Infrared photometry and spectroscopy of AM Canum Venaticorum stars

Bart Buijs

Supervision:
Associate prof. P.A. Woudt – University of Cape Town
Prof. dr. P.J. Groot – Radboud University Nijmegen
“The hardest part of surfing big waves is getting off the beach.”

– Some random dude

“We are not retreating. We are advancing in another direction.”

– General McArthur

Cover image: the evening sky at the start of an observing run at the South African Astronomical Observatory in the Great Karoo.
Abstract

We present the first infrared study of AM CVn systems. J-, H- and K_s-band magnitudes were obtained for AM CVn, HP Lib, SDSS J0926, GP Com, SN 2003aw and CE 315 with the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS) on the William Herschel Telescope (WHT) in La Palma, Spain. UBVRI magnitudes of AM CVn, HP Lib, SDSS J0926, GP Com and CE 315 were obtained with the WHT Auxiliary camera. Phase resolved photometry in the K_s-band of AM CVn and CE 315 shows no periodic variability. SDSS J0926 shows a periodic variability consistent with half its orbital period. We present J-, H- and K_s-band magnitudes of ES Cet and CP Eri obtained with the Simultaneous three-color InfraRed Imager for Unbiased Survey (SIRIUS) on the Infrared Survey Facility in Sutherland, South Africa. ES Cet and CP Eri show no periodicity in their phase resolved photometry. We obtained a NIR spectrum of HP Lib with WHT/LIRIS, that shows only a continuum. We found three helium emission lines in the NIR spectrum of GP Com obtained with WHT/LIRIS. The spectral energy distribution of GP Com, as well as fits to the SDSS spectrum and a VLT spectrum, show that the accretor is most probably a 0.6 M_⊙ 13 kK white dwarf. This implies the donor star is slightly bigger than it would be, when it would be a fully degenerate zero temperature white dwarf. Analysis of the contributions of different donor possibilities yield an upper limit for the donor temperature of 2500 K. The spectral energy distribution shows a flux excess in the infrared that can be explained by a 2500 K donor. A 2000 K white donor that contributes about 30% of the flux in the K_s-band seems the most likely scenario. For CE 315 we find 1500 K as an upper limit for the donor temperature. We recommend further study of the low state AM CVn systems by means of modelling of optically thin helium accretion discs and boundary layers, as well as parallax and Spitzer measurements of the currently known low state systems, SDSS J0804, SDSS J1411, GP Com, SDSS J1552 and CE 315.
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Chapter 1

Introduction

Many stars in our universe are not born alone, but with a companion. Together the two stars form a binary system. Because the separation between two stars in binary systems is usually quite large, the stars in a binary system evolve through a large part of their lives as if they were single stars. When one of the stars has finished its hydrogen burning phase and evolves from the main sequence up into the hydrogen shell burning giant branch, it swells up. In many cases the star becomes so large that its mantle extends all the way to its companion, in such a way that the companion star ends up inside its mantle. Such a situation is called a common envelope phase. At a given time the envelope can be ejected and a stellar remnant remains. What this remnant is depends on the initial mass of the object. For stars with a core less than the Chandrasekhar mass of 1.44 $M_\odot$ this will be a white dwarf.

During the common envelope phase the binary system loses a considerable amount of matter and orbital angular momentum, that is carried away mostly by the ejected envelope. The exact details of the common envelope evolution are so far poorly understood, due to the large three-dimensional hydrodynamical calculations with physics of very different length scales required to solve this problem. A description in only macroscopic parameters is given by Iben & Livio (1993). One of the results of the common envelope phase is that the separation of the binary’s components shrinks considerably during a common envelope phase. When the second star continues its evolutionary path in a similar way as the first one, what just was described roughly repeats itself. The star swells up, giving rise to another common envelope phase, the components spiral inwards, the envelope gets ejected and if the component do not merge we are left with two compact objects orbiting each other in a close orbit. This is called a compact binary. The masses, chemical abundancies (i.e. evolutionary stage) and the entropies (i.e. level of degeneracy and temperature) of both components now determine how close they can get together before they start interacting and what the further evolution of the system looks like.

When stars in a compact binary interact this can give rise to a whole range of interesting physical phenomena. When matter accretes onto a compact object the gravitational
energy released can for instance give rise to a the emission of cosmic rays with energies higher than those we can achieve in particle accelerators on Earth. Interacting binaries can form accretion discs, that are cosmic hydrodynamical laboratories. When a white dwarf is pushed over the Chandrasekhar mass because of accretion, it can become a type Ia supernova (SN Ia). The SNe Ia are our best measuring rods of cosmics distances and are an invaluable tool in measuring many cosmological processes, such as the acceleration of the universe.

AM CVn stars are hydrogen-depleted binary stars with orbital periods between five and sixty-five minutes. They consist of a white dwarf accreting from another compact object. They form an extreme end point of binary evolution. To form an AM CVn star the binary has to go through at least one (but in the most cases even two) common envelope phases, in which the system loses almost all its hydrogen. Therefore AM CVn stars are tools to study the common envelope evolution by parametrising the populations of systems that go into and come out of the common envelope phase. The hydrogen-depleted nature of AM CVn stars also allows us to study the dynamics of helium accretion discs. Comparing what happens in helium accretion discs to the more common hydrogen dominated discs, can teach us a great deal about the mechanisms and properties of accretion discs in general. AM CVn systems can also give rise to interesting outbursting phenomena, such as helium novae (Kato et al. 1989; Iben & Tutukov 1991, 1994; Woudt 2008) and Ia supernovae (Bildsten et al. 2007). As extremely compact binaries, AM CVn systems are the only known stable sources of gravitational waves radiation in the $mHz$-regime. This is regime where the Laser Interferometer Space Antenna (LISA), the most advance gravitational wave detector proposed, will be measuring. AM CVn systems will be invaluable calibration sources for LISA (Nelemans et al. 2004), that can provide us with a new window on the universe.

AM CVn stars have so far been mostly studied in the optical, UV and X-rays. Some radio measurements were done, but with little result (Ramsay et al. 2007). This thesis is a step into a new wavelength regime; the infrared. By studying AM CVn stars in the infrared we add information on the cooler parts of the system. This could potentially give us new information on the donor stars and the cooler parts of the discs.

In Chapter two of this dissertation I will describe the physics of compact binaries, our current knowledge about AM CVn systems and the theoretical background we use to interpret our data. Chapter three describes the observations and data reduction, the results of which can be found in Chapter four. We'll conclude with a discussion of the results in Chapter five, where we also make recommendations for future research.
Chapter 2

The AM Canum Venaticorum stars

2.1 Compact binaries

Before we elaborate on AM CVn systems it is useful to get an idea about the physics of compact binaries in general. Two stars in a compact binary obey Kepler’s third law

\[ P_{\text{orb}}^2 = \frac{4\pi^2a^3}{G(M_1 + M_2)}, \]  

(2.1)

with \( P_{\text{orb}} \) the orbital period, \( a \) the separation of the binary’s components and \( M_1 \) and \( M_2 \) the masses of the two components.

The gravitational potential of a synchronously rotating point-like binary in the co-rotating frame is described by the Roche potential (Frank et al. 2002)

\[ \Phi_R(r) = -\frac{GM_1}{|\mathbf{r} - \mathbf{r}_1|} - \frac{GM_2}{|\mathbf{r} - \mathbf{r}_2|} - \frac{1}{2}(\omega \wedge \mathbf{r})^2, \]  

(2.2)

with \( \mathbf{r}_1 \) and \( \mathbf{r}_2 \) the distances of the two stars to the center of mass and \( \omega \) the angular velocity of the stars. A surface representation of the Roche potential and a projection of the equipotential contours in the orbital plane is shown in Figure 2.1.

The point marked \( L_1 \) in Figure 2.1 corresponds to the saddle point in the Roche geometry, where the gravitational pull of both of the binary’s components are equal and is called the inner Lagrangian point. Because of the complex geometry, the distance \( b_1 \) between the centre of the primary and the inner Lagrangian point can only be approximated numerically by \( b_1/a = 0.500 - 0.227 \log q \), where \( q = M_2/M_1 \) is the mass-ratio of the components. When we look at the equipotential contours through \( L_1 \) we see the figure eight. The volume of the equipotential surface that encloses one of the components
Figure 2.1: Surface representation of the Roche potential and a projection of its equipotential contours in the orbital plane. In this case the mass ratio $q = M_2/M_1 = 0.5$. The star on the left is the heavier one. Figure by Martin Heemskerk (from Wikipedia).

is called that component’s Roche lobe. At points within the Roche lobe a test-particle is mainly influence by that component.

