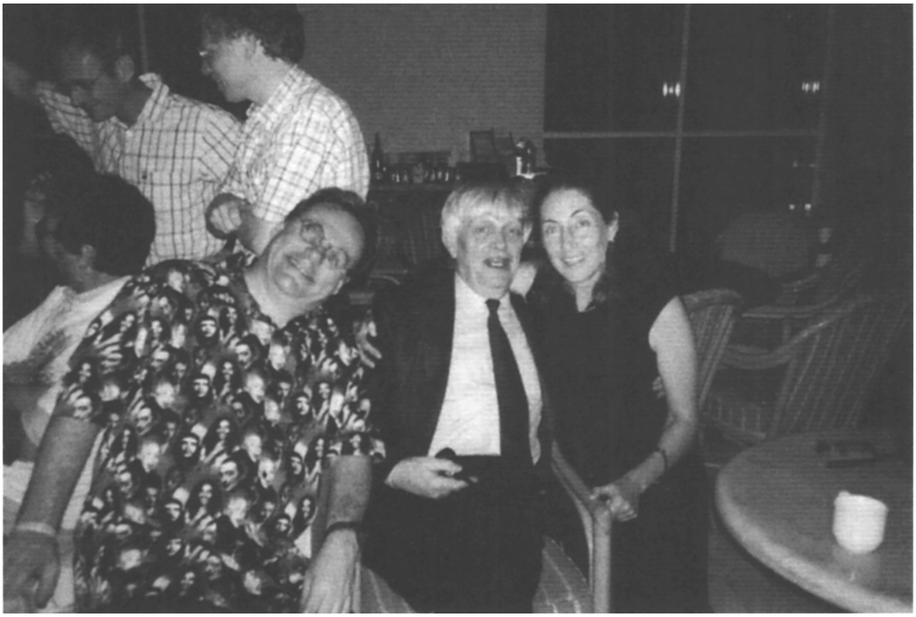
SESSION 5

Final Stages, Nucleosynthesis

A nice table with Sylvie Vauclair, Pascale Garaud, Michel Rieutord, Joergen Christensen-Dalsgaard, Ilkka Tuominen and François Lignières.



Jaymie Matthews, Ian Roxburgh and Gloria Koenigsberger in a close exchange of views.

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Rotation and Cataclysmic Variables

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Abstract. Cataclysmic Variables are binary star systems and so are closely connected to the subject of this meeting. The stars revolve around the center of mass of the system. The gas lost by the secondary through the inner Lagrangian point enters the Roche lobe of the white dwarf with the angular momentum of the L_1 point and, therefore, forms an accretion disk which rotates around the white dwarf. The gas must lose angular momentum to fall onto the white dwarf, and the white dwarf itself must rotate as it accretes infalling material and angular momentum and is gradually spun up. We will review what is known about these phenomena, and emphasize the new results about the white dwarfs that have been learned in the past few years.

1. Introduction

Cataclysmic variables (CVs) are close binary stellar systems in which one component is a large cool star that fills its Roche Lobe (in the Restricted Three-body Problem) and the other star is a hot white dwarf (WD). Orbital periods for these systems range from less than 80 minutes for dwarf novae to more than one year for the Symbiotic Variable systems. In addition, while the systems that we will concentrate on in this article contain WDs, there are related classes where the compact object is either a neutron star or a black hole. These systems are normally designated as Low Mass X-ray binaries (LMXRB) and some are also called X-ray novae since they exhibit X-ray outbursts that last for days to months.

Since CVs are binary star systems, they clearly belong to the rationale for this meeting. Every component is rotating and the effect of rotation pervades both the secular and episodic behavior. For example, the binary is rotating about its center of mass with some orbital period. Because of the reduced potential along the line connecting the center of mass of the two stars, the larger cooler star (which fills its Roche Lobe) is losing gas into the Lobe surrounding the WD. This material carries the angular momentum of the inner Lagrangian point and thus cannot fall directly onto the WD but flows into an accretion disk which surrounds the white dwarf. The material in the accretion disk is rotating around the WD and because of viscosity in the disk there is transport of mass inward and angular momentum outward through the disk. The source of this viscosity is unknown and it must be far larger than molecular viscosity for material to fall onto the WD. At least some material must be carried away from the system by this process while the rest ultimately falls onto the surface of the WD.

