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The Completeness of Cataclysmic Variables in the spectroscopic database of the Sloan Digital Sky Survey

by

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Dissertation submitted to obtain the degree of Master in Astronomy and Astrophysics

Academic year 2008-2009

Acknowledgements

When you reach the point where you can say (or scream), "I finished!", you start to think about the whole year of research that has been put into this one stack of papers and you realise how much work you could not have done without the help and support of so many people. At that point you know that you have not finished yet. The most important thing that still needs to be done before you can say that you successfully finished your thesis, is to say a few massive "Thank you!"s.

First of all – not because that is how it is supposed to be but because it is the best way to express my gratitude – I would like to thank my supervisor Dr. Boris Gänsicke from the University of Warwick. Next to the fact that he made it possible for me to do my Erasmus year in England and that he was my supervisor who helped me during the past year with his scientific experience so I could make a successful master thesis, he was there as a person for whatever other, even personal, problems I had. To him I say a first massive "Thank you!".

Secondly, I have to thank my "Erasmus-buddy" Steven Bloemen. During the past year he had to listen to all my stories (going from each book I read and each episode of Grey's Anatomy I saw to every social or concert I did with the Wind Orchestra), he was there to help me with whatever problem I had with whichever programming language I was trying to learn. But most importantly, he was there as a friend who knew how it felt to be far away from family and friends from home and who was a solid shoulder to lean on. A second sincere "Thank you!".

The next group of people I want to thank is the Instituut voor Sterrenkunde in Leuven. Roy Østensen as my co-promotor was there if I needed help. Even though I have not used that help a lot, it does not mean that I did not know I could reach him, for which I am most grateful. I want to thank the Instituut as a whole for the opportunity they gave me to do this Erasmus year without any problem. They let me do the project observing run at La Palma one year earlier than usual so that doing an Erasmus could be nicely combined with the project module. Apart from that I would like to thank all my fellow astronomy students with who I had a lovely time last year. I enjoyed the Astronomical Activities, the coffee breaks, the trip to London, etc. When we had a lot of work during Christmas break last year, it was an enormous support for

me to have you guys (and girls) around for both the help and the breaks from work. My third incredible "Thank you!".

The second group of people I would like to thank are all my (other) friends. First of all I would like to show how grateful I am to all the people from home that stayed in contact during the passed year I was abroad. It has not always been easy to hear or see each other, but somehow you always managed to be there to show your support, help and friendship. For that, I am most thankful. A second group of friends are the new ones I made in England. Both my physics and Wind Orchestra friends were there when I wanted to go out, watch a film or just meet for coffee. It has been incredible meeting you all and I really hope we can stay in contact. This is my one but last big "Thank you!".

Last but not least (quite cliché, but then, a lot of clichés are very true) I want to express my love and gratefulness to my parents, my grandmother, my two brothers Stefan and Kristof and their wifes Ine and Tatiana. To my grandmother I want to say *"Oma, ik ben je ongeloofelijk dankbaar voor alle liefde die je me gegeven hebt. Je stond altijd klaar voor ons en bent een belangrijk steunpunt in mijn leven."*. Stefan and Kristof, ever since we were young you have been there for me. I am incredibly proud of both of you and hope that some day I will be able to thank you for all you have done to bring me at this point. Ine and Tatiana, you are like sisters to me and have been a major support during the last years, thanks for that. To mam and dad, I want to say the following. I am really grateful that you have given me the opportunity to go on Erasmus. You were afraid of losing me, but you have no idea how much more you have won me. Thank you for all the love you have surrounded me with these past 23 years. During the last year I have realised how much I need my family around me. My last and eternal "Thank you!" goes to you, my family.

Ilse
Leamington Spa, 7 June 2009

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Chapter 1

Introduction

1.1 Close binary systems

A clear night's sky reveals millions of bright objects, some bigger than others. Lenses or telescopes can help to see the difference between point sources[1] (like stars) and extended objects (galaxies). However, not all point sources are single objects. More than half of the stars in the Universe belong to a binary system. This means that more than half of the stars have a companion star gravitationally bound to it, both rotating around a common centre of mass. Only five to ten percent of these systems are visual binaries where the two stars can be distinguished using optical lenses or telescopes. The other systems contain objects that are rotating so close around each other that they cannot be visually resolved anymore and they appear to be just one single point source at the sky. These last systems are referred to as *close binary systems* and are the type of binaries that will be used and described here.

1.1.1 Roche lobe mass transfer

One of the basic things to know about a star is its mass. When the star is part of a binary, its mass can be determined from the orbital period of the system, the size of the orbit and the velocity at which both objects are rotating around their common centre of mass[2], which is much easier than to calculate the mass of a single star with nothing bound to it. Binaries are thus very important for astronomers. In close binary systems however mass can be transferred from one star to the other. This happens because the shape of these mass transferring stars is distorted due to the near presence of the companion star. To understand this, the concept of *Roche lobe* and *Roche volume* must be introduced. The Roche lobe of a star in a binary system is the boundary surface of the

[1] Point sources are localized sources of light with a negligible extent which obey the Point Spread Function (PSF). This describes the luminosity spread of objects at the sky that can be approximated as single points.

[2] The sum of the masses of both objects can be computed with Kepler's third law of planetary motion by using the period and the separation of the binary. The mass ratio can be found by calculating the ratio of the radial velocities of both objects as done in e.g. Pyrzas et al. (2009). These two values together give the masses of the two components of the binary.

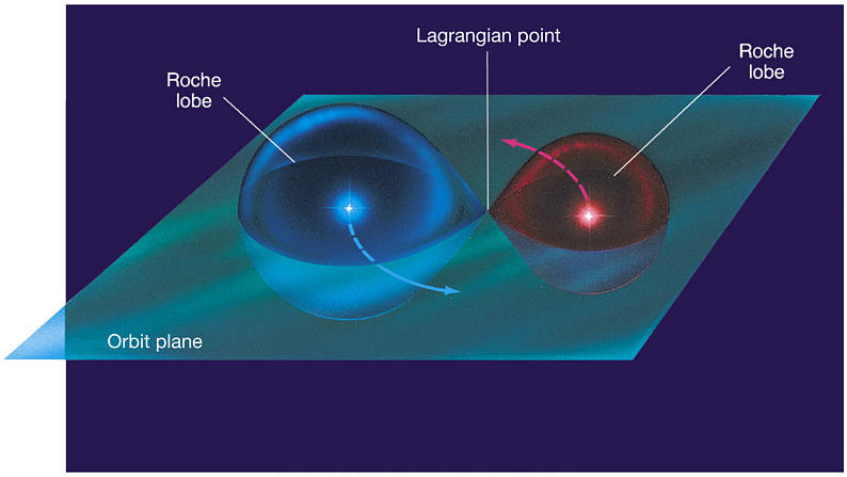

Figure 1.1: *An edge on view of a close binary system orbiting in its orbital plane. The balloon shaped Roche lobes are shown for both stars. The star with the blue Roche lobe is the more massive one since its Roche lobe is larger. The position of the inner Lagrangian point L1 is indicated on the figure.*

largest volume (called Roche volume) the star can occupy without losing mass. This surface is the largest closed surface of constant potential around the star[3] and encloses the largest volume in which all mass is gravitationally bound to the star alone. Around single stars the surfaces of constant potential are always closed spheres. In close binary systems however the shape of these surfaces changes due to the gravitational attraction of the companion star and they become more balloon shaped the further away they are from the centre of the star. The Roche lobes of both stars are connected at the inner Lagrangian point L1. At this point the gravitational force exerted by both stars is equal. Fig. 1.1 shows the Roche lobes around the two stars of a binary in blue and red. It can be seen that the left hand star is more massive than the other because its Roche lobe is larger: the more massive a star is, the larger its gravitational force is, the further its gravitational potential reaches and the further away from the star an object could be situated so that it still would be bound to that star alone.

In some cases the volume of a star will fill the entire Roche lobe. This can happen when the separation of the system decreases which leads to a decrease in the size of both Roche lobes[4] or when the size of the star increases. Just before the star fills its Roche volume, both components are so close together that the star that is going to fill its Roche lobe starts to feel the gravitational attraction of the companion. The part of

[3]A surface of constant potential is an imaginary surface around a star on which the gravitational force exerted by the star is the same everywhere. Each star has an infinite amount of these surfaces, going from the surface of the star itself to a surface at an infinite distance away from us where the gravitational force of the star is zero.

[4]The easiest way to see this is by remembering that the Roche lobes of both stars are always connected at L1. When the separation of the system decreases, the Roche lobes need to decrease too otherwise both volumes would start to overlap which is not possible.

the star closest to the companion gets pulled in the direction of the companion so that the star is no longer spherical but balloon shaped as its Roche lobe. When eventually the star becomes so big that it fills the Roche volume, the mass closest to the companion star is being spilled onto the companion through L1. The system now goes through a so called *Roche lobe mass transfer*.

1.1.2 Division into different types

Close binaries are generally divided into three groups depending on the fact that none, one or both objects in the binary are filling their Roche lobes. *Detached binaries* have a separation that is large enough so that none of the two stars fills its Roche lobe and there is thus no Roche lobe mass transfer. In *semi-detached binaries* one of both components fills its Roche volume and loses mass onto the companion star. *Contact binaries* consist of two Roche lobe filling stars that touch each other at L1 and that are in most cases surrounded by an envelope of matter from both stars. These systems can all evolve from one group to another, e.g. when a star overflows its Roche volume in a semi-detached or contact system, it can shrink back into its Roche lobe because it has lost mass and became smaller and can become a detached or semi-detached system.

When one of the components of a close binary overfills its Roche lobe, another subdivision into three groups can be made based on the evolution stage of the overflowing star. Following the notation of Hilditch (2001) I refer to Case A, Case B and Case C mass transferring binaries. In Case A systems the orbital period is so short (only a few days) that both stars are still main-sequence (MS) stars[5] at the moment one or both fill their Roche lobe. Case B binaries contain a star that stopped burning hydrogen in its centre (and so is no longer a MS star) but is in a core contracting phase at the moment it overflows its Roche lobe. The orbital period for these systems is larger than for Case A binaries (in the range of several to 100 days). In Case C systems, one of the components has evolved into a red giant (see Section 1.2.1 for the further explanation of a red giant) when the Roche lobe overflow phase starts.

1.2 Cataclysmic Variables

1.2.1 The origin of CVs

Cataclysmic variables (CVs) are close binary systems that consist of a white dwarf (WD)[6] and a low mass main-sequence star with a mass in the range 0.08 - 1 $M_\odot$ where the main-sequence star loses mass to the white dwarf. The question is now how such a system comes into existence. The binary starts off with two low mass main-sequence stars, one more massive than the other. The more massive a star is, the higher the central temperature and pressure are and the faster the star burns the hydrogen in its core. Consequently, the more massive star in the system (called the *primary*) is the first

[5]Main-sequence stars are objects that are burning hydrogen in their core. About 90 % of all stars in our Universe are main-sequence stars and so is our Sun. Their masses can range from 0.08 - 200 $M_\odot$ (solar masses). An example of a spectrum of a main-sequence star can be found in Appendix A.5.

[6]A white dwarf is the end product of a main-sequence star as our Sun with a mass between 0.08 - 8 $M_\odot$. In Appendix A.3 some more information is given and some examples of spectra are shown.

to burn all the hydrogen in the core and evolve. When most of the hydrogen supply is eventually exhausted, the core consists of helium. The temperature in the centre of the star is at this point not yet high enough to burn this helium. This means that there is no more outward pressure to sustain the inward gravitational force and the star starts to contract. There is however still hydrogen surrounding the helium core. Because of the contraction, the temperature in the deepest hydrogen layers becomes high enough and the star starts to burn the hydrogen at a very high rate in a shell around the core. The energy that is released through these reaction processes exerts a pressure on the outer hydrogen layers and causes the star to expand greatly. The surface temperature drops due to the expansion and the star becomes a much cooler *red giant*. The separation of the binary system is large enough to allow the primary to start with this expansion. At some point during the expansion however the red giant fills its Roche lobe because the volume of the star is becoming larger than the Roche volume and the system is at this stage a semi-detached Roche lobe filling Case C binary.

The red giant then starts to transfer mass through the inner Lagrangian point L1 to its lower mass companion (the *secondary*). Since the donor star is the most massive one, it is closest to the common centre of mass. The mass transferred from the Roche lobe filling star to the secondary therefore has to move further away from the centre of mass than it initially was. This leads to an increase in angular momentum of the transferred mass. Since the system must conserve angular momentum, it will respond to this by decreasing the separation between the two stars. The decrease in separation makes the Roche lobes of both stars smaller and even more mass is spilled from the primary to the secondary, resulting in an *unstable mass transfer*. In the end the whole hydrogen envelope of the red giant is dumped onto the accreting star. The secondary is however not able to accrete all this mass and the material overflows both Roche lobes. A *common envelope* (CE) of mostly hydrogen is formed around the two stars. This hydrogen cloud exerts a frictional drag force on the stars making them lose orbital energy which results in a further period decrease. The orbital energy lost by the binary expels the cloud which becomes visible as a so called planetary nebula around the binary. In the meantime the red giant lost so much mass that only a naked helium core with a layer of residual elements at its surface is left: the white dwarf. The end result is thus a white dwarf and a main-sequence star, called a white dwarf main-sequence binary[7] (WDMS binary) with a separation in the order of $1\,R_\odot$ (solar radius).