When two stars orbit each other they loose angular momentum $J$ due to gravitational wave radiation (GWR). This is given by Landau & Lifschitz (1971) as

$$
\left(\frac{\dot{J}}{J}\right)_{\text{GWR}} = -\frac{32}{5} \frac{G^3}{c^5} \frac{M_1 M_2 (M_1 + M_2)}{a^4}.
$$

(2.3)

Therefore the stars spiral towards each other and their Roche lobes shrink. After a while one of the stars may become bigger than its own Roche lobe. What follows is that matter flows through the inner Lagrangian point towards the other star. This process is called Roche lobe overflow. When the matter flowing through the inner Lagrangian point reaches the other star it is accreted by it. Therefore this star is called the accretor, or primary, and the star that is overflowing its Roche lobe is called the donor, or secondary. The best approximation (to 1% accuracy) for the size of the Roche lobe of the donor is given by Eggleton (1983) as
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\[ R_{L2} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} \]  

(2.4)

The mass transfer can stabilize when the donor fills the Roche lobe exactly all the time; this is called the Roche lobe filling condition. Paczyński (1967) uses this to derive the rate of mass transfer \( \dot{M}_2 \) to be given by, in the form of Nelemans (2005),

\[ \frac{\dot{M}_2}{M_2} = \left( \frac{j}{\mathcal{J}} \right)_{GWR} \times \left[ \frac{\zeta(M_2)}{2} + \frac{5}{6} - q \right]^{-1} \]

(2.5)

with \( \zeta(M_2) \) the logarithmic derivative of the radius of the donor with respect to its mass

\[ \zeta \equiv \frac{d \ln R_2}{d \ln M_2} \]  

(2.6)

This leads to stable mass transfer when the term in brackets is positive, so when

\[ q < \frac{5}{6} + \frac{\zeta(M_2)}{2} \]  

(2.7)

2.1.1 Accretion disc formation

When matter flows through the inner Lagrangian point with approximately the local sound speed, it will follow a ballistic trajectory. Because the matter still has considerable angular momentum it will try to get in a Keplerian orbit (because that has the lowest possible energy for a given angular momentum) with the same specific angular momentum it had when it went through the inner Lagrangian point. The radius of this orbit is called the circularization radius and is given by Frank et al. (2002) as

\[ R_{\text{circ}} = a(1 + q)[0.500 - 0.227 \log q]^4 \]  

(2.8)

For a compact primary this will only result in direct impact accretion when approximately \( R_1 > R_{\text{circ}} \). This occurs when \( a \) is very small and the orbital period is very short. The occurrence and stability of this situation was recently described more accurately in Motl et al. (2007). In most cases the matter will miss the primary completely and form rings close to the circularization radius, because the timescale for losing angular momentum is longer than the dynamical timescale. Between two such rings with slightly different radii, there is differential rotation that gives rise to shear viscosity. Because of this viscosity, torques are applied to the different rings spreading the matter to both larger and smaller radii, thereby redistributing the angular momentum. This is the simplest model of how an accretion disc is formed. Matter can then be accreted from the inner end of the disc, while on the outside of the disc angular momentum is removed by winds or torques.
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When the matter is accreted eventually we can approximate the energy this accretion will generate when $R_1 \ll b_1$ and $R_1 \ll R_{\text{circ}}$ as the gravitational potential energy available to be released as radiation

$$L_{\text{acc}} = \frac{GM_1 \dot{M}}{R_1}$$  \hspace{1cm} (2.9)

with $\dot{M}$ the accretion rate and $R_1$ the radius of the primary. This theoretical maximum luminosity is called the accretion luminosity. Where and when this energy is released depends on the specific configuration of the system. A large part of the energy can be released right away, when the accretion stream from donor hits the accretion disc. This gives rise to what is called a ‘hot spot’ in the disc. Some energy may be released by at the very end, when the matter falls from the last stable orbit onto the accretor. It is however the total accretion luminosity that determines whether a disc will be able to form. When the accretion luminosity exceeds the Eddington luminosity the situation will be unstable.

In our case however, the accretion luminosity is less than the Eddington luminosity. The accretion disc is said to radiate subcritical and the gas pressure dominates the radiation pressure. The structure of such an accretion disc was first described by Shakura & Sunyaev (1973), but is also clearly explained in Frank et al. (2002). The Reynolds number $Re$ for the gas in the accretion disc is given by

$$Re = \frac{\text{inertial force}}{\text{viscous force}} \sim \frac{v_\phi^2/R}{\lambda_t v_t/R^2} = \frac{R v_\phi}{\lambda_t v_t},$$  \hspace{1cm} (2.10)

with $v_\phi$ the velocity of a test particle in its circular trajectory in the accretion disc and $v_t$ the transverse velocity. When we assume $\lambda$ to be in the order of the mean free path $\lambda_d$ in the plasma and $v_t$ to be in the order of the sound speed $c_s$, the Reynolds number becomes of the order of $10^{14}$ which is significantly higher than the Reynolds number of $10^3$ at which the plasma becomes turbulent. For a turbulent plasma we know that $\nu \sim \lambda_t v_t$, with $\lambda_t$ the size of a typical Eddy current in the turbulent gas. Because turbulence is such a poorly understood part of physics, our knowledge of $\lambda_t$ and $v_t$ is poor. What can safely assume though, is the size of a typical Eddy current will not exceed the height of the disc $H$. Since $v_t \leq c_s$ we can parametrize our ignorance of viscosity $\nu$ with a single parameter $\alpha$ by

$$\nu = \alpha c_s H,$$  \hspace{1cm} (2.11)

with $\alpha \leq 1$. Now we have an expression for the viscosity determining the transport of angular moment and we can solve the local structure for a circular accretion disc. When particles in the disc reach the largest radii they can leave the system and carry angular momentum away. At the same time, matter can be accreted at the inner part of the disc and angular momentum is conserved globally. Alternatively the particles can also go into larger, non-circular, orbits, making the disc as a whole non-circular. If that
happens torques can be applied to the disc that act as a sink of angular momentum. In this case the disc will start to precess.

In this thesis I assume that the simplest possible ‘standard model’ of a circular accretion disc is valid for our purposes. Details about this and the equations for the local structure can be found in Frank et al. (2002). When conditions are more extreme than explained in this paragraph (because of large magnetic fields for instance) this model will break down. At this stage there are, however, no clues that a more complex accretion disc model should be used.

The amount of matter in the disc is so small that it is not self-gravitating, but the matter becomes however more and more gravitationally bound to the primary. Gravitational energy is therefore released during the spiral-in phase and angular momentum transport can result in a spin-up as described by Packet (1981). Another part can be released as radiation from the disc. For this we follow the deductions of Frank et al. (2002). The viscous dissipation per unit disc area $D$ as a function of the distance $R$ to the centre of the primary is in our situation given by

$$D(R) = \frac{3GM_1\dot{M}}{8\pi R^3} \left[1 - \left(\frac{R_1}{R}\right)^{1/2}\right].$$  \hspace{1cm} (2.12)

The luminosity of the disc is now given by

$$L(R_i, R_o) = 2\int_{R_i}^{R_o} D(R)2\pi RdR,$$ \hspace{1cm} (2.13)

with $R_i$ and $R_o$ the inner and outer radius of the disc respectively.

If the disc is optically thick we can assume it radiates as a black body. We now find the observed flux of the disc at a distance $D$ to be (Frank et al. 2002)

$$F_\lambda = \frac{2\pi hc^2 \cos i}{15D^2} \int_{R_i}^{R_o} \frac{RdR}{e^{hc/\lambda kT(R)} - 1},$$ \hspace{1cm} (2.14)

with

$$T(R) = \left\{\frac{3GM\dot{M}}{8\pi R^3\sigma} \left[1 - \left(\frac{R_i}{R}\right)^{1/2}\right]\right\}^{1/4}. $$ \hspace{1cm} (2.15)

If the disc is optically thin the physics becomes more complicated. What we can do however, is estimate the total luminosity by assuming the matter starts with negligible binding energy. That is, when we consider $R_1 \ll b_1$ so we can take $R_i = R_1$ and take the limit $R_o \rightarrow \infty$. We then find the steady state disc luminosity to be

$$L_{\text{disc}} = \frac{GM_1\dot{M}}{2R_1} = \frac{1}{2}L_{\text{acc}}.$$ \hspace{1cm} (2.16)
So half of the total accretion energy can be released in the disc and the other half can be released closer to the star, at the surface or in a boundary layer.

From observations it has become clear that the steady state description of an accretion disc is definitely not always valid (Hoshi 1979). When the energy balance in the disc is disturbed and the viscous dissipation no longer equals the disc heating the disc can become thermally unstable. When the mass-transfer rate drops the, density profile of the disc changes too, affecting the viscosity of the disc; the cooling curve $\Lambda(T_c)$ and with it the degree of ionization of the disc. This changes the optical depth of the disc and therefore its emissivity, which feedbacks to the viscosity. As a result, in certain mass-transfer regimes, the disc becomes unstable and oscillates (sofar unpredictably) between being optically thick and optically thin, thereby changing the entire system’s magnitude and spectral features. Because interplay of the ionization balance and the emissivity and viscosity of the disc, the emissivity becomes explicitly dependent on the form of the viscosity. Since this form is unknown, the instabilities can not be described in great detail. A disc instability model for AM CVn systems using only macroscopic properties is given by Tsugawa & Osaki (1997).

### 2.2 AM CVn stars

AM CVn systems are binaries with orbital periods up to about an hour, consisting of a helium accreting white dwarf primary and a sofar unseen donor. Because of these short orbital periods we know we are dealing with hydrogen depleted systems. Their spectra are dominated by helium. They are named after their prototype, variable star number AM in the constellation Canum Venaticorum (Hunting Dogs). It was first identified as a binary by Smak (1967) through its photometric variations. It was Warner & Robinson (1972) who first proposed that AM CVn was an interacting binary when they noticed a double-humped light curve with a period of 18 minutes. In the years that followed progress in understanding AM CVn systems was initially slow, but some more systems were discovered. Since the binaries cannot be spatially resolved and more than one period can be found in the photometric signal from AM CVn, the true orbital period remained unknown. Nelemans et al. (2001b) settled the debate by measuring the velocity variation of the hot spot emission. The slightly longer photometric period found in AM CVn systems is called the superhump period and is due to the precession of the non-circular accretion disc and asymmetric dissipation in the disc Roelofs et al. (2006b).