There is a boundary layer at the region where the material in the accretion disk actually reaches the "surface" of the WD. Theoretical studies indicate that this boundary region should emit about half the energy of accretion while the white dwarf surface emits the other half. Unfortunately, observations do not agree with the simple theoretical developments of boundary layer theory. Moreover, the shear mixing of accreted material with stellar material should gradually spin up the WD to the critical rotational velocities. As we shall show below, this also is not observed.

An important and exciting development in the study of the rotational properties of these systems has occurred recently though the realization that, when observed in the ultraviolet (UV), the atmospheres of the WDs are visible in some CV systems at or near quiescence. This makes it possible to obtain high resolution spectra that can be fit with stellar atmospheres and then use the results of the fits to obtain masses (through $\log g$ and effective temperature), rotational velocities, abundances, and distances. Most of this review is devoted to reporting on these results. Recent reviews of the properties of CVs can be found in Sion (1999), Warner (1995), Gänsicke (1998), and Szkody et al. (2002).

2. The Classes of Cataclysmic Variables

2.1. Dwarf Novae

These systems typically have orbital periods ranging from about 80 minutes to a few hours and thus the secondary must be similar in size to low mass main sequence stars. There is growing evidence that in some systems the secondary is of extremely low mass, is probably evolved, and must have lost a great deal of material. In other systems, it appears that the secondary may be sub-luminous for its mass. Nevertheless, in all well studied systems the secondaries appear to fill their Roche Lobes and lose mass via Roche Lobe overflow. The gas lost at the L_1 point spirals into an accretion disk and then, because of the viscosity in the disk, onto the WD.

Until X-ray surveys began finding dwarf novae at minimum, they were usually detected in an outburst which is marked, typically, by a 3 to 5 magnitude increase in light that lasts a few days and re-occurs on timescales of weeks to months. Originally thought to be a thermonuclear explosion, just as for Classical Novae, their outbursts are now believed to be accretion disk instabilities. The secondary is continuously losing mass into the accretion disk. The viscosity is low and the accretion disk gradually grows in mass until a critical surface density is reached. At this density the disk viscosity increases by large amounts, shear heating increases, and material is accreted by the white dwarf. The light from the outburst is the release of infall energy as the material reaches the surface of the white dwarf. Once the disk is emptied, the viscosity drops and the mass builds up in the accretion disk until it again reaches the critical density.

According to current theory, the mass transfer rate into the accretion disk must be lower than about $10^{-9}\,M_\odot yr^{-1}$ for the instability to occur (Shafter et al. 1986; King & Cannizzo 1998). While a great deal of work has been done on this scenario, the predicted evolution of the accretion disk implies that its brightness gradually grows during the quiescent phase, and this does not agree with the observations.

There are numerous subclasses of dwarf novae which divide them according to their outburst behavior. For example, one of the best known dwarf novae is WZ Sge which outbursts only very rarely but experienced an extremely well studied outburst in 2001 (Cannizzo 2001, and references therein). One interesting subclass of dwarf novae is the AM Her class. In these systems the WD has an extremely strong magnetic field which is capable of trapping the ionized gas from the secondary and focusing it onto the magnetic poles. In these systems the WD is rotating synchronously with the orbit.

2.2. Classical Novae

Classical Novae (CN) are those CVs which undergo massive explosions in which they are observed to eject $10^{-4\pm1}\,M_\odot$ at speeds up to 7,000 km s^{-1}. They are bright for about a year in the optical but, since a large fraction of their emitted energy appears outside the optical, the actual length of the outburst is WD mass dependent (Gehrz et al. 1998; Starrfield 2002). It is the X-ray observations which track the length of the outburst and the observed times for the WD to return to quiescence range from a few months to more than 10 years (Krautter et al. 2002). Although the gross features of the outburst are well understood to be caused by a thermonuclear runaway (TNR) in the accreted hydrogen-rich envelope on the WD, there are numerous features of the outburst still to be explained (Starrfield 2002). Two serious problems are that we do not know how accreted material is mixed with core material, and novae are observed to eject far more mass than thought possible from theoretical calculations.