Due to magnetic braking[8] and gravitational wave radiation[9], the system loses an-

[7]Some examples of typical spectra of white dwarf main-sequence binaries are given in Appendix A.4.

[8]Charged particles in a magnetic field follow the magnetic field lines. When the source of the magnetic field is a rotating star, the field itself will be rotating. The charged particles are then accelerated to high speeds and are shot off into space, taking away angular momentum from the star. The angular momentum loss will make the separation of the cataclysmic variable decrease.

[9]The general relativity theory of Einstein predicts that asymmetric high energy events send gravitational waves through space. These waves are like ripples on a water surface, distorting everything on its path. The energy needed to generate these waves is extracted from the system that sends out the radiation. When this system consists of two stars orbiting around each other, the energy loss makes the orbital period of the binary decrease. In cataclysmic variables gravitational waves are emitted when

gular momentum which results in a decreasing binary separation and smaller Roche volumes for both stars. At some point the main-sequence star (which has a bigger volume than the white dwarf) fills its Roche lobe and starts to transfer mass onto the white dwarf. This is a Case A Roche lobe overflow because the donor star is still a main-sequence star when it starts losing mass. At the moment this overflow happens, the cataclysmic variable is born. The mass transferring star is in most cases the least massive one and is thus the furthest away from the common centre of mass. The transferred mass loses angular momentum and the system responds by increasing the separation. The star now goes through a *stable mass transfer* phase[10]: the increase of orbital separation makes the Roche lobes larger again and since the main-sequence star generally becomes smaller as it loses mass, it shrinks safely back into its Roche lobe and the overflow stops. For the majority of the CVs, the mass transferred from the secondary to the white dwarf does not immediately fall onto the white dwarf (see Section 1.2.2 where polars are explained which form the exceptions on this). The flow of mass first spirals around the white dwarf and then settles into a circular orbit. As more mass falls onto this stream, a hot accretion disc forms around the white dwarf with the mass closest to it falling onto it. Because of magnetic braking and gravitational wave radiation, the CV keeps losing angular momentum and evolves towards shorter orbital periods (and thus smaller orbital separations) until the main-sequence star fills its Roche lobe again. In reality this process of decreasing Roche lobes due to angular momentum loss and increasing Roche lobes due to mass loss happens quite continuously so that the binary keeps transferring mass. It results eventually in a binary system of two low mass objects with an orbital period somewhere between 12 hrs and 78 min. See Hellier (2001) and Hilditch (2001) for more information.

1.2.2 Some typical characteristics of cataclysmic variables

A first important aspect about CVs is their variability in brightness. When mass is accreted from the accretion disc onto the white dwarf, it builds up at the surface of the white dwarf and once the density and temperature are high enough, the bottom layer of this mass of hydrogen ignites. This is visible as an outburst and can cause the brightness of the so called *classical novae* to momentarily rise with 10 - 20 magnitudes[11]. *Dwarf novae* are cataclysmic variables with much smaller luminosity increases during outburst: 2 - 7 mag. For these systems the variability has nothing to do with the ignition of hydrogen at the surface of the white dwarf but happens due to instabilities in the accretion disc around the white dwarf. Matter is accreted from the secondary onto the accretion disc, increasing the temperature and viscosity of the matter in the disc. At

the rotational velocity of the system is high enough and thus the orbital period of the system is small enough (smaller than 2 - 3 hrs).

[10]More specifically, stable mass transfer happens already when the mass of the secondary is smaller than 1.26 times the mass of the white dwarf. See Warner (1995) for a further explanation.

[11]Magnitude (mag) is a logarithmic scale used to measure the brightness of an object. When F is the flux that reaches the Earth and m is the magnitude that object seems to have on Earth, then F = $10^{-0.4*m}$. Note the minus sign in the exponent: the lower the magnitude, the higher the flux of the object and the more luminous the object seems to be from Earth.

some point the viscosity is so high that large amounts of matter are being dumped onto the white dwarf. This releases a lot of gravitational potential energy which is visible as an outburst. The CVs in the third variability category, the ones with the smallest brightness increases (only a few magnitudes), are called *nova-likes*. The variability for these systems is probably related to changes in the mass transfer rate instead of real outbursts.

The emission of X-rays is a second typical characteristic of cataclysmic variables. In the 1970s astronomers discovered that CVs are weak X-ray sources. Since the matter that is accreted from the accretion disc onto the white dwarf can reach temperatures up to 100 million degrees, such high energy emission is not an unnatural phenomenon. It is believed that the X-rays come from the region where the matter hits the surface of the white dwarf. Most of the stronger X-ray emitting CVs have a magnetic white dwarf. Cataclysmic variables with a magnetic white dwarf are called *polars* and *intermediate polars*, where the magnetic fields of the white dwarfs in the intermediate polars are less strong. Strong magnetic white dwarfs prevent the mass to flow into an accretion disc around it but make the mass follow the magnetic field lines up to the surface of these stars. Since the matter will fall more vertically onto the white dwarf in these cases, a stronger shock and stronger X-ray emission is expected.

A last important feature of CVs is their colour. When the continuum of the spectrum of the system is dominated by the cooler main-sequence star, the cataclysmic variable will be visible at the sky as a red point source. If however the white dwarf or the accretion disc around the white dwarf dominate the continuum spectrum of a CV, the system is intrinsically hot and is seen as a blue CV. At the point where the secondary has lost most of its mass, it will be really faint. The spectrum of the system is dominated by the white dwarf and the CV is called a white dwarf dominated CV. The next section explains why these white dwarf dominated CVs are the objects with a low period, close to the so called period minimum.

1.2.3 Period gap and period minimum spike

Due to magnetic braking and gravitational wave radiation, the separation of a cataclysmic variable decreases with time. In general CVs have orbital periods between 12 hrs and about 78 min. One of the most well known features about the period distribution of a CV is the *period gap*. Fig. 1.2 shows a histogram of the orbital periods of cataclysmic variables. There is a clear lack of CVs with a period of 2 - 3 hrs, indicated with a grey box. Cataclysmic variables born with a period larger than 3 hrs will evolve towards this period gap. These CVs barely send out gravitational wave radiation (which has most influence at smaller periods, < 2 - 3 hrs) and so above the period gap it will be mainly magnetic braking that causes the separation of the binary to shrink. Since the angular momentum loss makes a star fill its Roche lobe, the rate at which the star loses its mass will depend on the angular momentum loss mechanism. It has been calculated that systems that lose angular momentum through magnetic braking have a mass loss rate ($\dot{M}$) of 10^{-9} – 10^{-8} $M_\odot$ yr^{-1} while gravitational wave radiation leads to a lower mass loss rate around 10^{-10} $M_\odot$ yr^{-1}. CVs with an orbital period larger than 3 hrs appear to have an $\dot{M}$ that can be explained by magnetic braking, which confirms the

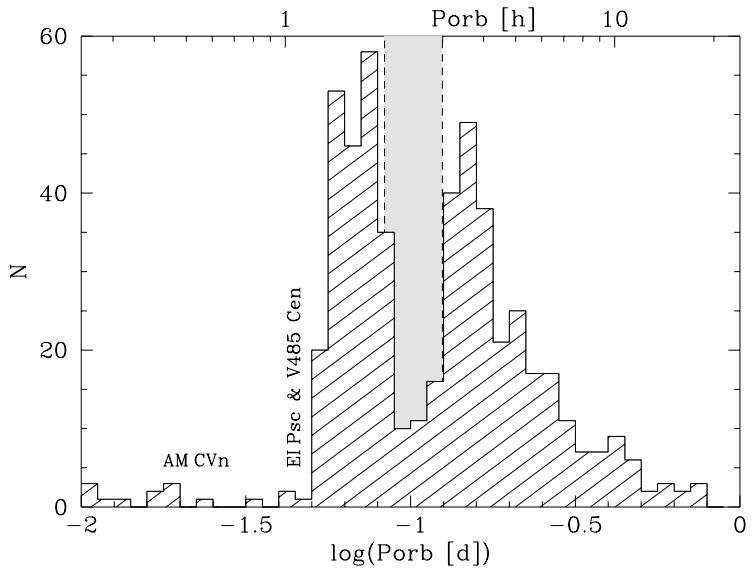

Figure 1.2: *The orbital period distribution of a sample of 532 CVs as shown in Gänsicke (2005). The grey band around 2-3 hrs shows the period gap. The histogram is cut off at low periods, around 80 minutes which indicates the period minimum.*

higher effect of magnetic braking over gravitational wave radiation for these systems. At a certain point however these binaries seem to stop transferring mass since almost no CVs are known with a period between 2 - 3 hrs (and CVs are defined as mass transferring systems). It is believed that for systems with an orbital period around 3 hrs, magnetic braking stops (Hellier 2001). Why the star stops losing mass at that point, is because the secondary had been driven out of hydrostatic equilibrium just before the cataclysmic variable reached a period of 3 hrs. As the secondary loses mass, the gravitational potential energy of the star decreases which results in a lower nuclear burning rate at the core of the star. Because less energy is generated at the centre of the star, the outward pressure decreases and the star contracts to maintain hydrostatic equilibrium. Due to the contraction, gravitational potential energy is released which is radiated away on a timescale called the *thermal timescale*. When the secondary loses mass on a timescale shorter than the thermal timescale, it loses its mass too quickly and cannot contract rapidly enough to remain in hydrostatic equilibrium. The radius of the star becomes larger than it would have been in equilibrium. At the moment the magnetic braking stops however, the mass loss mechanism turns off. The star can now contract on the thermal timescale and shrink to the size it would have had in normal circumstances. It is at that point smaller than its Roche volume, so mass transfer stops and the system is no longer a CV but a detached white dwarf main-sequence binary. Gravitational wave radiation takes over from magnetic braking and keeps decreasing the separation of the binary, but at a lower rate now. When the orbital period is small enough and the secondary fills its Roche lobe, the system becomes a cataclysmic vari-

able again and appears at the left side of the period gap.

A second feature of the orbital period distribution of cataclysmic variables is the *period minimum* (see King 1988, Kolb & Baraffe 1999, King et al. 2002). Theory says that once past the period gap, CVs evolve to shorter orbital periods up to a certain value around 78 minutes and then move back up to larger periods. A star with a period smaller than 3 hrs loses angular momentum due to gravitational wave radiation. When the mass of the secondary gets smaller than about 0.1 $M_\odot$[12], the gravitational wave radiation makes the secondary lose mass on a timescale shorter than the thermal timescale. The secondary is no longer in hydrostatic equilibrium and the radius becomes too large for a star in equilibrium. Next to this, a second thing happens to the secondary as the system approaches the period minimum. The main-sequence star has lost so much mass that it stops burning hydrogen and becomes a degenerate[13] brown dwarf. While a star normally gets smaller when it loses mass, the size of a degenerate star increases when its mass decreases. These two effects have the following result. When a non-degenerate star loses mass, its Roche lobe increases a little due to the mass loss, the size of the star decreases a little because it lost mass and returns to equilibrium and the separation of the system decreases due to angular momentum loss. However, when the secondary is degenerate, mass loss will increase the Roche lobe but will also increase the size of the star. This results in a star that still fills the expanded Roche lobe. When angular momentum is lost, the Roche lobe of the star decreases and since the brown dwarf was already filling its Roche volume, even more mass is spilled from the secondary. Since mass is lost, the Roche lobe increases, the size of the star increases and the secondary keeps losing mass. The final result is a system evolving towards larger periods.

This period minimum is also visible in Fig. 1.2. Theoreticians predict an accumulation of CVs around this minimum, called the *period minimum spike*, because the evolution rate slows down which increases the detection probability. There are several reasons why the evolution rate slows down for CVs with a period approaching 78 min. As said before, the angular momentum loss for systems with periods lower than 3 hrs happens through gravitational radiation which in general makes a system lose mass at a lower rate than when angular momentum is lost through magnetic braking. The rate at which gravitational waves are radiated by a system is also proportional to the product of the masses. As the secondary mass becomes lower, less gravitational wave radiation will be sent out so that the evolution to shorter periods slows down. Next to that there is also the fact that CVs bounce on the period minimum and thus go through the low orbital periods twice: once when they evolve from higher to lower periods and once when they return from the minimum and move up to higher periods again. Up until very recently (Gänsicke et al. 2009), astronomers were unable to find this accumulation of white dwarf dominated CVs in observational orbital period

[12]The secondary in these systems has a very low mass so that the spectra of these CVs are dominated by the white dwarf. These are the blue white dwarf dominated CVs from the previous section.