AM CVn systems have been recognised as a distinctive subclass of cataclysmic variable stars, extensively described in Warner (1995a). The first comprehensive review article on AM CVn stars is Warner (1995b). The first conference dedicated to AM CVn stars was organised in Nijmegen in 2005, close in time to which a second review article by Nelemans (2005). The most recent progress on AM CVn stars was discussed during the Second International Workshop on AM CVn stars\(^1\), held in Cape Town in September

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At the time, 22 systems are known to be AM CVn stars (Groot 2008). Two of those systems are of a new kind, called “hybrids” during the last conference. They are showing the characteristics of AM CVn stars, but also have hydrogen in their spectrum. Figure 2.2 is illustrative of the helium nature of AM CVn stars and shows peculiar the position of the two new hybrids. Furthermore, one system, SDSS J0926 is known to be eclipsing (Anderson et al. 2005). SDSS J0804, is possibly the first magnetic AM CVn star (Roelofs et al. 2008). The current best estimate of the space density of AM CVn stars is $1 - 3 \times 10^{-6}$ pc$^{-3}$ (Roelofs et al. 2007c) and they mainly reside at low Galactic latitude (see Figure 2.3). The discovery of the systems has hardly been systematic. Some of the first systems were found through their optical variability (systems with shorter periods) or high proper motion. More recently systems have been identified in the Sloan Digital Sky Survey because of their characteristic helium emission lines (Roelofs et al. 2005; Anderson et al. 2005, 2008).

Table 2.1 at the end of this chapter list the currently known AM CVn systems and some of their properties.

![Figure 2.2: The equivalent width of the 5875 Å helium line with respect to Hα illustrates the helium nature of AM CVn systems and the peculiarity of the newly found hybrids. The cataclysmic variables are all below the diagonal line. Figure from Groot (2008).](image-url)
Figure 2.3: Modelled surface density $\sigma$ (per deg$^2$) of AM CVn stars as a function of orbital period, down to $g = 21$ mag, for three Galactic latitude ranges. The solid line shows the ‘optimistic’ model, the dotted line the corresponding ‘pessimistic’ model. Figure from Roelofs et al. (2007c).
2.3 Formation channels

An AM CVn progenitor comes out of the common envelope phase detached. The two stars are then drawn closer together because of the loss of angular momentum due to GWR given by Equation 2.3. After a while the size of one of the stars will match the size of its Roche lobe. The heavier star has the biggest Roche lobe and is degenerate (so also more compact than the lighter star), so we can be sure that the lighter star will be the one to fill its Roche lobe. If the mass ratio satisfies Equation 2.7, the mass transfer will be stable because the Roche lobe filling condition can be satisfied. Conservation of angular momentum pushes the stars away from each other when mass is transferred. In the majority of cases the dynamical and thermal timescales are much shorter than the timescale for loss of angular momentum due to GWR (see Yungelson (2008) and references therein for a more detailed analysis). In this view the star will respond directly to losing mass by expanding or contracting, depending on the degeneracy of the donor. In any case, the rate of the mass transfer will drop exponentially with time (Nelemans et al. 2001a). What happens now basically depends on the mass ratio and the mass-radius relation of the secondary. We distinguish three formation channels of AM CVn stars that mainly differ by the nature of the donor star at first contact. Their evolution in the $P_{\text{orb}} - \dot{M}$-diagram is shown in Figure 2.4. Evolutionary calculations in a wide range of circumstances can be found in Paczyński (1971); Packet (1981); Nelemans et al. (2001a); Podsiadlowski et al. (2003); Townsley & Bildsten (2004); Bildsten et al. (2006); Motl et al. (2007); Yungelson (2008).

2.3.1 The white dwarf channel

If the donor is a fully degenerate white dwarf it will expand upon mass loss. It will therefore fill its Roche lobe at a larger and larger separation while losing mass. The system will thus evolve to longer orbital periods. We say the stars make contact at the period minimum. Only in this case, when the donor star is already fully degenerate before contact the stars orbital separation can become close enough for direct impact accretion to occur. Verbunt & Rappaport (1988) show that in this case the criterion for stability of mass transfer is a bit stricter because angular momentum is transferred more directly.

2.3.2 The helium star channel

In the helium star channel the donor star is not fully degenerate. In this scenario the donor star starts burning helium after the common envelope phase. From Yungelson (2008) we know helium stars are short lived and Nelemans et al. (2001a) shows they start overflowing their Roche lobes within the first 50% of their lifetime. Yungelson (2008) models from this that the stars will be in their helium burning state where, they expand up to 30% due to burning, for about 100 Myr. When they finish burning helium they will quickly become more degenerate as they loose their outer layers due to Roche lobe overflow. They hit a period minimum just above the limit for direct impact
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2.3.3 The evolved CV channel

In the evolved CV channel the AM CVn progenitor has only gone through one common envelope phase. The secondary in this case is an evolved main sequence star. Under the proper condition (Podsiadlowski et al. 2003) the donor can reveal its helium rich core upon mass loss. The evolution then proceeds similar to that of the helium star channel. In the evolved CV channel there should be (at least) traces of hydrogen. This formation channel therefore seems likely for the newly discovered “hybrids”.

Figure 2.4: Evolutionary tracks of AM CVn stars through the $P_{\text{orb}} - \dot{M}$-diagram for different donor types. $\dot{M}$ drops exponentially with time. Some typical system are indicated in the diagram. Figure from Nelemans (2005).
2.4 The accretion disc states

When the AM CVn system has formed it goes to a couple of very different observational phases. The main difference in these phases is the state of the accretion disc. The most important parameter that determines this state is the mass transfer rate, but observationally the classification with orbital period, which also plays an important role, is easier. The different states of the disc are drawn in Figure 2.5. Table 2.1 lists the known systems in each disc state in order of their orbital periods.

Figure 2.5: The state of the accretion disc for different $P_{\text{orb}}$ and $\dot{M}$. Figure from Deloye (2007).
2.4.1 Direct impact accretion

In systems with the highest mass transfer rates at the shortest orbital periods, there can be direct impact accretion. These systems are also called “ultracompacts”. About two systems, HM Cnc (Motch & Haberl 1995; Israel et al. 1999, 2002; Marsh & Steeghs 2002) and V407 Vul (Ramsay et al. 2002; Dolence et al. 2008) there seemed to be some consensus in the AM CVn community\(^2\) that is the case. There are nonetheless three models describing the details of this subclass, called (i) the polar (Motch & Haberl 1995) model, (ii) the direct impact model (Marsh & Steeghs 2002) and (iii) the unipolar inductor model (Wu et al. 2002). Recent SPH-modelling of these systems by Dolence et al. (2008) shows that the direct impact model is the most feasible of these models. We did not observe these systems, so we won’t go into this long-standing interesting discussion any further. Whether there is direct impact accretion in ES Cet (Warner & Woudt 2002; Espaillat et al. 2005), is still under debate. The most recent contribution (Wood 2009) to this debate is that of grazing impact of the accretion stream with white dwarf atmosphere, forming an intermediate stage between the direct impact model and the formation of an accretion disc as seen in the high state systems.

2.4.2 The high state systems

When an accretion disc form in an AM CVn system (either after the direct impact phase or immeditely), the system is always still young and the mass transfer rate high. Because there is a lot matter fed into the disc and a lot of friction, the temperatures in the disc are high. Therefore the disc is ionized and optically thick. In this phase the accretion disc dominates the spectrum at optical wavelengths. There are typically two periods in the optical lightcurves. One due to the orbital motion which can be clearly seen in Doppler tomograms (Marsh & Horne 1988) as the period of the bright spot. The slightly longer period is called the “superhump” and is due to precession of the accretion disc Patterson et al. (1993) and asymmetric dissipation in the accretion disc Roelofs et al. (2006b). The spectra of high state systems show doubly peaked helium absorption lines in the optical.

2.4.3 The outburst systems

When the mass transfer rate drops as the system has evolved to a longer orbital period, thermal viscous instabilities can form in the disc (see discussion at the end of Paragraph 2.1.1). The disc starts to oscillate between a high and low state. The pattern of these oscillations is known very poorly, but it is clear that systems at a shorter orbital period spend relatively more time in a high state than systems at a longer orbital period. The brightness of the systems can vary by as much as five magnitudes (Kato et al. 2000) between the two states. The outburst states of the systems resemble the high state systems; the quiescent states resemble the low state systems.\(^2\)Contributions of Ramsey and Dall’Osso at the 2nd International Workshop on AM CVn stars, http://mensa.ast.uct.ac.za/amcvn2008/ and following discussions.
2.4. THE ACCRETION DISC STATES

2.4.4 The low state systems

When the mass transfer rate becomes of the order of $10^{-11} \, M_\odot$ the disc return to a stable low state. The degree of ionization is now low and the disc is thought to be optically thin. We see these systems as emission line systems. Six new discoveries of these systems were made in the SDSS by looking for these characteristic emission lines. No photometric variability in the optical has been observed in the low state systems.

The presence of the white dwarf can be clearly seen in the spectrum of SDSS J1240 Roelofs et al. (2005). Buijs (2008) used DB models from Koester (1980) to show this more explicitly and determine the temperature of the white dwarfs. The example of SDSS J1240 is shown in figure 2.6. For accretors cooler than 15kK the absorption lines become very narrow and a single temperature black body is a good approximation for the spectrum energy distribution at optical wavelengths. Figure 2.7 shows the modelled evolution of AM CVnS and shows how the accretor may dominate the spectrum at long periods. Buijs (2008) shows that the single DB model for hotter and single black body model for colder AM CVn spectra dominated by the accreting white dwarf is a good at optical wavelengths.

Figure 2.6: Fit of a 18 kK log($g$) = 8.0 Koester DB model to the spectrum of SDSS J1240. Figure from Buijs (2008).
Figure 2.7: Time averaged accretion rate $<\dot{M}>$ (top), effective temperate of the accretor $T_{\text{eff}}$ (middle) and minimum visual magnitude of the accretor $M_v$ (bottom) as a function of orbital period. The grey line in the bottom panel indicates the average contribution of the accretion disc for different disc models. The models calculated by Bildsten et al. (2006) use accretors of different masses with hot and cold donors (coming from different formation channels). Figure from Bildsten et al. (2006).
### 2.4. THE ACCRETION DISC STATES

<table>
<thead>
<tr>
<th>Name</th>
<th>$P_{\text{orb}}$ (min)</th>
<th>$q$</th>
<th>$T_{\text{acc}}$ (1000 K)</th>
<th>Distance (pc)</th>
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<td></td>
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<td>&gt; 40</td>
<td>...</td>
<td>1,2</td>
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<tr>
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<td>&gt; 20</td>
<td>...</td>
<td>2,3</td>
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<td></td>
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<td></td>
</tr>
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<td>130</td>
<td>...</td>
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<td></td>
<td></td>
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Table 2.1: Overview of the currently known AM CVn systems and their main properties.