Of interest to this meeting, there were studies of the accretion of material with angular momentum onto the WD (Sparks and Kutter 1987; Kutter and Sparks 1987) which followed the evolution of the WD up to the onset of the TNR. These authors found that the TNR occurred too early; i.e. before sufficient material had been accreted to drive the TNR to high temperatures and densities and the resulting evolution did not agree with observations. Although they chose only one value of WD mass ($1.0\,M_\odot$), they did vary the amount of angular momentum per unit mass in the accreted material. They continued accretion until the material on the star reached the same velocity as the accreting material. However, it is not clear that the parameters used in their calculations, for the time of the onset of convection, agree with more modern studies such as Heger et al. (2000). This is not meant to be a criticism of work done 13 years earlier, but simply a statement that a great deal more work has to be done for us to claim progress in studies of accretion of material with angular momentum onto rotating WDs. In addition, it is also important to learn how much angular momentum is carried away by the explosion and how this affects the subsequent evolution of the WD. For example, one explanation for the WDs being slow rotators in CVs (see below) is that the nova outburst carries away angular momentum. However, no hydrodynamic studies of this conjecture have been carried out. Finally, the angular momentum of the ejected material may also be partially responsible for the oblate shapes of nova shells (MacDonald 1983, Porter et al. 1998; Bode 2002).

2.3. Recurrent Novae

Recurrent Novae (RN) consist of two-plus classes of binary star systems. One class contains systems such as U Sco, V394 CrA, and LMC 1990 #2 in which the orbital periods are short (a day or less) and there is no evidence for a red giant in the system (Starrfield et al. 1985; 1988; Shore et al. 1991). There is a second class of RN which do contain a red giant and the orbital periods are long (T CrB, RS Oph, V745 Sco, V3890 Sgr [Shore et al. 1996]). Neither the outburst nor binary characteristics of T Pyx resemble those of any other RN and it is considered to be its own class. In the last two years two new RN (CI Aql and IM Nor [Starrfield 2003]) have been discovered suggesting that the number of these systems is larger than currently thought.

These systems are designated as recurrent because they have been observed to experience more than one explosion during the lifetime of an astronomer. Moreover, hydrodynamic studies have shown that in order to obtain recurrence times as short as 10 years (such as for U Sco), the outburst must occur on a massive WD ($M_* \sim 1.35\,M_\odot$ or larger), and the mass accretion rate onto the WD must be high which requires an evolved secondary (Starrfield et al. 1985, 1988, 2003).

In addition, the material being transferred in the short period systems is extremely depleted in hydrogen. In fact, for U Sco the accretion disk does not show any hydrogen lines and the amount of hydrogen in the ejecta is less than the amount of helium (Williams et al. 1981). This implies that the secondary star is the evolved core of a red giant that has lost most, if not all, its hydrogen envelope. Another important result of combined observational plus theoretical studies of these systems is that the mass of the WD is growing as a result of the TNR. In fact, less than 10% of the accreted mass is ejected during the outburst, and the ejected gases show no evidence that core material was mixed into the accreted material. Accretion at high rates onto a massive white dwarf implies that the WDs should be rotating rapidly. This has yet to be confirmed by observational studies.

2.4. Symbiotic Variables and Symbiotic Novae

Unlike the other CV classes, the secondary is a red giant and the orbital periods are months to years. For many years, these systems were thought to be single red giants with a strange atmospheric structure. It was the UV studies of these variables done with IUE, that indicated the presence of a hot, compact source in the system and demonstrated their binary nature (Kenyon 1986). While in many, if not most Symbiotics the compact object is a WD (they show high ionization lines in their spectra), there are a minority of systems which probably contain a main sequence star. In some systems it seems likely that the secondary does not fill its Roche Lobe and the WD or main sequence star is accreting via a wind rather than an accretion disk. This will have the effect of reducing the rate of mass transfer (and angular momentum transfer) onto the WD and it remains unclear whether an accretion disk can even form from capture of material from a wind.