[13]Degeneracy in a star occurs when matter has such a high density that the quantum mechanical Pauli exclusion principle becomes the main pressure contributor to sustain the gravitational force in a star. The Pauli exclusion principle puts a limit to the closest distance two identical particles can get.

distributions.

1.2.4 What is the importance of CVs?

Depending on the initial mass, main-sequence stars evolve to white dwarfs, neutron stars or black holes at the end of their lifes. These end products of stellar evolution are called *compact objects*. The low mass main-sequence stars with a mass in the range 0.08 - 8 $M_\odot$ become white dwarfs. Binaries containing one or more of these compact objects are called compact binaries. Cataclysmic variables and white dwarf main-sequence binaries are two types of compact binaries with a white dwarf as compact object. Since the low mass main-sequence stars are the most numerous in our Milky Way, there will be more compact binaries containing a white dwarf compared to binaries containing neutron stars and black holes. For this reason it is very important to understand the process going on in white dwarf compact binaries in order to understand similar processes in the other more exotic neutron star and black hole compact binaries. E.g. accretion discs or common envelopes can happen in all kinds of compact systems and sometimes discoveries about these phenomena can be extrapolated to neutron star and/or black hole binaries.

To be able to get answers to questions concerning CVs, a uniform sample of cataclysmic variables is needed in the first place to test the theories on. This is has not yet been available up to now. Most of the cataclysmic variables found by previous surveys were bright blue objects, systems with frequent and bright outbursts or CVs with strong X-ray emission (Gänsicke 2005). This sample is clearly biased to objects that have clear detections for one or more of these features and is not representative for the Galaxy sample of CVs. E.g. systems with low mass transfer rates are rarely seen in outburst and are faint in X-ray emission. These systems are underrepresented in the CV sample obtained so far. This is however an important group of CVs because these old short period systems are thought to make up the majority of all CVs and are the ones that should populate the period minimum spike. The need for a uniform sample of CVs, covering both bright as faint, blue as red objects is high. The Sloan Digital Sky Survey is by far the largest and deepest survey that can be used to find CVs and is expected to provide the most unbiased sample of CVs obtained so far.

1.3 THE SLOAN DIGITAL SKY SURVEY

1.3.1 SDSS: 8 years of dedicated observations

The Sloan Digital Sky Survey (SDSS; York et al. 2000) has been the largest and most ambitious survey of the sky to date. Multi-colour images of 357 million unique objects were taken, spread over more than a quarter of the sky (11 663 square degrees). Over a million quasars (QSOs)[14], galaxies and interesting objects in the Milky Way Galaxy were targeted for spectra, allowing distance measurements and the creation of a 3-dimensional picture of the large scale structures in our Universe.

[14] A quasar is a galaxy whose luminosity is dominated by the accretion of matter onto a black hole. More information and an example of a spectrum of a quasar are given in Appendix A.2.

The survey made use of a dedicated 2.5 meter telescope situated at the Apache Point Observatory in New Mexico. It was equipped with two instruments: a CCD camera taking images in five filters (u, g, r, i, z)[15] and a pair of spectrographs with a total of 640 optical fibers available per exposure. The camera could image 1.5 square degrees of the sky at a time in a drift-scanning mode: it drifted over the sky and read in the data at the same rate as the camera was collecting it. This photometry was used to select the sample of objects that would get a spectrum. At the position of these objects, holes were drilled in an aluminum plate and optical fibers were plugged into the holes. The two spectrographs collected data simultaneously, one covering the red wavelength range, the other covering the blue range. A set of software pipelines kept pace with the enormous data flow from the telescope.

During the first phase of the survey (SDSS-I, 2000-2005), SDSS took images of about 8 000 square degrees of the sky. Next to that also a part of the southern Galactic cap was imaged repeatedly to look for objects that are variable in brightness. With new financial support and an expanded collaboration of institutes an extension of SDSS (SDSS-II, 2005-2008) took place. This second part was divided into three distinct surveys: the Sloan Legacy Survey, SEGUE and the Sloan Supernova Survey. The Sloan Legacy Survey mainly finished the work of SDSS-I by taking images of in total 8 400 square degrees of the sky and spectra of 930 000 galaxies, 120 000 quasars, and 225 000 other interesting objects in the Milky Way Galaxy. SEGUE (the Sloan Extension for Galactic Understanding and Exploration; Yanny et al. 2009) imaged our Galaxy at moderate to low Galactic latitudes[16] ($|b| < 35°$) and took spectra of objects selected from this sample. The Sloan Supernova Survey (Frieman et al. 2008) continued on doing repeated imaging and discovered about 500 spectroscopically confirmed Type Ia supernovae in the southern equatorial Stripe 82 (about 2.5° wide and 120° long). The Sloan Legacy Survey was the most uniform of all three surveys in targeting objects and will be the most important one for this research work. The two main parts of Legacy were the galaxy and the quasar survey. When there were spare fibers on the spectroscopic plates, quasars that were just too faint for the standard selection and objects that were interested because of extreme colours or distance, were targeted. All data from SDSS-I as SDSS-II will be used here without making any distinction and will be referred to as just SDSS. The last data release (DR7) of SDSS-II became available in October 2008.

In July 2008 SDSS-III began observations with four new surveys: BOSS (measuring the cosmic distance scale), SEGUE-2 (mapping the structure, kinematics and chemical evolution of the outer Milky Way disc and halo), APOGEE (looking through the dust to the inner Galaxy using high-resolution infrared spectroscopy) and MARVELS (probing the population of giant planets via radial velocity monitoring of 11 000 stars). Since SDSS-III has not yet released any data, this part of SDSS will not be used or discussed

[15]The five filters go from ultraviolet (u at 3543 Å) to green in the optical range (g at 4770 Å), red in the optical range (r at 6231 Å), near infrared (i at 7625 Å) and infrared (z at 9134 Å).

[16]The galactic coordinate system is used to define the position of an object at the sky. The system is centered at the position of our Sun. Longitudes are measured in the galactic plane with respect to the zero line that goes through the centre of the Milky Way. The latitude of an object is the angle between the galactic plane and the object.

anymore further on.

1.3.2 Quasar survey in SDSS

About 120 000 quasars have been targeted by the Sloan Digital Sky Survey at a galactic latitude of $|b| \geq 30°$ (excluding the Galactic disc) by making use of a specific spectroscopic target selection algorithm (Richards et al. 2002). The first stage of this algorithm was a flag-check. All photometric objects received a number of flags during the imaging. Some of these indicate that something was wrong with the image or that the object was saturated or too faint to be detected. Flags indicating saturation are examples of *fatal errors*. Objects with such a fatal error flag were immediately rejected from the sample of spectroscopic targets. The objects that did not have a fatal error were then matched against FIRST[17] radio sources (Becker et al. 1995). The ones that had been observed by FIRST were selected as spectroscopic targets in SDSS without any further selections. All the others had to go through the rest of the selection algorithm.

For these other objects the next important step was the colour selection[18]. Photometry was taken in five different wavelength bands so a 4-dimensional colour space using the colours (u-g), (g-r), (r-i) and (i-z) could be created. Since there are a lot of main-sequence stars and they do not overlap too much in colour space with quasars, a first colour cut was made for these stars. Normal hydrogen core burning stars occupy a very typical area in the 4-dimensional SDSS colour space. The largest part of this region was defined to be the *stellar locus* and only objects that were clear outliers passed this step of the colour selection. The others were rejected. The projection of the stellar locus onto ugr space is shown in Fig. 1.3. Everything inside the pink boxes was excluded from the quasar sample.

A second cut was based on the i-band magnitudes of the objects and it was made to allow only objects that were clearly visible: not too bright and not too faint. At the bright side no strict limit was used. In general objects with i-mag < 15 were not allowed because objects that were brighter than this limit contaminated the spectra of objects in adjacent fibers. The cut at the faint side was different depending on the redshift[19] of the objects. For the ones with a low redshift only the objects with a dereddened[20] i-magnitude smaller than 19.1 were selected. For the ones with a high redshift, objects

[17]FIRST stands for Faint Images of the Radio Sky at Twenty cm and is a radio survey that observed over 9 000 square degrees of the North Galactic Cap.

[18]For each object SDSS measured magnitudes in the five filters u, g, r, i, z. The difference between magnitude values in two filters gives a colour: e.g. an object with a negative u-g colour will have a higher magnitude in the g-filter than in the u-filter. Since a higher magnitude means a lower flux, this means that this object has a higher flux in the u-filter than in the g-filter so it has a very blue colour.

[19]According to the special relativity theory of Einstein, the light of an object that moves away from an observer at rest will look redder to this observer than it would be if the object would be at rest. This phenomenon is called redshift (when the object is moving towards the observer, it looks bluer and is called blueshift). Since the Universe is expanding, all the big formations in the Universe are moving away from each other and seem to be redder than they would be if the Universe would not be expanding. Quasars are galaxies far away from us, moving away from us, and thus they appear redder because of this redshift effect.

[20]The light from stars always looks slightly more red when it reaches us then it originally was. The reason for this is that dust and gas between the observer and the star scatter the light from the star. This

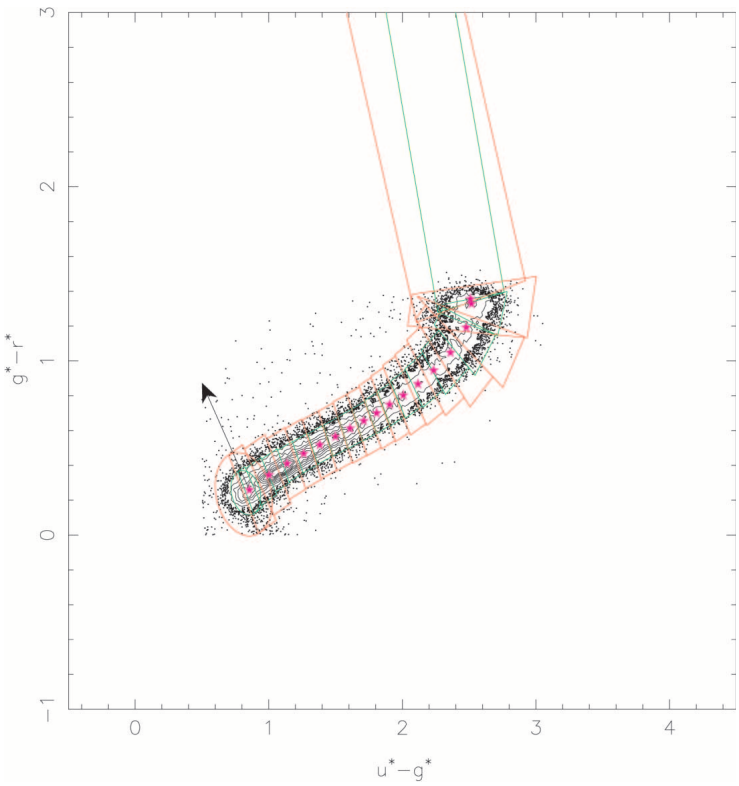

Figure 1.3: *The stellar locus cut as it was used in the quasar survey to exclude most of the main-sequence stars from the sample of spectroscopic targets (see Richards et al. 2002). All objects inside the pink boxes were rejected.*

up to a dereddened i-band magnitude of 20.2 were accepted. This distinction in low and high redshift objects was done by using different areas of colour space where the high redshift objects are the reddest ones.

Next to the main-sequence stars there are also groups of other stars and systems that are not quasars and do not overlap too much with the quasars in 4-dimensional colour space. Exclusion boxes were made for a couple of these systems and stars. For single white dwarfs, A stars[21] and white dwarf + M star pairs (WD+M, binaries containing a faint main-sequence star and a white dwarf), regions were selected where a lot of these objects are situated in colour space and everything in these boxes was eliminated from the quasar survey. In a final step a few small boxes that had been excluded by the main-sequence colour cut were included again because too many quasars had

effect is larger for blue light than for red light so that the blue light is more bent away from us than the red light. The result is that the further away a star is (and thus the more dust and gas the light encounters on its way to the Earth) the redder it looks. This is called reddening and one can correct for this effect which is then called dereddening.

[21] A stars are a type of main-sequence stars that were left out of the stellar locus and occupy a typical area in colour space close to the stellar locus.