Chapter 3

Observations and data reduction

3.1 Telescopes and instruments

3.1.1 The William Herschel Telescope with LIRIS and Aux

The William Herschel Telescope (WHT) is part of the Isaac Newton Group (ING) of telescopes located at the Roque de Los Muchachos Observatory, La Palma, Spain. It is a 4.2m telescope on an alt-azimuth mount with a classical Cassegrain optical configuration. The autoguider is based on the use of a CCD as detector, which is fed by means of a scanning prism assembly which can rotate about the instrument axis and be moved radially to acquire an appropriate guide star.

The Long-slit Intermediate Resolution Infrared Spectrograph

The Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS) is an infrared imager and spectrograph mounted at the Cassegrain focus of the WHT. LIRIS uses a 1024x1024 HAWAII detector for the 0.8 to 2.5 μm range. The pixel scale is 0.25′′/pixel, yielding a 4.27′ x 4.27′ field of view.

The Auxiliary Port Imager

In addition to the main instrument mounting face, the Cassegrain Acquisition and Guidance Unit has an auxiliary focal station. The Auxiliary Port Imager is mounted here. The detector is a 2148x4200 pixel E2V CCD44-82, with a pixel scale of 0.067′′/pixel and an unvignetted (circular) field diameter of 2.2′. The default mode for the detector is 2x2 binning in slow readout, which saves on readout time by a factor of two while preserving a small pixel scale of 0.134′′/pixel.
3.1.2 The InfraRed Survey Facility and SIRIUS

The Infrared Survey Facility is located at the Sutherland site of the South African Astronomical Observatory. The telescope was constructed by Nagoya University and Nishimura Co. Ltd. in Kyoto. It is a 1.4m classical Cassegrain telescope on an alt-azimuth mount. The effective aperture of the primary mirror is 1395mm, that of the secondary mirror is 382mm. The pointing and tracking accuracies are respectively 10″ rms and 0.3″ per 30s exposure time, which is accurate enough for the telescope not to need guiding. The telescope is cooled with a closed loop of liquid helium.

The Simultaneous 3-colour InfraRed Imager for Unbiased Survey

The Simultaneous three-colour InfraRed Imager for Unbiased Survey (SIRIUS) was constructed by Nagoya University and the National Astronomical Observatory of Japan. Two dichroic mirrors enable the simultaneous three-channel (J: 1.25 μm, H: 1.63 μm, K_s: 2.14 μm) observations with three HdCdTe 1024x1024 HAWAII arrays. The pixel scale is 0.45″/pixel, yielding a 7.7′ x 7.7′ field of view. Details can be found in Nagayama et al. (2003).

3.2 Photometric observations

3.2.1 Infrared observations in general

Astronomical observations are always influenced by the detector with which we observe our objects and by local weather conditions. Because we are interested in the intrinsic properties of the objects we observe and do not want our observations to be dependent on our instrument, we have to correct for these effects. In a large part these corrections are the same for optical and infrared observations. There are however some crucial differences that we have to take into account already when we start observing, in order to avoid problems later when we start the data reduction.

Bias subtracting

To ensure the proper operation of an infrared array, a pedestal level of electrons remain on it. This is called the bias level. The bias level of an infrared instrument changes significantly over the night. Therefore we can’t take bias frames in the beginning of the night and apply these to all our observations, like in the optical. This fact is already taken into account in the design of the infrared instruments we used. The bias is determined automatically before every exposure and subtracted right away.
3.2. PHOTOMETRIC OBSERVATIONS

Dark correcting

Sometimes there is a current running through the array even when it is not illuminated. This current is called a dark current. The dark current in LIRIS is sufficiently small to ignore it, but for SIRIUS a series of ten dark frames per exposure time are taken every night at the end of the night.

Flat fielding

The gain of the infrared array can vary across the chip(s). This is a multiplicative effect we have to take into account. Therefore twilight flat fields have been taken on every night of observation that are used to correct for this effect.

Dithering for bad pixel rejection and sky subtraction

There are a couple of reasons why dithering is used when observing in the infrared. First of all in the infrared the sky contributes significantly to the total flux. Therefore it is impossible to make a long exposure at one point, because the array will saturate quite quickly. Individual images have an exposure time typically $\leq 30$ s. To correct for the contribution of the sky, a sky model is made from the images themselves. By moving the telescope $10''$–$20''$ in a regular fashion after every exposure it becomes easier to make this sky model. A sequence of these slightly moved images is called a dithering pattern. Making a sky model can now be done by combining the images without realigning them, while applying an appropriate rejection mechanism. The most important reason for dithering is however the fact infrared arrays contain a notorious amount of bad pixels. It is hard to map out these bad pixels before the observations and try to avoid putting the object of your interest near one. The solution for this problem is again to make a dithering pattern so that the bad pixels have a different place in every exposure, so that they can be rejected when the images from the dithering sequence are combined.

Superflatting

When making multiple images at the same dither point with WHT/LIRIS another effect needs to be corrected. When the telescope is moved the infrared instrument is resetted. After resetting the instrument is believed to be in a resetting equilibrium, which is the same after every reset. When the instrument makes more than one exposure before moving to the next dither point (and is resetted again) it moves from the resetting equilibrium to the imaging equilibrium after about three exposures. Therefore the subsequent images at the same ditherpoint have to be processed separately until this effect is corrected for. Now that the other effects are taken out, a superflat is created from the differences between those images to correct for this resetting effect. After subtraction of the superflat a collapse effect might show up, that is due to the fact that this resetting has a slightly different offset for the different lines. If this is the case an average column can be subtracted to correct for this effect. This is called the collapse correction.
Recombining

After superflattting, the images in the dithering sequence have to be aligned in order to combine them. When the images are combined they are clipped on the sides as seen from the central position. Because of this the effective field of view will be twice the dithering radius smaller than the field of view of the chip itself. This has to be kept in mind when observing, so that objects of interest (or needed for calibration) don’t end up too close to the sides of the image.

3.2.2 Observations with the WHT

The observations with the WHT were done by P.J. Groot on the 23rd and 24th of February 2007. It involves broad band infrared photometry with LIRIS of the AM Canum Venaticorum stars AM CVn, HP Lib, SDSS J0926, SN 2003aw, GP Com and CE 315 and spectroscopy of AM CVn, HP Lib and GP Com. AM CVn, HP Lib, SDSS J0926, GP Com and CE 315 were also observed in the optical with Aux. An overview of the observations on the 23rd and the 24th are shown in Table 3.1 (this table only shows the data used in this thesis). In addition, narrow band photometry was taken. Unfortunately as yet there are no spectrophotometric standard stars available for calibration and no telluric standards were taken. An overview of the imaging obtained with the WHT is given in Table 3.1.

3.2.3 Observations with the IRSF

The observations with the IRSF were done by myself from the 22nd to the 28th of October 2008. The AM CVn stars ES Cet and CP Eri were both observed for six out of seven of these nights. Individual exposures were 20 seconds. A dithering pattern of fifteen ditherings with a dithering radius of 20″ was used. Table 3.2 gives an overview of the observations. Each night a number of skyflats was taken with an exposure time of 5 seconds. Out of quality considerations, the flats taken on the 24th were also used for the 25th and the flats taken on the 26th were also used for the 27th and the 28th. Every night ten dark frames were taken for each exposure time used that night. An overview of the observations with the IRSF is given in Table 3.2.
### Aux images 23-02-2007

<table>
<thead>
<tr>
<th>Object</th>
<th>Filters</th>
<th>Exp. time (s)</th>
<th># frames</th>
</tr>
</thead>
<tbody>
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<td>–</td>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>Skyflat</td>
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<td>Feige 34 (std)</td>
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<tr>
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</tr>
<tr>
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### LIRIS images 23-02-2007

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<td>1-9-1, 1-9-1</td>
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<tr>
<td>AM CVn (phase res.)</td>
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<td>CE 315 (phase res.)</td>
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### LIRIS images 24-02-2007

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<td>20</td>
<td>2-5-10</td>
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</table>

Table 3.1: Overview of the observations done with the WHT that are used in this thesis. The Dith pat. column represents the dithering pattern in the format: (number of exposures per position) - (number of positions) - (number of sequences). The dome flats on the 24th were taken without dithering, so here the number of frames is given.
### IRSF Observations

#### Evening twilight flats

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<tr>
<td>26-10-2008</td>
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<tr>
<td>27-10-2008</td>
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</tr>
<tr>
<td>28-10-2008</td>
<td>flats of 26-10 were used</td>
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- Table 3.2: Overview of the observations done with the IRSF.
3.3 Data reduction

As described in Paragraph 3.2.1, astronomical data need work before it can be used to do photometry. The way the described actions are performed varies with the instrument used. Most of the work was done with PyRAF scripts written by myself, apart from the first reduction steps of the LIRIS and SIRIUS data, that could easier be done with existing pipelines. PyRAF (STScI website 2008) enables the use of tasks from the astronomical data reduction software IRAF (IRAF documentation 2008) within Python, a powerful programming language. Unless specified otherwise, the default settings of PyRAF 1.6 and IRAF 2.14 were used.

