbital periods less than 80 minutes are non-existent or extremely rare. The first reason is that the period distribution does not fade gradually to zero at the limit, it terminates abruptly. There are 9 cataclysmic variables with orbital periods between 80 minutes and 100 minutes. It is difficult to imagine any selection effect that would permit so many systems to be found in such a narrow range of orbital periods, but render invisible all systems with orbital periods just shorter than 80 minutes. The second reason is that four binary stars with orbital periods shorter than 80 minutes are known, but none of them are cataclysmic variables. AM CVn and GP Com have orbital periods of 17.5 min and 46.5 min respectively, but are binary white dwarfs (Faulkner, Flannery, and Warner 1972; Nather, Robinson, and Stover 1981); 4U 1626-67 and 4U 1915-05 have orbital periods of 41.5 min and 50 min respectively, but the accreting stars in these systems are neutron stars not white dwarfs (White and Swank 1982; Walter et al. 1982; Middleditch et al. 1981). Therefore, there is nothing preventing observers from finding binary systems with short orbital periods.

Paczynski and Sienkiewicz (1981), and Rappaport, Joss, and Webbink (1982) have provided a theoretical explanation of the minimum period that appears to be at least qualitatively correct. The mass of the late type star in a cataclysmic variable decreases as it transfers mass to its white dwarf companion. While the mass of the late type star is large enough to support hydrogen burning in its core, it is near the main sequence mass-radius relation, and its radius decreases as its mass decreases. However, once the late type star has lost so much mass that it cannot burn hydrogen in its core, it must switch to the mass-radius relation for hydrogen white dwarfs, and thereafter its radius increases as its mass decreases. Thus, there is a minimum radius for the late type stars in cataclysmic variables. The minimum radius translates directly into a minimum orbital period, because the radius of the late type star must equal the radius of its Roche lobe to have mass transfer, and the radius of the Roche lobe sets the orbital period of a cataclysmic variable to within narrow limits.

While the late type star is switching from the main sequence mass-radius relation to the white dwarf mass-radius relation, it does not really fit either relation. During the switch the time scale for mass transfer becomes comparable to the thermal time scale of the late type star, and the late type star is thrown out of thermal equilibrium. The radius of the late type star becomes larger than its equilibrium radius; the greater the mass transfer rate, the larger its radius becomes. In the theoretical calculations by Rappaport, Joss, and Webbink (1982) and Paczynski and Sienkiewicz (1981), the rate of mass transfer, and thus the minimum orbital period, was set by the rate at which gravitational radiation carries angular momentum away from the binary system. Their calculations gave minimum periods between 60 and 70 minutes depending on the parameters of their models. Although the theoretical minimum period is close to the observed minimum period, Rappaport, Joss, and Webbink were unable to raise the theoretical minimum to 80 minutes without altering their models beyond reason. As the observed 80 minute limit is firmly established, the source of the discrepancy appears to be in the theory, not the observations.

b) The Period Gap

The gap in the distribution of orbital periods between 2 and 3 hours is striking. Figure 2 divides the period distribution into narrower period bins than Figure 1 to show more detail near the edges of the gap. The data used to make Figure 2 is not exactly the same as that for Figure 1. The periods of the four cataclysmic variables for which only superhump periods are available have been reduced by a few percent according to the formula of Stolz and Schoembs (1981) to give a better approximation to their true orbital periods. In particular, we have taken periods of 2.10 hr for YZ Cnc 1.75 hr for