There are systems in which the WD accretes enough material to experience an outburst and these are called Symbiotic Novae. The outburst takes so long (AG Peg has been in outburst since about 1850) that they must be occurring on low mass WDs. In some cases, spectroscopic studies also imply WD masses below $0.5\,M_\odot$ (Kenyon & Mikolajewska 1995). With such a low WD mass and low accretion rate, transfer of a significant amount of angular momentum seems unlikely. However, as noted in the discussion of Recurrent Novae, there are Symbiotic Novae in which the outburst has been observed to re-occur and the behavior of the outburst implies a TNR caused explosion on a massive WD. These systems are RS Oph, T CrB, V745 Sco, and V3890 Sgr (Shore et al. 1996).

2.5. Super Soft X-ray Sources

The final class of CVs that are of interest to this meeting are the Super Soft X-ray Sources (SSS). These systems were first identified as an astrophysical class by studies with ROSAT (van den Heuvel et al. 1992; Greiner 1996; Kahabka & van den Heuvel 1997). Most members of this class are binaries with one star (probably) a WD and the other star thought to be transferring mass onto the WD at high rates. In contrast to classical or dwarf novae, where the rates of infall are sufficiently low to allow a TNR to occur, in the SSS the infalling material is thought to be burning at the same rate that it is being accreted (this is called steady burning). Since little or no mass is thought to be lost (although jets or jet-like features have been identified in the spectra [Cowley et al. 1998]), the mass of the WD is supposed to be growing toward the Chandrasekhar limit. Again, the rates of mass accretion and the mass of the WD imply that a large amount of angular momentum is being transferred onto the WD and it should be rotating rapidly. To our knowledge, however, no such studies have been done in the UV. Unfortunately, at the proposed high mass accretion rates, light from the accretion disk dominates the UV spectrum and the WD is not visible.

3. The Measured Rotation Rates of Cataclysmic Variables

One of the most exciting developments in the studies of CVs has been the recent realization that in some systems it is possible to directly observe the atmospheres of the WDs in the UV (Sion 1999; Szkody et al. 2002a). This is because *at quiescence* the mass transfer from the secondary decreases to such a low value that there is almost no material in the accretion disk and, therefore, it is not optically thick. As a direct result, there are now a reasonable number of CV systems where it has become possible to measure the effective temperature, the rotation velocity, the gravity, and the surface abundances. These studies also provide realistic estimates of the mass transfer rate onto the WD and they show that this rate is lower than previously thought.

An excellent review of the global properties of WDs in CVs can be found in Sion (1999). Here we concentrate on the rotational velocities and briefly describe some of the other measured properties. Table 1 gives the rotational velocity for a number of CVs plus the orbital period and the effective temperature determined

Table 1. White Dwarf Global-Averaged Rotational Velocities, Orbital Periods and Effective Temperatures

System	$T_{\rm eff}$ (10^3)K	$P_{\rm orb}$ (hr)	$v \sin i$ km s^{-1}
U Gem[1]	30	4.24	≤ 100
VW Hyi[2]	20	1.78	400
WZ Sge[3]	15	1.36	1200
SS Cyg[4]	37	6.60	300
AL Com[5]	16	1.36	<800
OY Car[6]	16	1.51	<200
RX And[7]	35	5.04	150
LL And[8]	14	1.33	<500
EF Peg[8]	17	2.05	300
HV Vir[9]	13	1.39	400
EG Cnc[9]	12	1.44	600
EK TrA[10]	19	1.53	200
SW UMa[11]	14	1.36	200
WX Cet[11]	13	1.4	400
VY Aqr[11]	14	1.52	400
BC UMa[11]	15	1.52	300
DW UMa[11]	46	3.28	400

References. 1: Sion et al. (1994); 2: Sion et al. (1996,2001a); 3: Cheng et al. (1997); 4: Mauche (1998); 5: Szkody et al. (1998); 6: Cheng et al. (1994); 7: Sion et al. (2001b); 8: Howell et al. (2002); 9: Szkody et al. (2002b); 10: Gänsicke et al. (2001); 11: Szkody et al. (2002a)

from the studies that also determined the velocities. Table 1 is an updated version of Table 6 from Sion (1999). More recent results are found in tables given in Szkody et al (2002a), and some of those data are also given here.