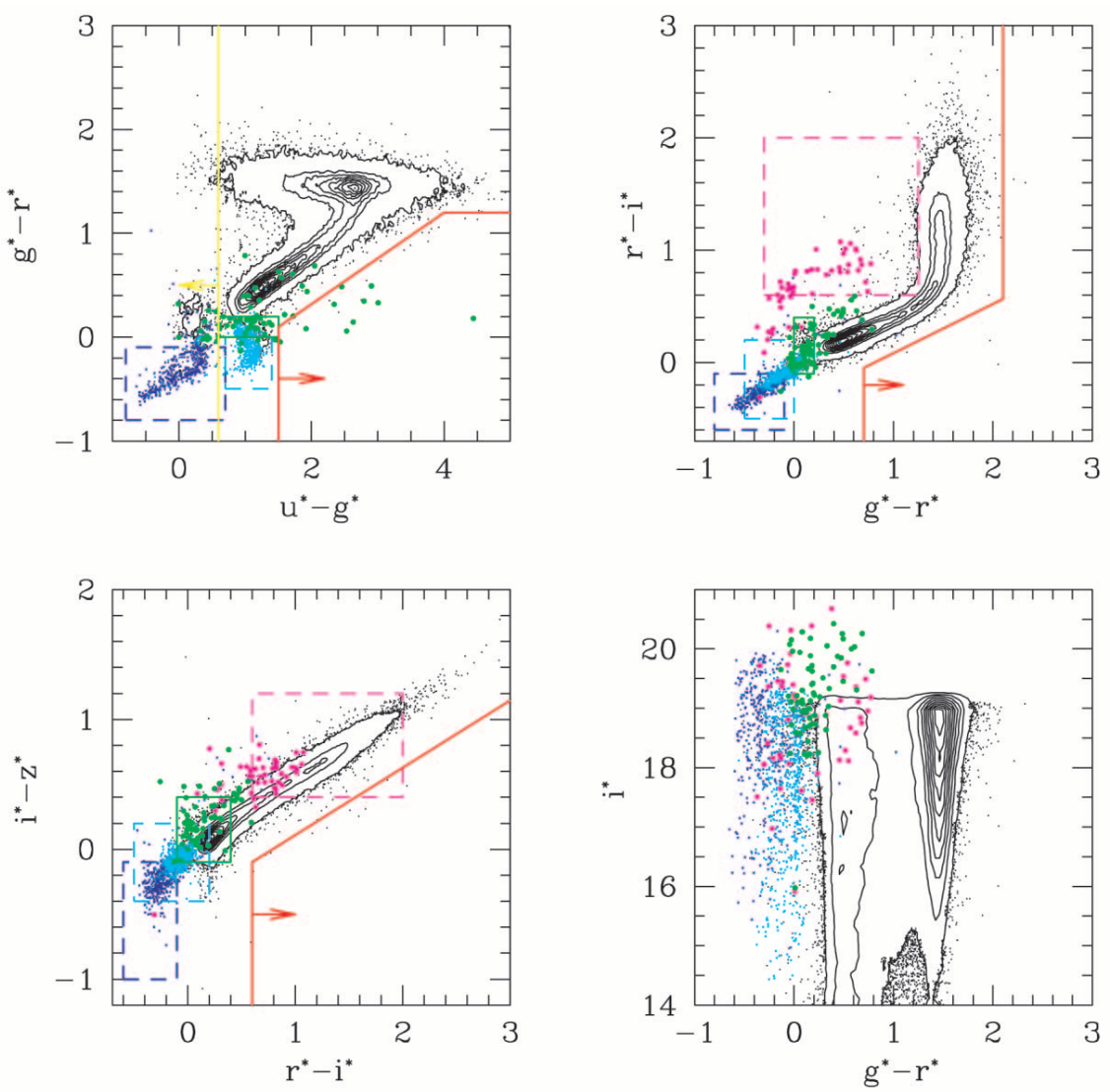

Figure 1.4: *Two colour-colour plots showing the different exclusion boxes that were used in the quasar survey. The white dwarf box is shown in dark blue, the one for A stars in light blue and the one for white dwarf + M star pairs in magenta. This figure is taken from Richards et al. (2002).*

been left out by them. Fig. 1.4 shows the exclusion boxes of white dwarfs, A stars and white dwarf + M star pairs in dark blue, light blue and magenta respectively.

All the objects that passed this quasar selection algorithm or that had been allowed because of a FIRST match were selected and got a spectrum in SDSS. Since the quasar survey selected its targets mainly based on colours, there were a lot of other point sources that had the same colours as quasars and could not be excluded because too many quasars would be eliminated at the same time. Some examples of these objects are white dwarf main-sequence stars, white dwarfs and main-sequence stars that were

missed by the exclusion boxes and most importantly for us cataclysmic variables.

1.3.3 Cataclysmic variables in SDSS

Cataclysmic variables have colours that can easily be distinguished from those of main-sequence stars but that overlap with the colours of low redshift quasars, white dwarfs and white dwarf main-sequence stars. Since quasars were primary targets for spectroscopic fibers in Legacy (next to galaxies), most CVs could be found in the spectroscopic database[22] of the quasars sample. Next to the main samples of galaxies and quasars, SDSS took spectra of interesting objects when there were excess fibers. These extra fibers were given to e.g. objects that had an i-magnitude just above the 19.1 limit but would have been selected trough the quasar sample if their i-magnitude was just below the limit (called QSO_FAINT objects) or objects that passed the serendipity criteria. This serendipity sample is an open category of targets with different selection criteria (extreme blue, red or distant objects). A lot of CVs have been found in the serendipitously blue objects which are blue objects outside of the stellar locus.

Over the years, quite some CVs have been found in the spectroscopic database of SDSS. The gross amount of CVs was recognized by looking at their spectrum. As explained before, the main-sequence star in a CV transfers mass to the accretion disc around the white dwarf. The hydrogen in the accretion disc is visible in the spectrum of a CV through quite broad hydrogen emission lines. Appendix A.1 gives an explanation of this and some examples of spectra of CVs. More than 90 % of the CVs that have been gathered during the past 8 years from SDSS were found by searching for these broad hydrogen emission lines and have been published by Paula Szkody et al. (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009). A lot of research has already been done on individual CVs from SDSS: orbital periods have been calculated for a lot of them (Dillon et al. 2008, Southworth et al. 2007, 2008) and really interesting CVs have been investigated further (Gänsicke et al. 2006, Littlefair et al. 2006, 2007, Peters & Thorstensen 2005, Southworth et al. 2006, Wolfe et al. 2003). However, no research has yet been done on the whole sample of spectroscopic CVs.

There are several reasons to believe that SDSS should give the most uniform and most representative sample of CVs in our Galaxy ever. First of all, the quasar survey has not targeted objects by specific criteria but has eliminated objects with typical colour characteristics. This means that in contrary to previous surveys all kinds of CVs should have been targeted and not only the very blue, variable or strong X-ray emitters. Apart from that, SDSS has targeted objects up to a much larger i-magnitude limit (19.1 compared to 17.5 for previous surveys). This allows the detection of CVs that are further away from us but also allows to detect the intrinsically faint old objects which populate the period minimum spike. The goal of this thesis is to check how complete SDSS really has been in targeting CVs. Since CVs have the same colours as quasars, a lot of them are expected to have a spectrum in SDSS. The only real limitations should be in the brightness of the CVs.

[22]The spectroscopic database contains all objects from SDSS that have a spectrum. The photometric database has al objects from SDSS that have been imaged, both the ones with and without a spectrum.

1.4 A PREVIEW ON THE RESEARCH DONE

Chapter 2 starts by discussing the cataclysmic variables that were already known before SDSS started its observations. All the ones that are in the footprint of SDSS are checked to see which ones have a spectrum, which ones do not and why this last group was not targeted. Dereddened i-magnitude histograms are shown and discussed for all these cataclysmic variables. I close this part by showing the percentage of CVs that has been targeted for a spectrum. This number is the so called *spectral completeness* of the previously known cataclysmic variables in SDSS.

Chapter 3 shows how good SDSS has been in targeting CVs in general by working with all the ones that have a spectrum in SDSS. A sample of 279 cataclysmic variables is used with both newly discovered and previously known CVs with a spectrum in SDSS. All these variables are shown on colour-colour plots together with all the point sources that have been imaged by SDSS. Afterwards it is explained how, based on these colour-colour plots, an estimate can be made of the number of CVs that are still in the photometric database but were not targeted by SDSS for a spectrum. Combining the list of cataclysmic variables with a spectrum and the ones that did not get a spectrum, the spectral completeness of all CVs in SDSS is computed.

Since most of the cataclysmic variables that have a spectrum in SDSS are found in the quasar sample and almost no objects with an i-magnitude higher than 19.1 were targeted by the quasar survey, there are very few faint CVs in the spectroscopic database of SDSS. Chapter 4 shows how it could be possible to find CVs in the photometric database of SDSS that did not get a spectrum, using proper motions and GALEX magnitude measurements.

I finish this report with the conclusions of the thesis work and the future prospects in Chapter 5.

One side note needs to be made about dereddening magnitude values. Since SDSS wanted to target quasars and galaxies, dereddening is very important for those objects because they are so far away from us and the light that reaches us has already encountered a lot of dust and gas. The extinction values SDSS gives for each object is the dereddening factor that accounts for all the dust and gas in our Milky Way Galaxy at the position of the object in the sky. This is okay for the quasars and galaxies because they are outside the Galaxy, but since the cataclysmic variables that came in together with the quasars lie inside our Galaxy, these extinction values are too high. It is not possible to know for how much scattering the CVs need to be corrected and so in this research work no correction has been made in general. Chapter 2 however talks about dereddened i-magnitudes. The reason for this is that the quasar sample made its faint end limit of 19.1 for dereddened i-magnitudes. To be able to know if a CV was selected by the quasar sample or by other means, it is useful to show the dereddened i-magnitudes of the CVs instead of the uncorrected values. In the other chapters, mainly the difference in magnitudes between two different magnitude bands are used and so no correction was done there.

Chapter 2

Previously known CVs in SDSS

Over the years more and more cataclysmic variables were discovered. The first ones were very bright with a noticeable variability in luminosity. As people found more CVs, more characteristics of these binaries became evident. In this chapter I make use of all the CVs that were found from the very beginning until now, excluding all the cataclysmic variables discovered by the Sloan Digital Sky Survey. Section 2.1 shows the CVs that were gathered by Ritter & Kolb into a large catalogue. In Section 2.2, CVs from the Catalina Real-Time Transient Survey are discussed and used. Results from these two lists of CVs are then put together in Section 2.3.

2.1 Ritter & Kolb Catalogue

In 1982 H. Ritter started gathering all cataclysmic variables, low-mass X-ray binaries[1] (LMXBs) and objects closely related by stellar evolution with known or suspected orbital periods into a catalogue, in an attempt to keep track of the considerable increase in new detections. The first edition contained 137 binaries with a more or less well established orbital period. 21 years later the 7th edition was published by H. Ritter & U. Kolb with a catalogue of 472 CVs, 71 LMXBs and 113 related objects (Ritter 1984, 1987, 1990, Ritter & Kolb 1998, 2003). During the years, the catalogue has been updated continuously and at the moment it is a collection of 731 CVs, 90 LMXBs and 190 closely related objects. All of these objects have been gathered through different surveys and programs e.g.the Palomar-Green survey discovered blue CVs, ROSAT found CVs through X-ray emission, quasar surveys (e.g. the Hamburg Quasars Survey) found cataclysmic variables because the colours overlap. The last list of 731 CVs is what I call from now on the Ritter & Kolb Catalogue, ignoring the LMXBs and the closely related objects since they are not useful in this research.

To be able to see how good SDSS has been in targeting these previously known

[1]Low mass X-ray binaries consist of an accreting neutron star or black hole and a slowly evolving low mass main-sequence donor star.

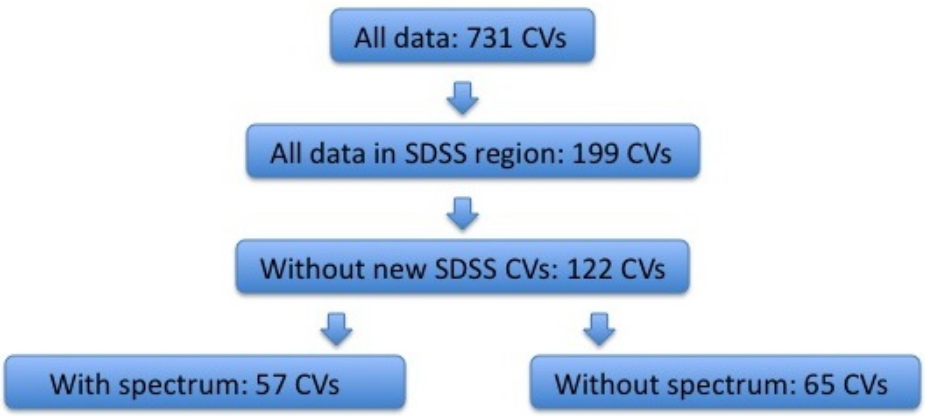

Figure 2.1: *A diagram showing the number of cataclysmic variables from the Ritter & Kolb catalogue. The full catalogue contains 731 CVs. 199 of these were in the right area of the sky for SDSS to get a spectrum. 77 however were newly discovered by SDSS and needed to be eliminated since the interest at the moment goes to the CVs known before SDSS started observing. 57 of the remaining 122 CVs got a spectrum, the other 65 CVs did not.*

CVs, all the ones that were in the right part of the sky to be observed by SDSS[2] were selected. 199 of the 731 CVs were in the footprint of SDSS and have thus been observed. Since Ritter & Kolb update their catalogue regularly, all of the new SDSS discovered CVs with known orbital periods were already put into their list. 77 newly discovered CVs had been added to the catalogue and needed to be eliminated here, resulting in a final list of 122 previously known cataclysmic variables that were imaged by SDSS. 57 of these were selected by SDSS and got a spectrum, the other 65 CVs did not get a spectrum (7 of these 65 CVs were selected for a spectrum but did not get one in the end). This means that from the 122 cataclysmic variables about 47 % got a spectrum, the other 53 % did not. All these numbers are summarized in a diagram, shown in Fig. 2.1. The CVs with and without a spectrum are discussed separately in the following sections.