3.3.1 The Aux data and PyRAF

A single PyRAF script was used to subsequently:

1. remove the overscan and trim section from all images with `ccdproc`;
2. combine the bias frames to a single bias image with `zerocombine`;
3. subtract the bias image from all other images with `ccdproc`;
4. combine the flats for the U,B,V,R and I filters with `flatcombine`;
5. flatfield the images of the different objects in the different filters with `ccdproc`.

3.3.2 The LIRIS data and THELI

The LIRIS@WHT cookbook (Schirmer & Santander 2008) was followed for the first steps of the reduction of the LIRIS data. It closely follows the steps described in Paragraph 3.2.1. LIRIS automatically subtracts the bias from the images before they are stored and dark subtraction is not necessary. In the calibration step the flats are processed and the sequence is spread to take into account the different states of the instrument after resetting. The superflats and sky models are calculated to be subtracted in the superflatting step. After the superflatting the sequenced is merged again and a collapse correction is applied (to remove resetting anomalies). Rough astrometry with 2MASS was done using the ‘shift only’ option. Aligning the images was done with the IRAF task `imalign`. Aladin was used to find the world coordinates for the objects in the images, that were used by `ccfind` and `ccmap` to give the images the correct wcs coordinates.

3.3.3 The SIRIUS data and pipeline

The SIRIUS pipeline guide (SIRIUS website 2002) and the update (Nakajima 2005) were used to reduce the data until the sky subtraction. Alignment was done with a separate PyRAF script. The script used `daofind` to find all objects in all images.

Text in `truetype` represents an IRAF task.
An isolated bright object was identified to serve as a reference object. The output of daofind was then used to calculated the shift by looking for the closest object to the reference position, corrected with a nightly shift of the reference image. These shifts were then used by imalign to align and clip all the images of the two objects in the different bands.

### 3.4 Differential photometry

The variability of AM CVn, SDSS J0926, GP Com and CE 315 was studied in the LIRIS $K_s$-band. The variability of ES Cet and CP Eri was studied in the SIRIUS JHK$_s$-bands. In differential photometry the variability of an object is studied by comparing its brightness to a set of references objects believed to be on average non-variable. If an object appeared to have a clear variability of its own it was removed from the set of reference objects. The photometry itself was done with daophot with apertures ranging from 3 to 20 pixels. The results of daophot were used by mkapfile to fit a curve of growth to determine the aperture corrections and the aperture-corrected magnitude with the smallest error. The input variables for the script were:

- the total number of exposures;
- the number of exposure to combine into an image;
- the positions of the AM CVn system and the reference objects;
- the full-width half maximum (fwhm) of the point spread function (psf);
- the section of the image used to estimate the standard deviation in the sky background;
- the saturation level, gain and readout noise of the instrument.

The following steps were performed to build up a lightcurve:

1. The individual exposures were combined with imexam (median combine with average sigmaclipping) to form the series of images to be used for the lightcurve.
2. The headers of the images were updated with the correct average readout noise and gain using hedit.
3. The starting time of the series was taken from the average time of the exposures forming the first image of the series.
4. The elapsed time since the starting time was calculated for each image. The standard deviation in the sky was estimated and the aperture-corrected photometry was performed. This gave a time and instrumental magnitudes. The time of the image and the instrumental magnitudes of the objects in the image was saved in an array. If any of these steps failed or gave a significant error the image would not be used for the construction of the lightcurve.
5. The average magnitude of each object was subtracted and the variability of the object was estimated by the standard deviation around this average magnitude with respect to the error in the determined magnitude.

6. The resulting magnitudes of the reference objects were averaged at each time and subtracted from the magnitude of the AM CVn system. The error on the magnitude of the AM CVn system was taken as the square root sum of the error in the magnitude determination of the system itself and the standard deviation in the magnitudes of the reference objects.

7. A discrete fourier transform was applied to find a dominant period in the lightcurve. If a dominant period was found the whole script was run again, but now combining a different number of images, to check the consistency of the period.

3.5 Absolute photometry

The steps performed for determining the instrumental magnitudes are the same as steps one to four of the differential photometry. Only this time all the images were combined and time information was neglected. After the following calibration steps the magnitudes were corrected for Galactic extinction. Since the details of this vary for the different object we will discuss this Paragraph 4.1.

3.5.1 Calibrating the optical data

The spectrophotometric standard stars Feige 34, BD 33 D2642 and G191 B2B (Oke 1990) were used to calibrating the Aux data. Their spectra (STScI Calspec 2008) as well as the spectrum of α-Lyrae were convolved with the filter throughput curves (ING filter database 2008) to find the magnitudes of the standard stars in those filters in the Vega system. The instrumental magnitudes of the standard stars and objects were corrected for the airmass extinction and the zero points for the different filters were calculated. These zeropoints were applied to find the magnitudes of the AM CVn systems.

3.5.2 Calibrating the infrared data with 2MASS

To calibrate the infrared data the stars in the field with an AAA quality magnitude determination in 2MASS were selected (Cutri et al. 2003). The SIRIUS filter set is not exactly the same as the IRSF filter set. To convert from SIRIUS magnitudes to 2MASS magnitudes and vice-versa we used Nakajima et al. (in prep.). First the SIRIUS magnitudes of our calibration stars were converted from their 2MASS magnitudes to find the SIRIUS magnitudes. The zero points found were applied to find the SIRIUS magnitudes of the AM CVn systems. Nakajima et al. (in prep.) was used again to get the corresponding 2MASS magnitudes of the AM CVn systems.
CHAPTER 3. OBSERVATIONS AND DATA REDUCTION

Figure 3.1: Determination of the colour transformation between LIRIS and 2MASS. When a first order polynomial fit was significantly (see text) better than a zeroth order polynomial fit we used a colour term. Only the J-band has a significant first order colour term. There are no second order colour terms.

To calibrate the LIRIS photometry I started looking for colour terms. In every field I calculated the average zero point. I plotted the deviation from that average for all the fields in the colour-magnitude diagrams that are shown in Figure 3.1. The $\chi^2 / \text{NDF}$ of the fit of a zeroth ($\chi^2_{r0}$) and a first ($\chi^2_{r1}$) order polynomial fit to the colour-magnitude diagram was calculated. An $F_{\chi^21} = \frac{\chi^2_{r1} - \chi^2_{r0}}{\chi^2_{r0}} > 0.1$ was accepted as a significant colour term. There is no significant colour term for the H- and Ks-band. The first order colour term for the J-band was taken into account in the results. There is no second order colour term.
3.6 Spectroscopic observations and data reduction

The spectroscopic observations with WHT/LIRIS where done by P.J. Groot on the 24th of Februari 2007. The ZJ-spec (lrzj8) and HK-Spec (lrlk) grisms have a resolution of R=700, the K-spec (mrk) grism of R=2500. A 1.0" slit was used. Exposures were taken with an ABBA pattern, where the object are 50 pixels further along the slit in B than in A exposures. Consecutive spectra are used to subtract the sky as is explained in Paragraph 3.6.2. An overview of the spectroscopic observations is given in Table 3.3.

3.6.1 Making and applying the bad pixel map and the masterflat

The task lcpixmap from the lirisdr package was executed on the flat field images to correct the shift of the pixels on the detector with respect to their geometrical location. A bad pixel map was created from the combined (average combine without rejection) flats using the IRAF task ccdmask. ccdproc was used to trim the flat field images and apply the bad pixel mask. The processed flat field images were then combined (median combine with average sigma clipping) into a masterflat. Now the object images were run through lcpixmap and ccdproc to correct the pixel mapping, fix the bad pixels, trim the image and flatfield them.

3.6.2 Sky subtraction and spectrum extraction

The sky subtraction was done by making the images A-B and B-A from every AB pair in the ABBA sequence. From here on the kpnoslit package was used for the reduction. The spectra that showed up positive were extracted in 1D-format using the apall task. The aperture was found automatically by apall and was centered and traced interactively. We summed over seven dispersion lines (the average width of the positive features in the spatial direction) and subtracted the background. In the case of the HK- and K-spectra of GP Com, the trace wasn’t found clearly in every image.
Therefore the trace was determined in the best sky subtracted A- and B-images. Those same traces were then used in all A- and B-images. Examination of the position of the sky lines in the different reference images of GP Com shows a variation of about 0.3 pixels along the dispersion axis; examination of the variation in the position along the coordinate axis of a bright emission line gave the same central pixel for every image. The fact that all variations are smaller than a pixel justifies our choice of using the same traces for all A- and B-images.

3.6.3 Wavelength calibration

Since there were no specific arcs taken, the sky lines in the original images were used for the wavelength calibration. So A was used as the arc image for A-B and B was used as the arc image for B-A. The arc spectrum of the sky lines was extracted by using the database file of the object image as a reference and not applying the background correction. The skylines were identified first by eye with Rousselot et al. (2000) complemented with Osterbrock et al. (1996) and Osterbrock et al. (1997) for the bluest part of the ZJ-spectra. The main skylines in the appropriate wavelength regimes were put in a lineslist. All spectra were added at first to identify the most prominent skylines by eye as input to the IRAF task identify. The task reidentify was then run on all the individual arc spectra to optimize the calibration. The task dispcor was used to assign the dispersion solutions to the object spectra. The ZJ-spectra run from 0.89 to 1.56 µm with a scale of 6.0 Å/pix. The HK-spectra run from 1.39 to 2.39 µm with a scale of 9.7 Å/pix. The K-spectra run from 1.92 to 2.40 µm with a scale of 4.6 Å/pix.