As described in detail in the references given in Table 1, the rotational velocities are obtained by fits of observed spectra to spectral syntheses obtained from model stellar atmospheres. The fits are done to spectra obtained in the UV region of the spectrum since at those wavelengths, if $\dot{M}$ is sufficiently low, the accretion disk makes little contribution to the energy emitted by the WD. The spectral fitting to the observed spectra is done with programs developed by Hubeny. TLUSTY195 and SYNSPEC45 are used and are described in Hubeny (1988) and Hubeny and Lanz (1995). These programs are used to compute grids of model stellar atmospheres and spectra. Approximate values of log g and $T_{\rm eff}$ are chosen along with a number of choices for the metallicity. Because of the short time scale for gravitational settling of the heavy elements out of the WD stellar atmosphere (Sion 1999 and references therein), the atmospheres should show only hydrogen and (possibly) helium lines unless accretion is ongoing in the system. A large number of stellar atmospheres and predicted emergent spectra are computed and then compared (in a χ^2 sense) to the observed UV spectra.

Once log g is determined, either the Hamada & Salpeter (1961) mass-radius relation or evolutionary sequences of hydrogen-rich WDs with carbon-oxygen cores by M. Wood are used to obtain the WD mass and radius. More details can be found in the papers cited in Table 1.

An interesting corollary to this discussion is that for a number of systems not only does an accretion disk have to be included in the fit to the observations but also an accretion belt. An accretion belt is a component to the fit in which it is assumed that material is being accreted only in regions close to the equator of the WD. This additional feature has a solar composition and a higher rotation velocity than that measured for the WD atmosphere. That accretion belts have been found necessary to obtain a reasonable solution, implies strongly that mass transfer onto the WD is occurring on only a small fraction of the WD surface. More details can be found in Sion (1999; and references therein) and Szkody et al. (2002a).

While single WDs in the field are slow rotators ($v \sin i < 60$ km s^{-1} [Pilachowski 1984, 1987]; $v \sin i < 15$ km s^{-1} [Koester et al. 1998]), the WDs in CVs are rotating faster. This is to be expected since the material being accreted by the WD from the accretion disk must impact the surface of the WD with the angular momentum of the inner part of the disk. For typical dwarf and classical nova systems accretion over long times should spin up the WD to critical velocities. (This argument does not apply to the AM Her variables since the magnetic torques are sufficient to force the WD to rotate synchronously with the orbit.)

As can be seen in Table 1, however, this is not the case for any WD in the systems that have been studied in the UV. In fact, given that material has been accreting for a long time, they are rotating slowly, although above the values for single WDs in the field. Therefore, while some angular momentum is being accreted by the WD, there must be some mechanism for removing the angular momentum of the accreted material. Additional evidence that the WDs are accreting material can be found in their effective temperatures. In general, they are too hot for their evolutionary stages, and dwarf novae studied after outbursts show that the WDs are cooling (Sion 1999; Szkody et al. 2002a). Finally, they show elemental abundances that are significantly enhanced over single WDs. Since diffusion acts rapidly under the high gravity of a WD, the observed metals must be coming from accreted material that has yet to diffuse down into the interior of the WD.