2.1.1 The distribution of CVs with no spectrum in SDSS

65 CVs (53 % of the previously known CVs from the Ritter & Kolb catalogue) did not get a spectrum in SDSS. 7 CVs were targeted for a spectrum but did not get one. This may be due to a lack of spare fibers on the spectroscopic plates of these objects. Since SDSS first targeted objects selected by the main surveys (galaxy and quasar survey) and took spectra of other objects only if there were spare fibers, these 7 CVs may have been interesting enough to get a spectrum but there were probably no more spare fibers left. A lot of the other CVs were not in the right magnitude range to be selected for a spectrum: 12 CVs were too faint, 20 were saturated. 6 CVs were eliminated by the

[2]There were objects in the Ritter & Kolb catalogue with wrong coordinates. This was noticed during project work done by Eleanor Rothery and I made use of those adjustments.

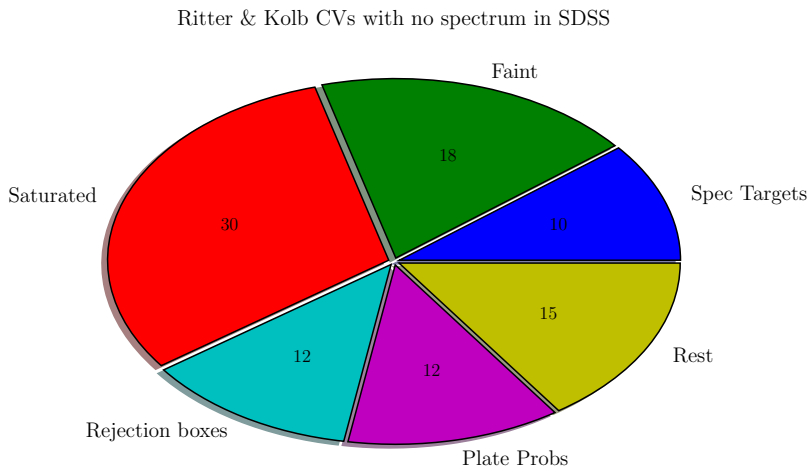

Figure 2.2: *A pie chart displaying the distribution of CVs from the Ritter & Kolb catalogue into different categories according to the reason they did not get a spectrum. The percentage of each piece is shown inside of it. Almost half of these objects were too bright or too faint, 10 % had been targeted but without receiving a spectrum, 12 % got into an exclusion box, another 12 % suffered from plate or fibre problems and the remaining 15 % did not get a spectrum for some unknown reason.*

white dwarf rejection box, 2 by the WD+M binary box. For 8 objects there had been problems with the whole spectroscopic plate or with the fibers in it, so that nothing on the whole plate got a spectrum. For the 10 remaining CVs there is no clear reason why they were not targeted. The pie chart in Fig. 2.2 shows the distribution of CVs (in percentage) for the different reasons.

The luminosity of almost 50 % of these CVs was not in the right range for SDSS to target. The histogram in Fig. 2.3 shows the dereddened i-magnitudes of all Ritter & Kolb CVs that did not get a spectrum. Two main features are visible, one at the faint end (i-mag = [19.1 - end]) and one at the bright side (i-mag = [13 - 16]). These two groups represent the 50 % of systems that were too bright or too faint to be observed. The specific 19.1 limit is the dereddened faint side limit used by the quasar survey (indicated in the figure with a dashed line). Since most of the CVs were targeted by this quasar survey, it is not abnormal to see that the 19.1 limit is also important for the CV sample. This histogram is made specifically in the i-magnitude of the cataclysmic variables to show this faint end limit.

2.1.2 The number of CVs with an SDSS spectrum

57 of the previously known CVs did get a spectrum. This means that even though SDSS did not look for CVs, it still took spectra of about 50 % of the previously known CVs. A histogram with their dereddened i-magnitude distribution is shown in Fig. 2.4. The histogram is again made for the i-band magnitudes of these objects because most

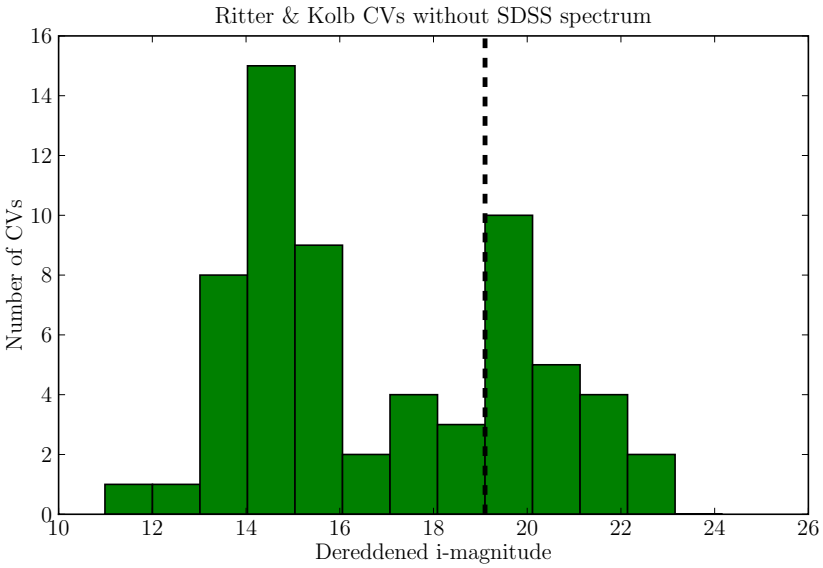

Figure 2.3: *An i-magnitude histogram for all Ritter & Kolb CVs that did not get a spectrum in SDSS. Two groups can be distinguished in this histogram. At the faint end, most of the objects have a dereddened i-magnitude larger than the 19.1 quasar limit (shown with a dashed line). At the bright end, the CVs are centered around an i-magnitude of 15, which is about the limit for saturation of SDSS.*

of them have been found by the quasar survey and for this sample the limits were made based on the dereddened i-magnitudes of the objects. The histogram shows the whole list of 122 Ritter & Kolb CVs in the background with the ones that got a spectrum in front of them. The i-mag = 19.1 limit for the quasar sample is shown with the black dashed line. The majority of CVs with a spectrum ($\sim$ 85 %) have a dereddened i-magnitude measurement between 15 and 19. The 7 CVs with i-mag > 19.1 got a spectrum because they were either serendipitously blue or QSO_FAINT objects. By comparing the whole sample (shown in the background) to the ones with a spectrum (in the foreground), one can see that the relative difference between the two groups is largest at the bright and the faint end where the quasar survey did not target anything.

2.2 Catalina Real-Time Transient Survey

The Catalina Sky Survey (CSS; Larson et al. 2003) is a cooperation of 3 different surveys. The first and original Catalina Sky Survey started in 1998 and made use of the 0.7 meter Catalina Schmidt Telescope at Tuscon, Arizona. Two more surveys were added later on: the Mt. Lemmon Survey (MLS) with a 1.5 meter telescope near Tuscon and the Siding Spring Survey (SSS) using the 0.5 meter Uppsala Schmidt telescope at Siding Spring, Australia. The mission of CSS is to contribute to the discovery of 140m or larger Near Earth Objects (NEOs) and Potentially Hazardous Asteroids (PHAs) that are a risk to Earth. On a clear night CSS typically covers about 1200 square degrees

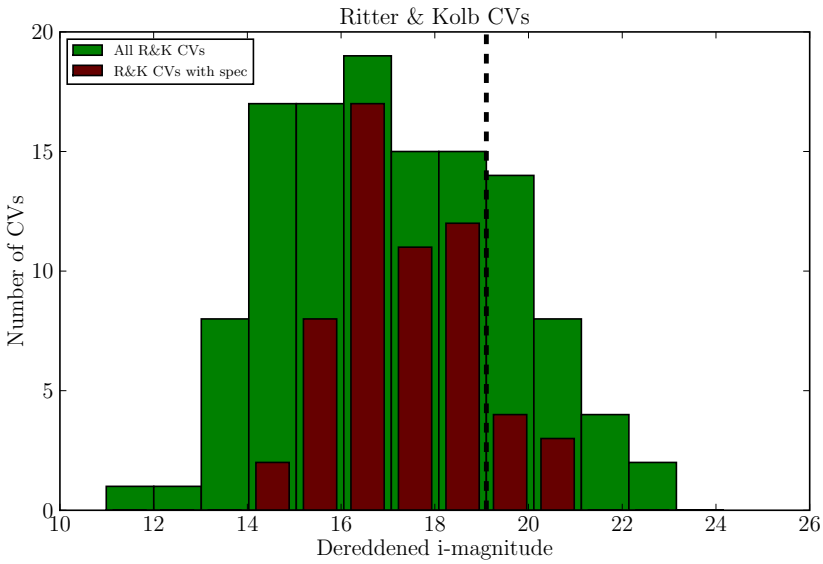

Figure 2.4: *A dereddened i-magnitude histogram showing all Ritter & Kolb cataclysmic variables in the background (in green) and the CVs from Ritter & Kolb with a spectrum in SDSS on the foreground (in brown). The 19.1 quasar border line at the faint end is shown with a dashed line. More than 85 % of the CVs with a spectrum are in the region between bright and faint, between a dereddened i-magnitude of 15 and 19.1.*

of sky in a sequence of four 30 second exposures. This set of four images taken in sequence allows to detect transients[3] varying on timescales from minutes to years. To date, the NEO Observations Program (NEOO) has discovered hundreds of PHAs and currently leads the rate of NEO discoveries.

In November 2007, the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2008) started searching for Optical Transients (OTs) with brightness variations differing by more than 2 magnitudes from previous detections, using the data gathered from CSS. The observed transients are both compared to previous CSS observations and to clean source catalogues to minimize the number of objects arising from image artifacts. The mission of CRTS is to understand known types of variables as well as the search for new OTs. More than 100 cataclysmic variables have already been detected this way, since outbursts make CVs variable in brightness. The results of this survey are put online and are updated in real-time as optical transients are discovered. This is being used as a testbed for VOEventNet technology[4] (Drake et al. 2006).

The last list of CVs that was downloaded for this research (April 2009) contained 172 cataclysmic variables. 82 CVs were in the right area of the sky to be imaged by

[3]Transients are luminous events of varying intensities. These events could be meteors passing by or just any other variable event that is going on at the sky.

[4]The VOEventNet project works on a transient event follow-up network which distributes structured data packets called VOEvents, designed to contain data for transients seen at all wavelengths, yet interpretable by robotic telescope systems.

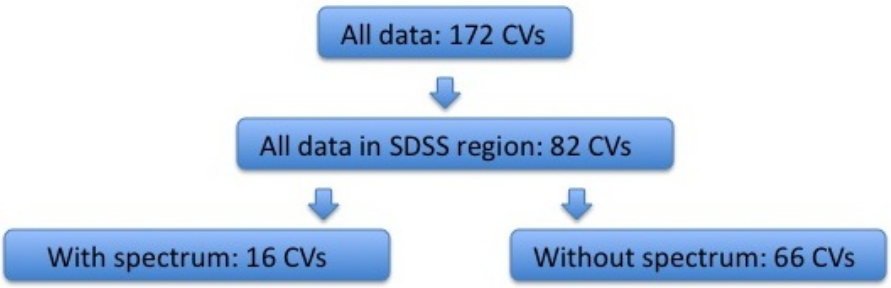

Figure 2.5: *A diagram showing the distribution of the 172 cataclysmic variables from the Catalina Real-Time Transient Survey. 82 CVs were in the right area of the sky to be detected by SDSS: 16 got a spectrum, the other 66 did not.*

SDSS. From this sample, 16 were targeted and got a spectrum, 66 did not get a spectrum (with 10 targeted objects without a spectrum). Fig. 2.5 shows all these numbers in a diagram. Less objects were targeted here compared to the Ritter & Kolb catalogue: about 20 % of the CRTS CVs got a spectrum, 80 % did not.