3.6.4 Normalization and cleaning

No telluric standards were taken so flux calibration could not be performed. We therefore chose to get rid of the continua by normalizing the spectra using the kpnoslit task continuum. Since we are limited by the atmospheric transparency in all our bands we have cut out wavelength ranges where this plays a big role. We also discarded the ends of our spectra based on the noise in the spectra themselves. We therefore have good data in the wavelength ranges 0.90–1.12 µm and 1.16–1.30 µm (ZJ-spec), 1.50–1.78 µm (HK-spec) and 2.03–2.25 µm (HK-spec and K-spec).
Chapter 4

Results

4.1 Apparent magnitudes and spectral energy distributions

The three brightest systems, HP Lib, AM CVn and GP Com are also contained in 2MASS. The 2MASS data are not correct for Galactic extinction. The magnitudes we found before correcting for Galactic extinction are consistent with 2MASS. The magnitudes I found for AM CVn and HP Lib are consistent with 2MASS in all bands, those of GP Com about 0.3 magnitudes fainter than 2MASS.

To perform the Galactic extinction correction we used the total extinction in the V-band, $A_V$, values of Roelofs et al. (2007a) for AM CVn, HP Lib and GP Com. For CE 315 we assume no Galactic extinction since it is out of the Galactic plane and at a short distance (Thorstensen et al. 2008). We then assume an $R_V = 3.1$ extinction law to get the extinction in all our bands with the use of Cardelli et al. (1989). For ES Cet, CP Eri and SDSS J0926 we don’t have a distance and we don’t have an $A_V$. They are all however expected to be quite far away, so we use the values from the NASA Extragalactic Database, based on Schlegel et al. (1998) to correct with the total extinction in the line of sight. The used values for $A_V$ are given in Table 4.2. Table 4.1 shows the extinction corrected magnitudes found for the AM CVn systems.

I converted the magnitudes into the spectral energy distributions (SEDs) by convolving the Vega spectrum (STScI Calspec 2008) with the filter transmission curves to get the flux of Vega at the effective wavelength of the filter. The flux of Vega for a filter is given by

$$ F_\lambda(\lambda_{\text{eff}})_{\text{Vega}} = \frac{\int F_\lambda(\lambda)_{\text{Vega}} \cdot t(\lambda) d\lambda}{\int t(\lambda) d\lambda}, $$

(4.1)

at the effective wavelength of that filter.
Table 4.1: The extinction-corrected apparent magnitudes of the AM CVn systems. Note that the high state systems have a typical \( V_0 - K_0 = 0.97 \) $\pm$ 0.05. GP Com has a high state system with $\Delta V_0 - K_0 = 0.57$. CE 315 even a $\Delta V_0 - K_0 = 0.98$.

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<th>$K_0$</th>
<th>$H_0$</th>
<th>$J_0$</th>
<th>$I_0$</th>
<th>$R_0$</th>
<th>$V_0$</th>
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4.1. APPARENT MAGNITUDES AND SPECTRAL ENERGY DISTRIBUTIONS

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</tr>
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<td>0.02</td>
</tr>
<tr>
<td>CE 315</td>
<td>0</td>
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</tbody>
</table>

Table 4.2: Total extinction used for our AM CVn systems in the V-band. Cardelli et al. (1989) with an $R_V = 3.1$ extinction law was used to correct the obtained magnitudes for Galactic extinction.

$$\lambda_{\text{eff}} = \frac{\int \lambda \cdot t(\lambda) d\lambda}{\int t(\lambda) d\lambda}, \quad (4.2)$$

with $t(\lambda)$ the filter transmission.

The fluxes of the AM CVn systems at the effective filter wavelength are then found by using the definition of the Vega system

$$F_\lambda(\lambda_{\text{eff}})_{\text{obj}} = F_\lambda(\lambda_{\text{eff}})_{\text{Vega}} \times 10^{-\frac{m_{\text{filt}}}{2.5}}, \quad (4.3)$$

with $m_{\text{filt}}$ the apparent magnitude of the object in that filter.

Both the Galactic and atmospheric extinction are now removed. The extinction corrected SEDs of AM CVn, HP Lib, SDSS J0926 are shown in Figures 4.1 and 4.2. GP Com will be discussed separately in Paragraph 4.4, CE 315 in 4.5. For comparison, SEDs of AM CVn and HP Lib can be found in Roelofs et al. (2007a). We did not find any new information for these two systems, so we don’t analyse these SEDs any further. For SDSS J0926, which we found in quiescence, we have no distance determination. Therefore we have a degeneracy between the distance and the temperature of the systems that hinders further analysis.
Figure 4.1: Spectral energy distributions of AM CVn (top) and HP Lib (bottom).
4.1. APPARENT MAGNITUDES AND SPECTRAL ENERGY DISTRIBUTIONS

Figure 4.2: Spectral energy distribution of SDSS J0926.
4.2 Lightcurves

Phase-resolved photometry was done with the $K_s$-band images of AM CVn, CE 315 and SDSS J0926 with the WHT. All lightcurves shown for AM CVn, CE 315 and SDSS J0926 are thus in the $K_s$-band. Phase-resolved photometry of ES Cet and CP Eri in the J-, H- and $K_s$-band was obtained with the IRSF.

4.2.1 AM CVn

The method by which we created the lightcurves is explained in Paragraph 3.4. The normalised lightcurves of AM CVn and the reference objects, where ten exposures are combined into a single image is shown in Figure 4.3. For each point of this lightcurve, the average magnitude offset (based on all available reference stars) is determined, i.e. at a given time the difference between the observed and mean magnitude is determined for all reference stars. This difference is then averaged per timing and subtracted from the magnitude of the target (AM CVn). The reference stars are thus explicitly considered stable. Figure 4.4 shows the differentially-corrected lightcurves of AM CVn when ten, twelve, fifteen, seventeen and twenty exposures are combined into an image. Their discrete fourier transforms are shown in Figure 4.5. We see that we combine more exposures the errors in the differential magnitudes go down only slightly. When we do this, the Nyquist frequency $f_{Nyq} = 2/\Delta T$ with $\Delta T$ the average time between two points, which is the maximum frequency that can be identified unambiguously, drops rapidly.

![Figure 4.3: Normalised lightcurves of AM CVn and the three reference objects used for the differential photometry.](image)

From Figure 4.5 we can conclude that there is no clear periodicity in the signal. The orbital period of AM CVn is 1029s (Skillman et al. 1999). The dominant photometric period is the superhump of 1051s. Our observations cover about four orbital cycles. From Figure 4.4 we can see there is variability of the order of 0.1 magnitudes, whilst the errors are of the order 0.05 mag. The amplitude of the superhumps in AM CVn in
4.2. LIGHTCURVES

Figure 4.4: From top to bottom: differentially-corrected lightcurves of AM CVn when ten, twelve, fifteen, seventeen and twenty exposures are combined into a single image.
Figure 4.5: From top to bottom: discrete fourier transforms of the lightcurves of AM CVn when ten, twelve, fifteen, seventeen and twenty exposures are combined into a single image. The orbital frequency is indicated by the dashed line. The fourier transform stops at the Nyquist frequency.
4.2. LIGHTCURVES

the optical are of the order 0.04 mag (Smak 1967; Warner & Robinson 1972; Solheim et al. 1984).

### 4.2.2 CE 315

The situation for CE 315 is harder. With an orbital period of 3906s (Ruiz et al. 2001), we have only one orbital cycle of measurements at our disposal. The lightcurve is shown in Figure 4.6. CE 315 is a low state AM CVn system, so the accretion disc is thought to be optically thin and thermal-viscously stable and no variability is seen in the optical wavelengths (Woudt & Warner 2001; Nelemans 2005). The variations we find in the infrared are not much larger than the measurement errors and no significant features were found in the discrete fourier transform. It would be worthwhile to obtain a longer coverage of this object.

![Figure 4.6: Lightcurve of CE 315.](image)

### 4.2.3 SDSS J0926

SDSS J0926 is an eclipsing AM CVn system with an orbital period of 1699s (Anderson et al. 2005). When combining from six up to thirteen exposures into an image we found a consistent periodicity of 871 ± 27s with an amplitude of 0.19 ± 0.03 mag. Both the period and the amplitude are consistent with the optical observations that show a double humped profile Marsh (2008). The lightcurve combining ten exposures into a single image and its discrete fourier transform are shown in Figure 4.7.
Figure 4.7: The $K_s$-band lightcurve (top) of SDSS J0926 and its discrete fourier transform (bottom), when ten exposures are combined into a single image. The dotted line in the discrete fourier transform indicates half the orbital period.
4.2.4 ES Cet

ES Cet was discovered as an AM CVn by Warner & Woudt (2002). The photometric period of 621s is argued to be a superhump from the accretion disc by Warner & Woudt (2002). Espaillat et al. (2005) argues for a direct impact scenario with the period being orbital. Wood (2009) suggests an intermediate model (see discussion in Paragraph 2.4.1), but does not discuss the nature of the observed photometric period for ES Cet in particular. We obtained infrared lightcurves of ES Cet, consisting dithering series of fifteen exposures where the first and the last image of each series are separated by about 400s. In order not to average out too much of the variations within a period, we could to combine only five exposures into a single image. The lightcurve this gives for the J-band is shown in Figure 4.8. The amplitude of the variation in the optical is about 0.1 mag Espaillat et al. (2005), which is the size of our errors on the photometry. The same holds for the H- and the Ks-band. In the fourier transform (Figure 4.9) we have marked where the optical frequency (and its first two harmonics) would be located. There is no excess power in the J-band light curve at these frequencies.
Figure 4.8: J-band lightcurve of ES Cet obtained in a six nights with the IRSF.
Figure 4.9: Fourier transform of the J-band lightcurve of ES Cet. The dashed lines indicate the dominant photometric period in the optical and its first two harmonics.
4.2.5 CP Eri

With CP Eri we encountered a similar problem. The orbital period of CP Eri in the optical is 1701s (Abbott et al. 1992), but the main photometric period in the optical is the superhump period of 1740s (Howell et al. 1991). We therefore could go further than combining a single dithering series of exposures into an image. Unfortunately CP Eri is quite faint, with 18.64 ± 0.17 mag in the J-band. A typical $V - K_s = \pm 0.5$ (minus for high state, plus for low state) suggests that CP Eri was in quiescence at the time of observation, with $V \sim 19.1$, close to its lowest measured quiescent value of $V = 19.7$. Because of this, the photometry failed for a lot of individual dithering series. The best lightcurve we could construct is shown in Figure 4.10; its fourier transform is shown in Figure 4.11. The photometric variability of CP Eri in quiescence was measured by Howell et al. (1991) to be about 0.2-0.4 mag in the B-band and 0.1-0.2 mag in the V-band. The variations in the J-band are of similar size, but we see no convincing periodicity.
Figure 4.10: J-band lightcurve of CP Eri in six nights with the IRSF.
Figure 4.11: Fourier transform of the J-band lightcurve of CP Eri. The dashed line (right) indicates the orbital period. The dash-dotted line (left) indicates the superhump period.
4.3 Spectroscopy of HP Lib

The ZJ- and HK-spectrum of HP Lib is shown in Figure 4.12. The spectrum is not flux calibrated, but we didn’t subtract the continuum to show its presence. The absorption features seen between 0.93 and 0.97 µm are atmospheric. There are no other significant emission or absorption features.