A discussion of this problem can be found in Livio and Pringle (1998; see also Sion 1999) where they use a relationship obtained by Papaloizou & Pringle (1978) to show that if the typical lifetime of a CV is 10^9 yr and it accretes at an average rate of $10^{-10}\,M_\odot$ yr^{-1}, then it should be rotating at or near breakup. The Keplerian rotation rate for a $1.0\,M_\odot$ WD corresponds to a maximum surface velocity of $V_{MAX} = 5000$ km s^{-1} and that is far higher than observed (Table 1). Livio & Pringle propose that angular momentum is removed by a nova outburst (see also MacDonald 1986).

The prediction is that older CV systems should be rotating more rapidly because they have had sufficient time to accrete more material. The age of the system is thought to correlate with the effective temperature although the heating from accretion must complicate this picture. In order to test this prediction; Sion, Szkody, and their collaborators have recently been studying CVs with cool white dwarfs (Szkody et al. 2002b; Howell et al 2002). They find that there is no *significant* correlation of effective temperature with rotation velocity implying that a better understanding of angular momentum loss mechanisms is needed for accretion onto WDs in CV systems.

The spread of measured velocities raises interesting questions about the amount of angular momentum transfer during tangential accretion and the amount of angular momentum lost either during nova explosions or dwarf nova outbursts. For example, during a dwarf nova outburst the material in the accretion disk becomes hot and grows to large radii where tidal forces from the secondary must become important and could transfer angular momentum from the accreting material back into the binary. Another possibility is that if the WDs have reasonable but undetectable magnetic fields (a field $< 10^5$ G cannot be detected by present methods), then these fields could still play a role in braking or moderating the rotation of the WD. Moreover, it is possible that an accretion belt could generate its own field by wrapping field lines as accretion feeds differential rotation on the surface of the WD.

4. Rotation and Mixing

Considering the number of questions about the transport of angular momentum onto the WD, we then turn to what happens to the interior of the WD as the accreted layers increase in mass. A CN explosion is the consequence of a TNR in the accreted hydrogen-rich envelope on the WD in the CV. One dimensional hydrodynamic studies, have shown that the envelope grows in mass until it reaches a temperature at its base that is sufficiently high for ignition of the hydrogen fuel to occur. The further evolution of nuclear burning on the WD depends upon the mass and luminosity of the underlying WD, the rate of accretion, the chemical composition in the reacting layers, the rotation speed, and the convective history of the envelope.

In addition, observations of novae ejecta show that core material has been mixed up into the accreted layers and then ejected by the explosion. What is not yet known, is the influence of rotation on this process. This problem is also connected with the growth of the convective region as the TNR reaches maximum temperature and energy generation. One of the mechanisms proposed for the cause of the mixing is shear mixing (Kutter and Sparks 1987; Sparks and Kutter 1987). They assumed that material was accreted tangentially onto the surface of the WD and the shear induced by the difference in velocity between the accretion disk and the WD caused the infalling material to mix into the WD. They based their development on the work of Kippenhahn and Thomas (1978) and assumed that material was accreted only in the equatorial regions. They did find deep mixing but not enough material was accreted to match the observations of nova ejecta (Starrfield 2002, 2003). This problem has recently been re-investigated with the FLASH multi-dimensional computer code (Rosner et al. 2001; Calder et al. 2002). They also find that mixing occurs but too early in the accretion process so that insufficient material is accreted and ejected to agree with observations. Further work is indicated.

5. Conclusions

There are a number of important questions to be answered by further studies of these exciting objects. In addition, accretion disks exist in proto stars, nuclei of galaxies, newly forming neutron stars in Supernova explosions, and probably in γ-ray bursts if the connection to hypernovae turns out to be correct. Nevertheless, it is in CVs where the changes in the accretion disk can be mapped and studied in great detail both in quiescence and outburst.

UV observations have found that the WDs in CV systems are rotating faster than single WDs in the field and they are more than twice as hot as the oldest single WDs. These results imply that the WDs in CVs have accreted significant amounts of material from the secondary.

However, the WDs in CV systems are rotating much slower than "break-up" implying, for the oldest systems, that some mechanism is removing angular momentum from the accreting WD. It may not be a classical nova outburst. It could be dwarf nova outbursts where tidal forces transport WD angular momentum into orbital angular momentum.

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