2.2.1 The CVs with no spectrum in SDSS

From the group of 66 CVs without a spectrum, 10 objects were targeted but did not get a spectrum because there were no spare fibers for these objects. 45 CVs were too faint to be observed by SDSS. For 6 objects there were problems with the spectrograph at the moment the spectra were taken, resulting in no spectra on the whole plate. 1 CV was rejected by a white dwarf exclusion box. The reason why the other 4 objects did not get a spectrum is not known. Fig. 2.6 shows all these numbers (in percentages) in a pie chart. Their dereddened i-magnitudes are shown in a histogram in Fig. 2.7. The big group of faint CVs is clearly visible at the right side of the 19.1 quasar limit shown with a dashed line in this figure. However, this group contains about 82 % of the CVs instead of 68 % (as shown in the pie diagram). This is because 9 out of the 10 objects in the group of CVs that were targeted but did not get a spectrum also had an i-mag > 19.1. The CVs at the left side of the 19.1 quasar limit are all the objects that did not get a spectrum due to spectroscopic problems, rejection boxes and some unknown reasons, together with 1 CV that was selected but did not get a spectrum.

It is pretty clear that CRTS found mainly faint objects. The reason for this is that all these CVs were observed at a moment they were in outburst, since CRTS looked for variability at the sky. At that time they were visible at a dereddened i-magnitude < 20 (limit of CSS). When the objects return to quiescence, they can become in average 5 - 6 magnitudes fainter. The large majority of these CVs was observed by SDSS at quiescence (no longer in outburst) and thus had a dereddened i-magnitude > 19.1 at the moment SDSS imaged them. At that point most of them were clearly too faint to get a spectrum.

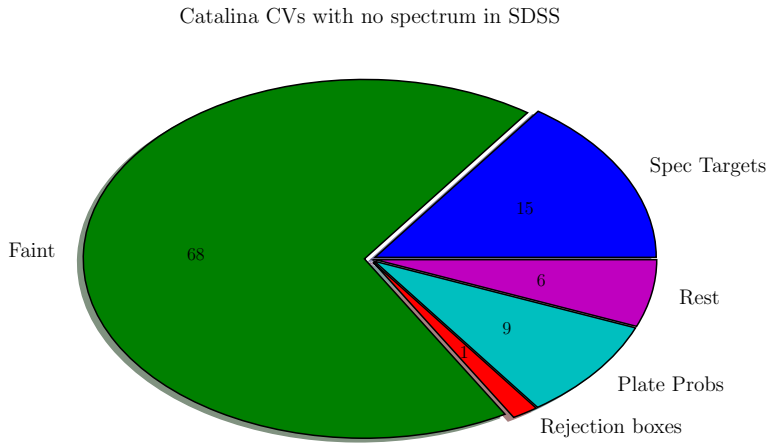

Figure 2.6: *A pie chart with the CVs from the CRTS put into different groups according to the reason they did not get a spectrum. 68 % of these CVs were too faint for SDSS, 15 % of the objects were targeted but did not get a spectrum, 1 % was rejected by the WD-rejection box, 9 % had spectroscopic problems and the last 6 % did not get a spectrum for some unknown reason.*

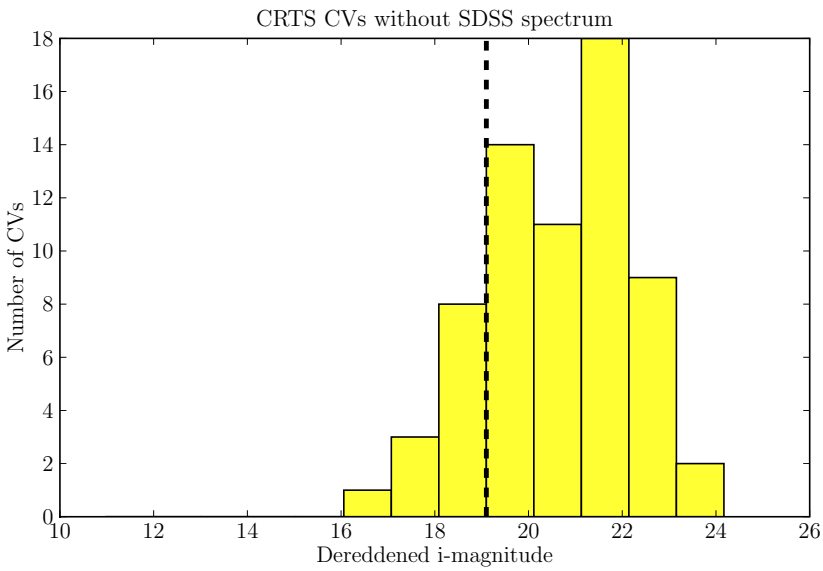

Figure 2.7: *A dereddened i-magnitude histogram showing the CRTS CVs that were imaged by SDSS but did not get a spectrum. The dashed line indicates the faint limit used by the quasar sample. The majority of objects have an i-mag > 19.1 and 80 % of these were too faint to be targeted by SDSS. For the few objects at the bright side there were problems with the spectrograph, they got into a rejection box or there was some other unknown problem.*

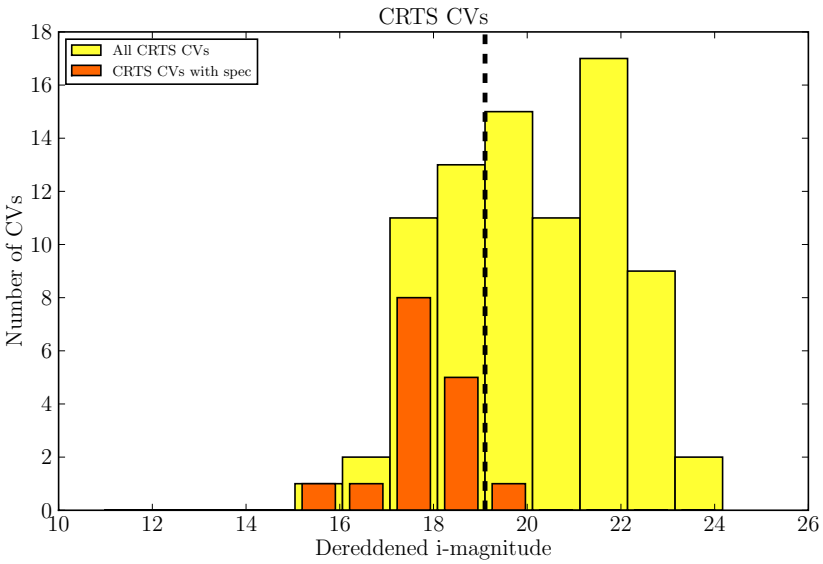

Figure 2.8: *A dereddened i-magnitude histogram for all CRTS CVs. The distribution of the full sample is shown in the background and the objects with a spectrum are put in front of them. Almost all objects that got a spectrum are at the left side of the 19.1 limit (shown by the dashed line) and were probably found by the quasar survey since they have the right luminosity.*

2.2.2 The distribution of CVs with an SDSS spectrum

Fig. 2.8 shows a histogram for the dereddened i-magnitudes of all the CVs from CRTS in the background with the 16 cataclysmic variables that got a spectrum in SDSS in front of them. 15 of the 16 CVs are at the bright side of the 19.1 dashed line, the one CV with an i-mag > 19.1 was targeted as a QSO_FAINT object. 94 % of all objects with a spectrum have an i-magnitude between 15 and 19.1. Comparing this to the 85 % of the Ritter & Kolb catalogue, less objects from the CRTS have been targeted with an i-magnitude outside the quasar magnitude range.

2.3 Spectral completeness of previously known CVs in SDSS

Both lists of CVs are now put together in order to be able to compute how complete SDSS has been in targeting the previously known CVs. From the previous two sections it is already clear that SDSS has been very incomplete in targeting CVs outside the quasar magnitude range (i-magnitudes higher than 19.1 and lower than 15). For the dereddened i-magnitude region in between these limits, SDSS seems to have done much better. How complete or incomplete SDSS really has been is discussed in the following sections.

2.3.1 CVs that did not get a spectrum

Fig. 2.9 shows all CVs that did not get a spectrum from the Ritter & Kolb Catalogue on top of the ones from the Catalina Real-Time Transient Survey. The CVs that were

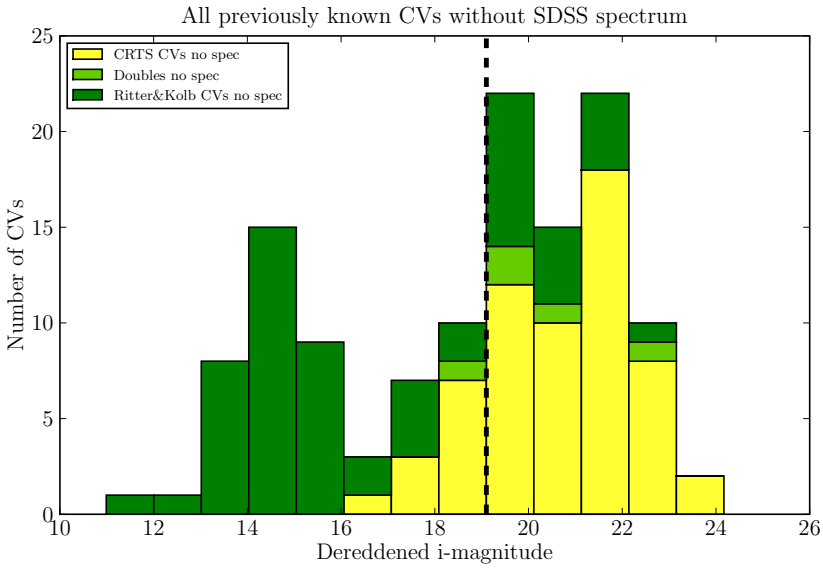

Figure 2.9: *A histogram showing the dereddened i-magnitudes of all objects from the Ritter & Kolb catalogue and the Catalina Real-Time Transient Survey with no spectrum in SDSS. The Ritter & Kolb CVs are plotted on top of the CVs from CRTS. The CVs that were present in both lists are shown between these two groups of CVs. The number of CVs at the faint end is more than half of the whole sample which shows that SDSS missed a lot of faint CVs.*

present in both lists of CVs are shown in a third colour in between these two groups. The height of each bin in the total histogram is the sum of the equivalent bins for the CRTS (without doubles), the Ritter & Kolb Catalogue (without doubles) and the doubles from both lists. This histogram clearly shows the incompleteness of SDSS towards the faint end: 57 % of all CVs with no spectrum are at the right side of the 19.1 quasar i-magnitude limit.

2.3.2 CVs that got a spectrum

The same summation over the two catalogues has been done for the total sample of CVs in SDSS and the sample of CVs with a spectrum. Fig. 2.10 shows the all the previously known cataclysmic variables in the background with the ones with a spectrum in front of them. All the objects from the Ritter & Kolb Catalogue are shown on top of the ones from the Catalina Real-Time Survey with the doubles in a third colour in between the two groups. As already said in the previous sections, the number of objects with a spectrum compared tot the total number of objects is largest for i-magnitudes between 15 and 19.1.

2.3.3 Discussion on spectral completeness

The spectral completeness of a sample of objects expresses the ratio of the number of objects with a spectrum to the total number of objects. Fig. 2.10 can be used to show the spectral completeness of SDSS as a function of i-magnitudes. The histogram in Fig. 2.11

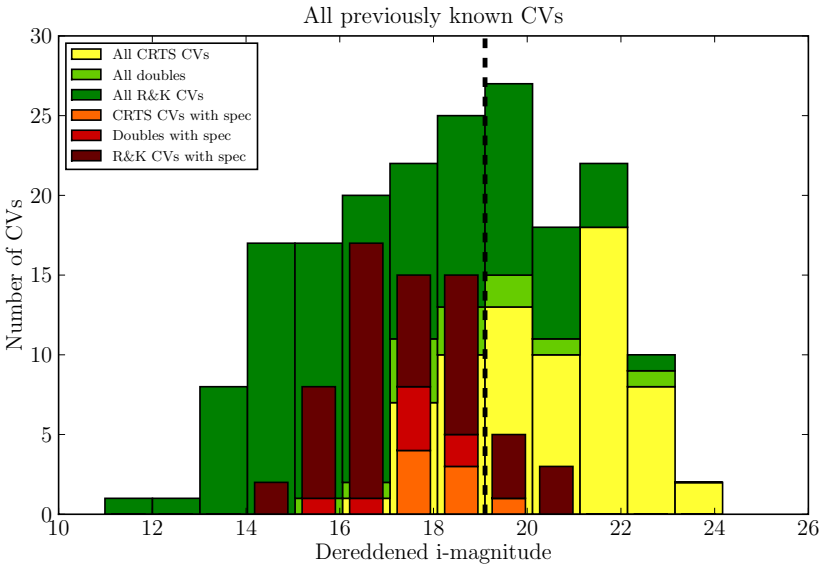

Figure 2.10: *A dereddened i-magnitude histogram for the previously known CVs taken from the Ritter & Kolb catalogue and the Catalina Real-Time Transient Survey. The full sample is shown in the background and the ones with a spectrum are in front of them. The number of objects from these two lists are plotted on top of each other for each magnitude bin, with the Ritter & Kolb CVs on top of the Catalina CVs and the doubles in between them.*

shows how complete SDSS has been in targeting the previously known CVs for each i-band magnitude bin. For objects with a dereddened i-magnitude between 15 and 19.1, the average completeness is 65 %. Only 18 % of all objects with an i-mag > 19.1 were targeted. This is as expected since most of the CVs were found in the quasar sample and the quasar survey did not target any object with a magnitude higher than 19.1. The overall spectral completeness (for the full magnitude range) is 34 %.