Figure 4.12: Spectrum of HP Lib in the ZJ- (top) and HK-region (bottom).
4.4 Photometry and spectroscopy of GP Com

The spectrum of GP Com shows emission lines and little continuum. The raw spectrum in the ZJ- and HK-band is shown in Figure 4.13.

![Figure 4.13: Average low resolution spectrum of GP Com. The three IR photometric pass bands we used for the photometry are indicated with the dashed lines.](image)

We normalised the spectrum by dividing by the continuum to get an idea of the relative strength of the emission lines. We know however that in the optical GP Com shows flaring behaviour. The phases of the flares are different for all the HeI lines and the continuum Morales-Rueda et al. (2003). Since we averaged only a very limited amount of spectra, these relative strengths should be interpreted with caution. The normalised spectrum of GP Com with the identified emission lines is shown in Figure 4.14. Table 4.3 gives more information on the emission lines. Figure 4.15 shows plots of the emission lines in velocity space.

From Paragraph 2.4.4 we know that the spectrum of GP Com is dominated by the primary at optical wavelengths. Roelofs et al. (2007a) determined the distance to GP Com to be 75 ± 2 parsec. Using Nelemans (2005) citing Steeghs (priv. com.) we take GP Com to be a typical 0.6 $M_\odot$ DB white dwarf. Using the approximate mass-radius relation for a fully degenerate helium white dwarf from Warner (1995a)
4.4. PHOTOMETRY AND SPECTROSCOPY OF GP COM

Figure 4.14: Normalised spectrum of GP Com with identified emission lines. The left part is the ZJ-spectrum, the middle part is from the HK-spectrum, the right part is the K-spectrum (higher resolution).

\[ R_1 = 0.73 \times 10^9 \left( \frac{M_1}{M_\odot} \right)^{-1/3}. \]  \hspace{1cm} (4.4)

gives us its radius of \(8.7 \times 10^8\) cm.

The spectral energy distribution of GP Com, overplotted with black bodies of different temperatures, is shown in Figure 4.16.

We see that the amount of flux corresponds best to a black body of about 13 kK. From Koester (1980) we know that DB white dwarfs of these temperatures are well approximated by black bodies as the absorption lines become very narrow below 15 kK. The conclusion of Bildsten et al. (2006) that the accretor is only 11 kK was based on a wrong distance determination of 70 pc.
Table 4.3: Lines identified in the spectrum of GP Com. All lines show a double line profile. $\lambda_{\text{lit}}$ is the literature value of the line (Peter van Hoof 2009), $\lambda_c$ is the central wavelength in my spectrum. $v_l$ and $v_r$ are the velocities of the left and right peak respectively, when fitted with a single width double gaussian; $\text{Fwhm}$ is the full width half maximum of those gaussians. $\text{Eqw}$ is the average equivalent width of the line as a whole.

<table>
<thead>
<tr>
<th>Line</th>
<th>$\lambda_{\text{lit}}$ (µm)</th>
<th>$\lambda_c$ (µm)</th>
<th>$v_l$ (km/s)</th>
<th>$v_r$ (km/s)</th>
<th>$\text{Fwhm}$ (µm)</th>
<th>$\text{Eqw}$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He I</td>
<td>1.0833</td>
<td>1.0836</td>
<td>-498</td>
<td>498</td>
<td>0.0028</td>
<td>-0.0285</td>
</tr>
<tr>
<td>He I</td>
<td>1.7007</td>
<td>1.7011</td>
<td>-511</td>
<td>564</td>
<td>0.0033</td>
<td>-0.0047</td>
</tr>
<tr>
<td>He I (HK)</td>
<td>2.0587</td>
<td>2.0584</td>
<td>-670</td>
<td>393</td>
<td>0.0059</td>
<td>-0.0235</td>
</tr>
<tr>
<td>He I (K)</td>
<td>2.0587</td>
<td>2.0584</td>
<td>-640</td>
<td>364</td>
<td>0.0048</td>
<td>-0.0295</td>
</tr>
</tbody>
</table>

Figure 4.15: Profiles of the emission lines in GP Com. The resolution is 167 km/s for the 1.0833 µm line, 171 km/s for the 1.7007 µm line and 67.6 km/s for the 2.0587 µm line. For the 2.0587 µm line we use that of the higher resolution K-spectrum. We see no signal of the central spike, that is a prominent feature of GP Com’s emission lines in the optical and UV.
Figure 4.16: Spectral energy distribution of GP Com with black body accretor models of different temperatures. We see there is a flux excess in the $K_s$-band.
Figure 4.17: Behaviour of $\chi^2$ as a function of $T_{\text{eff}}$ of the accretor for the SDSS spectrum of GP Com.

Figure 4.18: Fit of a 13 kK Koester DB model to the SDSS spectrum of GP Com.
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Figure 4.19: Behaviour of $\chi^2$ as a function of $T_{\text{eff}}$ of the accretor for the VLT spectrum of GP Com.

Figure 4.20: Fit of a 13 kK Koester DB model to the VLT spectrum of GP Com.
Fits to the shape of GP Com’s spectrum from the Sloan Digital Sky Survey (SDSS) and the average VLT spectrum from Steeghs (priv. com.), with the method from Buijs (2008), indicate this is correct. For the SDSS spectrum we find a temperature of $13 \pm 1$ kK at a distance of $87 \pm 8$ pc with a surface gravity $8.0 < \log(g) < 8.5$. The behaviour of the reduced $\chi^2$ of the fits of different temperatures is shown in Figure 4.17. The best fit is shown in Figure 4.18. For the VLT spectrum we also find a temperature of $13 \pm 1$ kK at a distance of $76 \pm 7$ pc with $8.0 < \log(g) < 8.5$. The behaviour of the reduced $\chi^2$ of the fits of different temperatures is shown in Figure 4.19. The high $\chi^2$ in due to underestimation of the errors, but that doesn’t influence the resulting parameters. The best fit is shown in Figure 4.20.

Schmidt (1996) discusses in detail how to translate $\log(g)$ and $T_{\text{eff}}$ into a mass for the accretor. Unfortunately in GP Com we don’t see the wings of the accreting white dwarf, so can’t use the gravitational redshift method. What we can do is use the surface gravity

$$g = \frac{GM_1}{R_1^2},$$

(4.5)

together with Equation 4.4 to find

$$\frac{M_1}{M_\odot} = 9.16 \times 10^{-6} \cdot 10^{-\frac{8}{2} \log(g)}.$$  

(4.6)

The fact that $\log(g) \geq 8.0$ fits better indicates a mass of at least $0.58 M_\odot$.

Compared to our simple black body model we see that there is excess flux in the U-band (possibly due to the hot spot or boundary layer) and, more interestingly, the Ks-band. The fact that most of the spectrum is well described by the black body gives us confidence that we can use the excess flux in the Ks-band to put upper limits on the contributions of colder parts of the system.

When we subtract the flux from a 13 kK black body we are left with $1.19 \times 10^{-17}$ erg/cm²/s/Å in the Ks-band ($\lambda_{\text{eff}} = 2.147 \ \mu m$) and $0.58 \times 10^{-17}$ erg/cm²/s/Å in the H-band ($\lambda_{\text{eff}} = 1.699 \ \mu m$). We see no flux excess in the J-band, so we assume that any other source will contribute less than 20% (high estimate of the measurement error) of the total flux, limiting the flux in the J-band to a maximum of about $2.29 \times 10^{-17}$ erg/cm²/s/Å.

We see from the raw spectrum (Figure 4.13) that considerable flux in the Ks-band is in the emission line. To estimate the maximum possible donor contribution we subtract this from the total flux excess. Figure 4.21 shows the flux in counts of the spectrum in the Ks-band region. The shaded area is assumed to be due to the accretion disc. We now calculate the contribution of the disc by calculating the total flux $F_t$ in both the spectra with:

$$F_t = \int \frac{hc}{\lambda} \cdot t(\lambda) \ \text{d}\lambda$$

(4.7)

The flux in the spectrum with the emission line is ten percent higher than in the
4.4. PHOTOMETRY AND SPECTROSCOPY OF GP COM

Figure 4.21: Spectrum of GP Com in the K$_s$-band region. The flux in the shaded area is assumed to be due to the accretion disc. It is calculated to contribute 10% percent of the total flux in the K$_s$-band.

spectrum where we cut out the emission line. So we use $1.07 \times 10^{-17}$ erg/cm$^2$/s/Å as the maximum flux due to the donor at $\lambda_{\text{eff}} = 2.147$ μm.

From Nelemans (2005) citing Steeghs (priv. com.) we take the mass-ratio of GP Com to 0.018, yielding a donor mass of 0.0108 $M_\odot$. When we use the mass-radius relation for such light objects (Zapolsky & Salpeter 1969; Rappaport & Joss 1984) in the form of Nelemans et al. (2001a)

$$R_2/R_\odot = 0.0106 - 0.0064 \ln (M_2/M_\odot) + 0.0015(M_2/M_\odot)^2.$$  \hfill (4.8)

This gives us a secondary radius of $2.75 \times 10^9$ cm. We can also apply the Roche lobe filling condition and approximate the size of a sphere with equal volume as the Roche lobe of the secondary with Eggleton (1983)

$$R_L = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} a.$$ \hfill (4.9)

To find $a$ we can use Kepler’s third law (Equation 2.1) in the form of Warner (1995a)

$$a = 3.53 \times 10^{10}(M_1/M_\odot)^{1/3}(1 + q)^{1/3}P_{\text{orb}}^{2/3}(h) \text{ cm},$$ \hfill (4.10)

with $P_{\text{orb}}(h)$ the orbital period of the binary in hours.

Taking the orbital period to be 0.776 hours Morales-Rueda et al. (2003) and again $M_1 = 0.6M_\odot$ and $q = 0.018$, we find $a = 2.529 \times 10^{10}$ and $R_L = 3.11 \times 10^9$ cm.
CHAPTER 4. RESULTS

Figure 4.22: The flux excess in the H- and K$_s$-band and the upper limits for the donor contribution in the J-band of GP Com. Donor black body models of different temperatures are overplotted. We see that the donor can't be hotter than 2500 K.

This is an indication that the donor is about 10% larger than a fully degenerate, zero temperature, white dwarf would be. These calculations are only weakly dependent on the mass of the primary in the regime $0.5 < M_1/M_\odot < 0.7$ as the we typically see dependencies of $M_1^{1/3}$. We therefore assume the donor to be not fully degenerate from Equation 4.8, but rely on the Roche lobe filling condition from Equation 4.9. Figure 4.22 shows black body spectra of donors with different temperatures. The flux excess in the K$_s$-band that can be due to a donor and the upper limit on the donor contribution in the H-band are indicated in the figure.

If we take the accretor to be only $0.5M_\odot$ the donor can’t be larger than a zero temperature white dwarf to satisfy the Roche Lobe filling condition. In this case we find the temperature of the accretor to be 12 kK. If on the other hand we take the accretor to be $0.7M_\odot$ the donor will have a radius 20% larger than that of a zero temperature white dwarf to satisfy the Roche Lobe filling condition. In that case we find the temperature of the accretor to be 14kK. In all these three situation we find no flux excess in the J-band and the flux excess in the H- and K$_s$-band to be of the same order. From this we can conclude that the donor is no hotter than 2500 K.
4.5 Spectral Energy Distribution of CE 315

For CE 315 we use a distance of 90 pc from Thorstensen et al. (2008), a 0.6 $M_\odot$ accretor and a mass-ratio $q = 0.0125$ from Nelemans (2005) after Steegs (priv. com.). We use the same strategy as for GP Com. The SED with overplotted black bodies is shown Figure 4.23.

We now take the accretor to be a 8000 K white dwarf. We see a small flux excess in the $K_s$-band of $0.23 \pm 0.17 \times 10^{-17}$ erg/cm$^2$/s/A. In the H- and the J-band we see no flux excess, so we again take an upper limit of 20% of the total flux in the band. We use equations 4.10 and 4.9 to find the donor to have a radius of $3.45 \times 10^9$ cm. Whereas from the zero temperature donor (Equation 4.8) we would find $2.94 \times 10^9$ cm. Using the Roche lobe filling solution leads to Figure 4.24, from which we can conclude that the donor can be no hotter than 1500 K.
Figure 4.24: The flux excess in the $K_s$-band and the upper limits for the donor contribution in the H- and the J-band of CE 315. Donor black body models of different temperatures are overplotted. We see that the donor can’t be hotter than 1500 K.
Chapter 5

Discussion

5.1 Overview of results

In this dissertation I determined the infrared magnitudes of eight AM CVn systems. For the three of brightest systems, AM CVn, HP Lib and GP Com, 2MASS magnitudes were already available and are consistent with our results. For the other five systems, ES Cet, SDSS J0926, CP Eri, 2003aw and CE 315 we made the first infrared observations and determined their magnitudes in the J-, H- and Ks-bands. I analysed spectroscopy of HP Lib and found no significant emission or absorption features. I obtained infrared lightcurves of ES Cet and CP Eri. The quality of the lightcurves was limited by the short orbital periods and faintness of the systems. I found no periodicity in any of the infrared bands for ES Cet and CP Eri. I did phase resolved photometry of AM CVn, SDSS J0926 and CE 315 in the Ks-band. AM CVn shows a variability of the order 0.2 mag, but no periodicity. SDSS J0926 shows variability consistent with the periodic optical variability due to the eclipsing nature of the system. Within our limited sample of measurement I found no significant variability in CE 315. By analysing the SED of CE 315 we found it has a 8000 K accretor and a donor no hotter 1500 K.

5.2 GP Com

Three He I emission lines were found in the near infrared spectrum of GP Com. The central spike that is a prominent feature in the optical was not found in the infrared. Most of the spectral energy distribution of GP Com is consistent with a 13 kK black body model of the accretor. In the Ks-band we found a flux excess with respect to this model. In Paragraph 4.4 we show that a 2500 K is compatable with our observations and would explain the flux excess completely. A 2000 K donor would contribute at least half of the flux excess and about 30% of the total flux. A 1500 K donor would contribute only 6% of the total flux; a 1000 K donor only 1%. A colder donor would mean there a considerable contribution from other components of the system, such as
the accretion disc. Unfortunately we don’t have a good accretion disc models for the optically thin disc in GP Com.

If the accretor is lighter than $0.5 M\odot$ then the donor will become bigger than the Roche lobe. This means that the accretor has a temperature of at least 12 kK. The three independent determinations of the accretor temperature we show in Paragraph 4.4 all yield the same temperature of 13 kK. If we look back at Figure 2.7 we see that from the evolutionary models from Bildsten et al. (2006) that we are dealing with a heated accretor. This indicates that there has been a relatively fast evolution, i.e. a relatively high mass transfer rate, in the past. On the other hand, Roelofs et al. (2007a) compared different mass-radius relations (for an estimated donor mass) to the evolutionary tracks of the Nelemans et al. (2001a) population synthesis models and found a degenerate donor to be preferred over a semi-degenerate one. Combining all this, a $0.6 M\odot$ accretor with a donor, about 10% bigger than a 0 K white dwarf, being probably about 2000 K (Panei et al. 2000) seems the most likely scenario.

5.3 Recommendations for future research

The shape of the emission lines in the infrared is different from the emission lines in the optical. The central spike seems to loose strength towards the redder wavelengths as can be seen in Figure 5.1.

CE 315 and GP Com are the only systems in which we see the central spike. In both these systems we also see a UV exces. The fact that central spike is produced near the accreting white dwarf (Morales-Rueda et al. 2003), which is a hot region in the system, and that it looks to be stronger at shorter wavelengths suggests the central spike and the UV excess may be related. This would be worth investigating further, for instance by examining models of inner the regions of the accretion disc and the boundary layer. Morales-Rueda et al. (2003) suggest that the central spike is caused by forbidden He I transitions. They give a short analyses of the probabilities of the forbidden transitions on the basis of Beauchamp & Wesemael (1998). Analysis of the central spike at larger wavelength may contribute to describing the central spike in more detail, by comparing its strength to the transition probabilities for the different forbidden transitions under different conditions. The X-shooter spectrograph for the VLT, that will be commissioned soon, can be instrumental in this, because of its capability to take spectra from 3000 Å to 2.5 μm in a single shot. The difference in the flaring behaviour between different lines and the continuum can than be studied with a much longer wavelength coverage.

It is quite likely that the optically thin accretion disc contributes significantly further in the infrared. Unfortunately we don’t have a good model for GP Com’s accretion disc. Optically thin accretion discs are less well modelled than their optically thick counterparts, due to larger contributions of non-thermal processes. Furthermore, the rate of mass-transfer and the inclination are not very well constrained. It would be worthwhile to come up with a set of accretion disc models applicable to GP Com. We can look how different temperature donors would contribute further in the infrared. The
5.3. RECOMMENDATIONS FOR FUTURE RESEARCH

contribution of a Roche lobe filling donor when we assume a $0.6M_\odot$ accretor of 13 kK is shown in Figure 5.2. The Spitzer telescope could be used to compare those to the spectral energy distribution up to 160 $\mu$m. Deviation from the shapes plotted in Figure 5.2 will give information on the accretion disc contribution.

For CE 315 the constraints on the donor can be tightened by more accurate photometry and by determining the donor contribution from spectroscopy and further accretion disc modelling. Furthermore, similar studies could be performed for the other low state systems SDSS J1411 and SDSS J1552. Parallax measurements for these systems would be necessary. These would also help to further constrain the space density of the AM CVn population. The same thing holds for the newly discovered SDSS J0804 (Roelofs et al. 2008), possibly the first magnetic AM CVn, discovered in a campaign that could yield up to forty more AM CVn systems. Future discoveries of low state systems, as well as outburst systems when they are confirmed to be in a low state, could be included as well.
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3.3 Overview of the spectroscopic observations with WHT/LIRIS.

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4.3  Lines identified in the spectrum of GP Com. All lines show a double line profile. $\lambda_{\text{lit}}$ is the literature value of the line (Peter van Hoof 2009), $\lambda_c$ is the central wavelength in my spectrum. $v_1$ and $v_2$ are the velocities of the left and right peak respectively, when fitted with a single width double gaussian; $\text{Fwhm}$ is the full width half maximum of those gaussians. $\text{Eqw}$ is the average equivalent width of the line as a whole.

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