This however needs to be nuanced. Chapter 1 explained how most of the spectra in SDSS were taken during the quasar survey and the spare fiber selections of the Sloan Legacy Survey. The Sloan Supernova Survey only did repeated imaging. SEGUE however imaged objects in some parts of the sky and took spectra of a selection of these, using totally different criteria. Since SEGUE mainly searched for objects in the Galactic disc, it had to adapt its criteria to the large amounts of dust in the disc. Given the criteria used by SEGUE to select targets, the possibility that CVs were targeted is extremely small. SEGUE however imaged 5 % of the sky, independently of Legacy and no flag or indication has been found yet that says by which survey an object was imaged. This means that some of the previously known CVs might have been observed by SEGUE and not by Legacy so that these CVs are not part of the uniform sample and should be eliminated. A way to exclude a lot of photometric objects imaged by SEGUE is by excluding the area of the sky where the Galactic disc is situated. None of the previously known CVs was situated at the position of the Galactic disc, so that

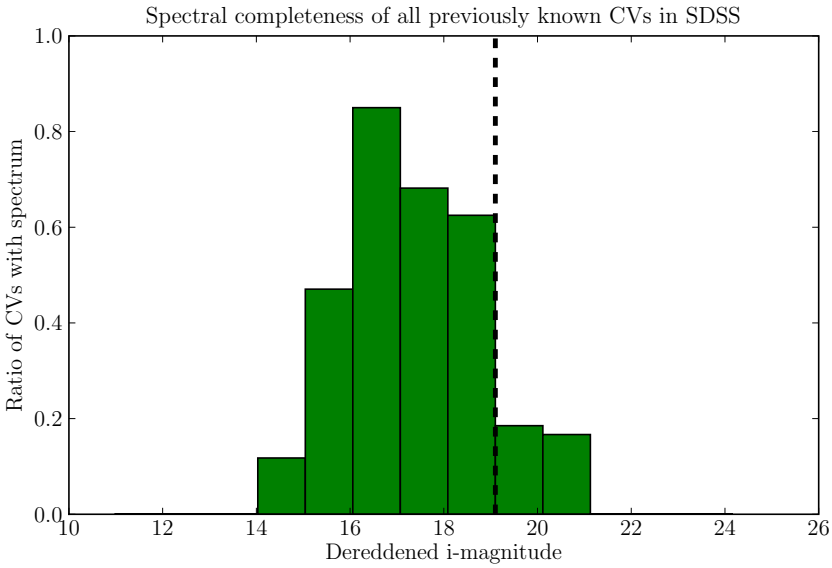

Figure 2.11: *An i-magnitude histogram giving the ratio of objects with a spectrum to the total number of objects for the different dereddened i-magnitude bins. This is called the spectral completeness of the previously known CVs in SDSS, where the previously known CVs from the Ritter & Kolb Catalogue and the Catalina Real-Time Transient Survey are used.*

is no problem. Some other smaller regions further away from the disc however were also imaged by SEGUE. The influence of these regions still needs to be considered in the future. Excluding the photometry from SEGUE should increase the spectral completeness computed here.

Chapter 3

All CVs with a spectrum in SDSS

Before SDSS started observing, cataclysmic variables were discovered by different methods, making use of different characteristics of these binaries: variability, X-ray emission and blue colours. SDSS is the largest and deepest survey ever that took spectra of CVs in a broad range of colour and brightness. The previous chapter showed that in the luminosity range [15 - 19.1], SDSS recovered about 65 % of all previously known cataclysmic variables. Next to these however, SDSS also discovered a lot of new CVs. Up to now, people have found 279 CVs with a spectrum in SDSS.

Section 3.1 first discusses all objects that have been observed by SDSS (called the photometric database of SDSS): the density and the spectral completeness of all point sources is shown in 2 and 3-dimensional colour-colour plots. Section 3.2 shows the position of the 279 CVs on these colour-colour plots and uses specific regions in colour space to estimate the spectral completeness of all CVs in SDSS.

3.1 Photometric point sources in colour space

3.1.1 Data Release 7

Over the years, the Sloan Digital Sky Survey released its data in pieces. In July 2008, SDSS-II finished its observations and in November that same year the last data release (data release 7 or DR7) was made public (Abazajian & Sloan Digital Sky Survey 2009). This data can be downloaded from CASJobs (the Catalog Archive Server Jobs System) which takes your query and returns the data that was asked for. For this thesis a sample of point sources[1] was downloaded from the photometric database, covering a very broad magnitude range: all objects with a g-magnitude[2] between 13.0 and 23.0 were allowed. For each object in this list the following parameters were downloaded: the

[1]Remember that both CVs as quasars are point sources and not extended objects.

[2]For this query, objects were selected based on the values of their magnitudes in the g-band. This could as well have been done based on the magnitudes of any other band. Since a lot of previous surveys

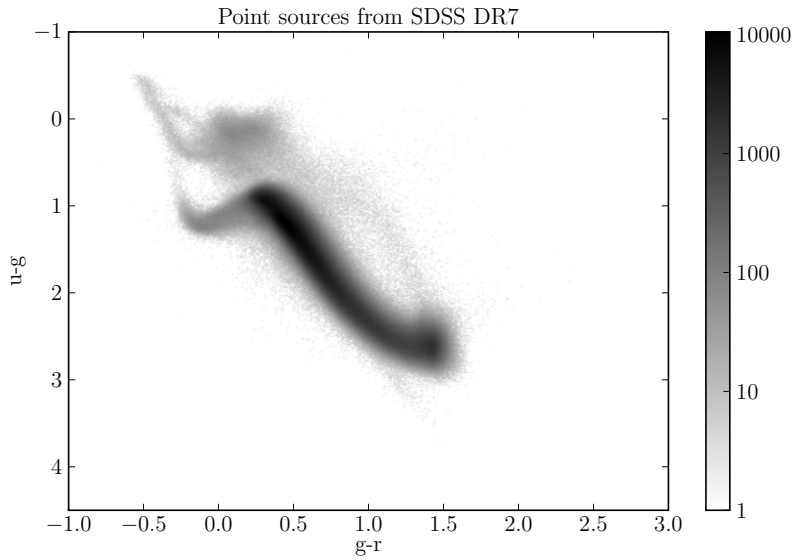

Figure 3.1: *A colour-colour density histogram for u-g as a function of g-r showing the density distribution of all point sources in SDSS on a logarithmic greyscale. The main-sequence is visible in the middle of the figure as a black broad line. On top of the main-sequence the region of the low redshift quasars can be seen as a grey spot.*

magnitudes in 5 bands, the errors on the magnitudes, the extinction in each magnitude band, the coordinates and an entry to indicate if a spectrum was taken or not. After downloading this data, a few cuts were made on the whole set of point sources. Even though the majority of objects were targeted at galactic latitudes $|b| > 30°$, SEGUE made observations in the region of the galactic disc ($|b| < 30°$). Since SEGUE used different selection criteria, it is best to try to keep this data out of the sample. This is why only point sources with galactic latitudes $|b| > 30°$ were allowed into the photometric data list. Next to that, for most of the work in this chapter only objects with an i-magnitude smaller than 19.1 (the limit used by the quasar sample to target objects) are used for the calculations and figures. Since SDSS did not target a lot of objects with an i-magnitude higher than 19.1 (as was shown in Chapter 2), this chapter will mostly focus on the point sources with an i-magnitude lower than 19.1. For some parts however it will be important to use all the objects and then it will be mentioned in the text.

3.1.2 Density histogram of all point sources

The colours of all the objects in the photometric data list are part of a 4-dimensional colour space (u-g), (g-r), (r-i), (i-z) in SDSS. Figs. 3.1 (ugr colour space), 3.2 (gri colour space) and 3.3 (riz colour space) show all the point sources in different 2-dimensional

searched for CVs with blue colours, it has become more common to use the blue g-band to look for CVs instead of for example the red i-magnitude band.

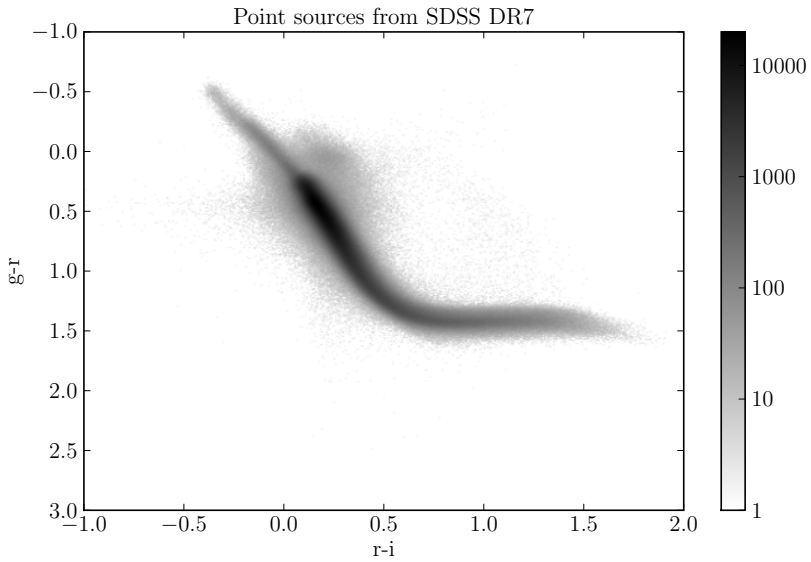

Figure 3.2: *A colour-colour density plot made with r-i on the x-axis and g-r on the y-axis displaying the number of point sources in SDSS in a 2-dimensional greyscale histogram. The dark grey region in the middle of the figure going diagonally from upper left to lower right and then horizontally to the right is the main-sequence.*

colour-colour projections. Instead of putting all the objects as regular points on the colour diagrams, each of the colour axes was divided into 400 equal parts. In this way a grid of 400 by 400 was made to create 2-dimensional histograms. The logarithmic greyscale expresses the third dimension of these plots so that a black grid element contains the maximum number of objects and a white grid element none. In all three figures a dark grey region is visible with a high density of point sources. This region represents the main-sequence (the region in colour space containing the core hydrogen burning main-sequence stars as our Sun). In Fig. 3.1 the main-sequence is represented by the dark grey broad line going from the upper left corner to the lower right corner of the rectangle with sides g-r = [0.3 - 1.5] and u-g = [1 - 3]. In this figure the region of the low redshift quasars is also visible as a grey spot above the main-sequence, centered at g-r = 0.25 and u-g = 0.75. Some more features about this colour-colour density histogram are explained in Smolčić et al. (2004). In Fig. 3.2 the main-sequence can be found as a dark line going from the upper left corner to the lower right corner of the rectangle with sides r-i = [0.1 - 1.8] and g-r = [0.2 - 1.5] where the left part of the line makes an angle of 135° with the right part. Fig. 3.3 shows the main-sequence as a straight line from the upper left corner to the lower right corner of the rectangle with sides i-z = [0 - 1] and r-i= [0 - 1.7].

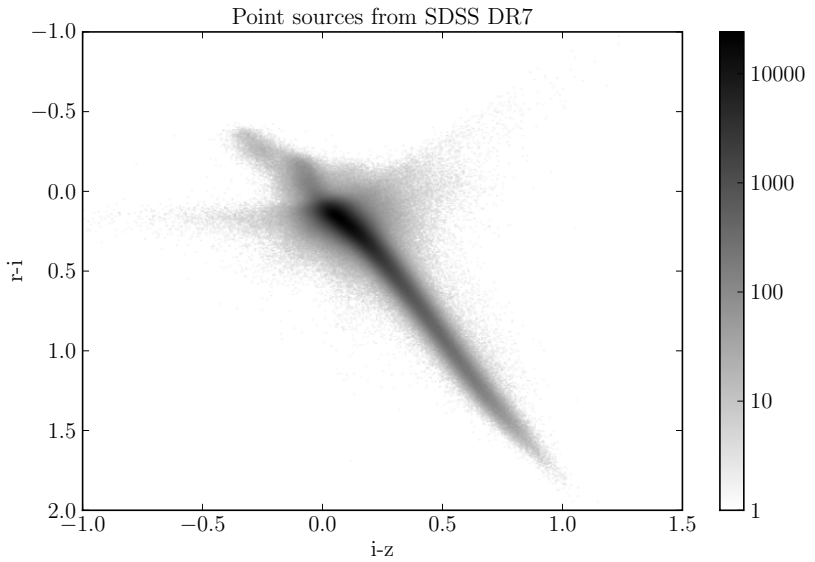

Figure 3.3: *A colour-colour density plot with r-i as a function of i-z showing the distribution of all point sources from SDSS DR7 in a logarithmic greyscale histogram. The main-sequence is visible as a dark grey straight line in the middle of the figure that goes from upper left to lower right.*

3.1.3 Spectral completeness histogram of all point sources

Using the entry in the photometric data list that indicates if an object has got a spectrum or not, the spectral completeness[3] of all point sources in SDSS can be calculated. Again, 2-dimensional projections were made of the 4-dimensional colour space of SDSS. A grid of 400 by 400 was created and for each grid element the spectral completeness was computed and displayed using a linear greyscale (with black indicating a spectral completeness of 100 % and white a spectral completeness of 0 % or just no objects in that grid element). The three projections are shown in Figs. 3.4 (ugr colour space), 3.5 (gri colour space) and 3.6 (riz colour space). The main-sequence is now visible as a white area in each of these three spectral completeness histograms. This is not unexpected since main-sequence stars have barely been targeted in SDSS (the quasar survey for example excluded the largest part of the main-sequence with the stellar locus cut). The quasar region on the other hand is almost black in Fig. 3.4. Remember that the point sources displayed here have an i-mag < 19.1. During the first tests of SDSS, Richards et al. (2002) predicted that the spectral completeness of the final quasar sample (so for objects below the 19.1 limit) would be larger than 90 %, which can be confirmed with these figures. Apart from that, the exclusion boxes used by the quasar survey are visible on these colour-colour histograms as regions with a clearly lower spectral completeness (look at Fig. 1.4 to find the positions of the boxes).

[3]The spectral completeness of a sample of objects is the ratio of the number of objects with a spectrum to the total number of objects.

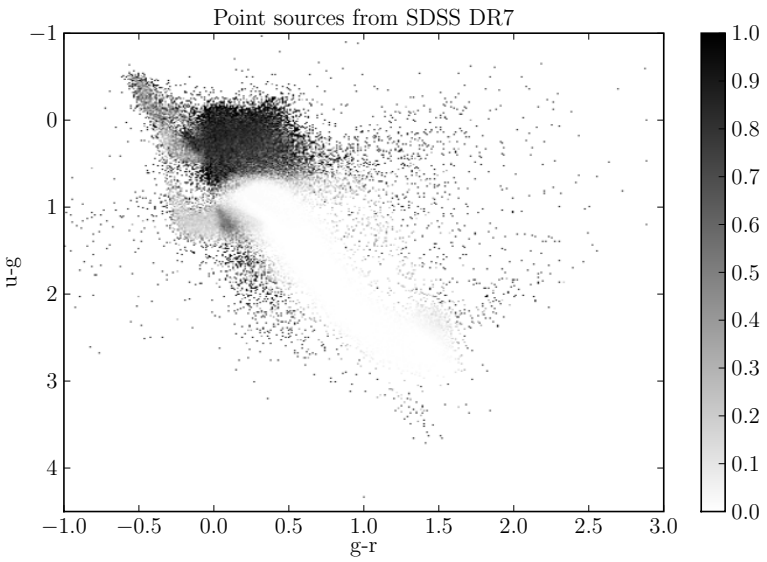

Figure 3.4: *A colour-colour histogram with u-g as a function of g-r showing the spectral completeness of all point sources in SDSS DR7. The main-sequence has barely been targeted but the quasar region above the main-sequence on the other hand has a very high spectral completeness. The A star and white dwarf exclusion boxes are also visible at the left side of the quasar region.*

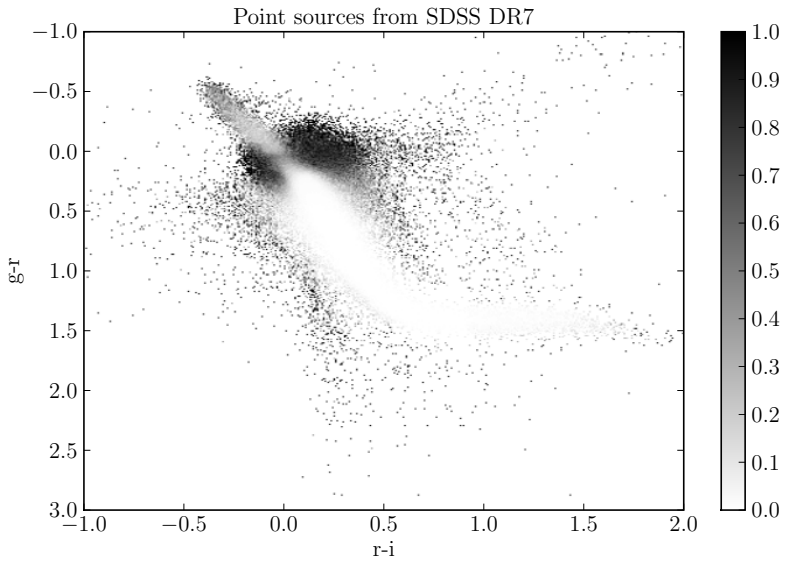

Figure 3.5: *A greyscale colour-colour plot made with g-r on the x-axis and r-i on the y-axis giving the spectral completeness of all point sources in SDSS through a 2-dimensional greyscale histogram. The white region on the plot corresponds to the main-sequence which has a very low spectral completeness. Both white dwarf, A star and white dwarf main-sequence boxes are visible on this plot.*

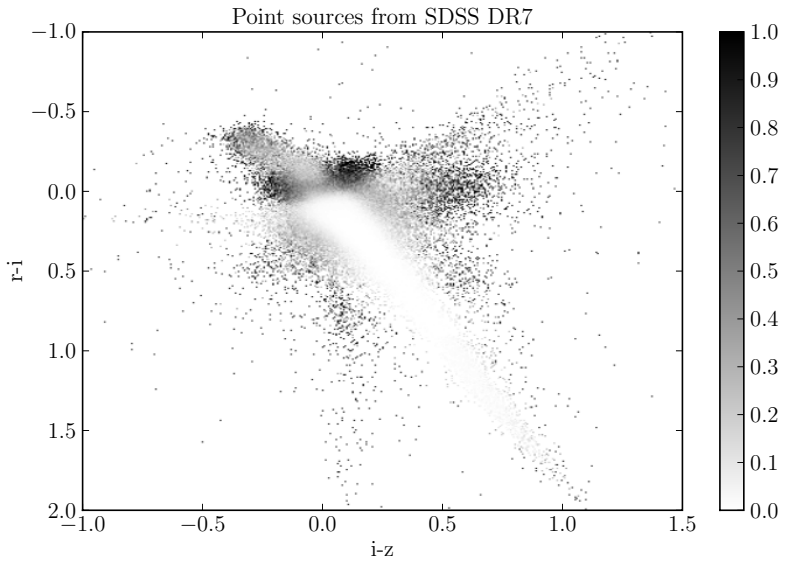

Figure 3.6: *A colour-colour histogram with r-i as a function of i-z showing the spectral completeness of all the point sources in SDSS in a linear greyscale. The main-sequence has a really low spectral completeness and can be seen as a broad white region in the middle of this histogram. The position where objects were excluded through the white dwarf, A star and white dwarf main-sequence boxes are visible.*

3.1.4 The density and spectral completeness in 3 colour dimensions

The density and spectral completeness histograms that were shown in the previous sections are all 2-dimensional projections of the 4-dimensional colour space of SDSS. There are two more colour dimensions to each of these figures that cannot be shown in these representations. A way to make parts of one of these two other colours visible is by cutting the whole sample of objects in slices based on the third colour. For all the different subsamples the density and spectral completeness histograms can be made, allowing one to look into a third colour dimension. This has been done for the density histograms in Figs. 3.7 (ugri colour space) and 3.8 (griz colour space) and for the spectral completeness histograms in Figs. 3.9 (for ugri colour space) and 3.10 (for griz colour space). Each figure shows the original histogram for the whole sample at the top and the histograms made for two slices below. The reason that only two slices were used is that the most prominent features are always situated around the middle part of the whole colour range. One cut then shows the direction of these features in the third colour dimension. These histograms are still made using a grid of 400 by 400 for the two original colours.

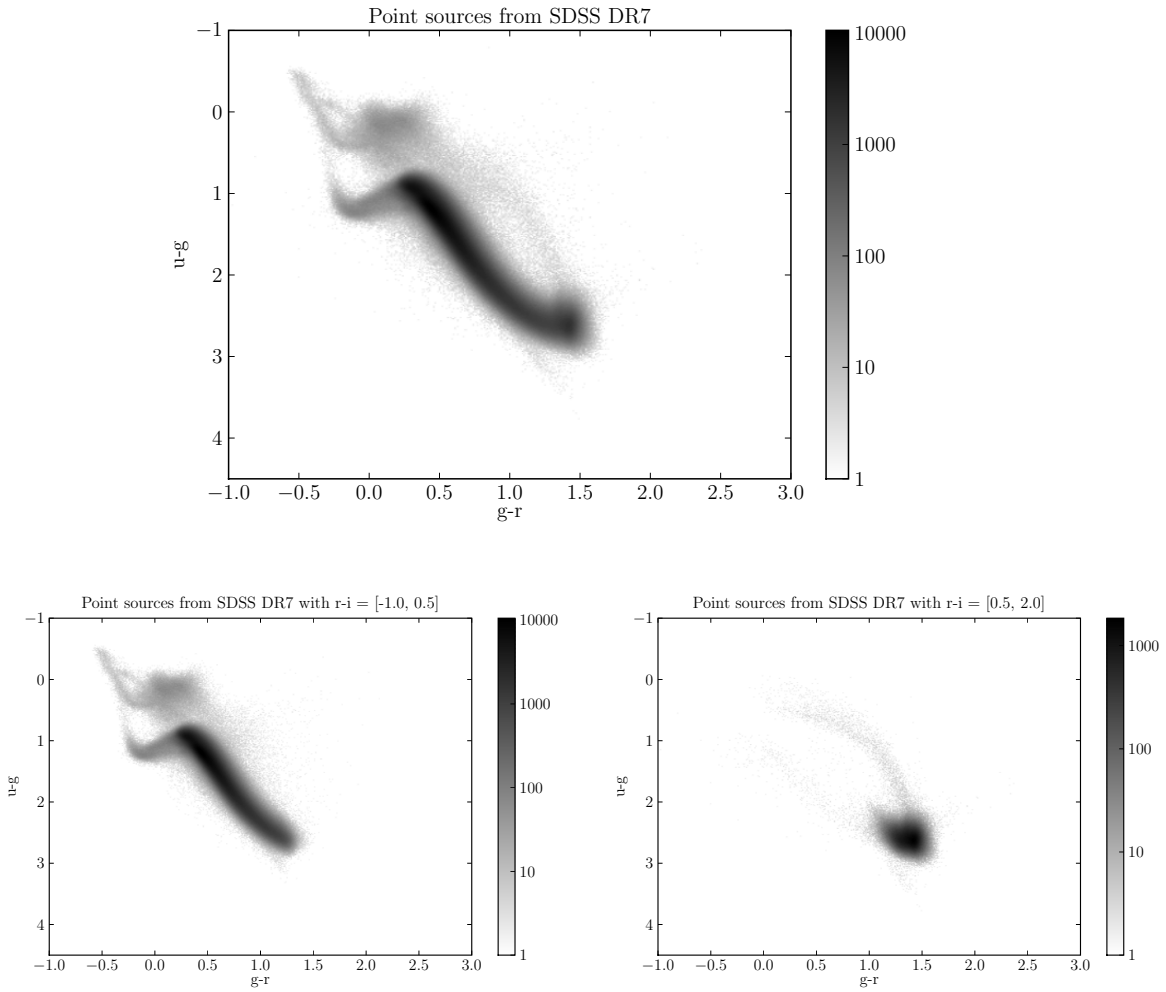

Figure 3.7: *Three colour-colour histograms showing the density distribution of all point sources in SDSS in different projections of the 4-dimensional colour space. At the top Fig. 3.1 is shown again. For the two figures underneath it, only objects with certain values of a third colour (r-i) are selected: the figure at the left contains objects with an r-i = [-1.0 , 0.5], the one at the right with r-i = [0.5 , 2.0]. Summing over all objects in the corresponding grid element of both figures, would again lead to the figure at the top.*

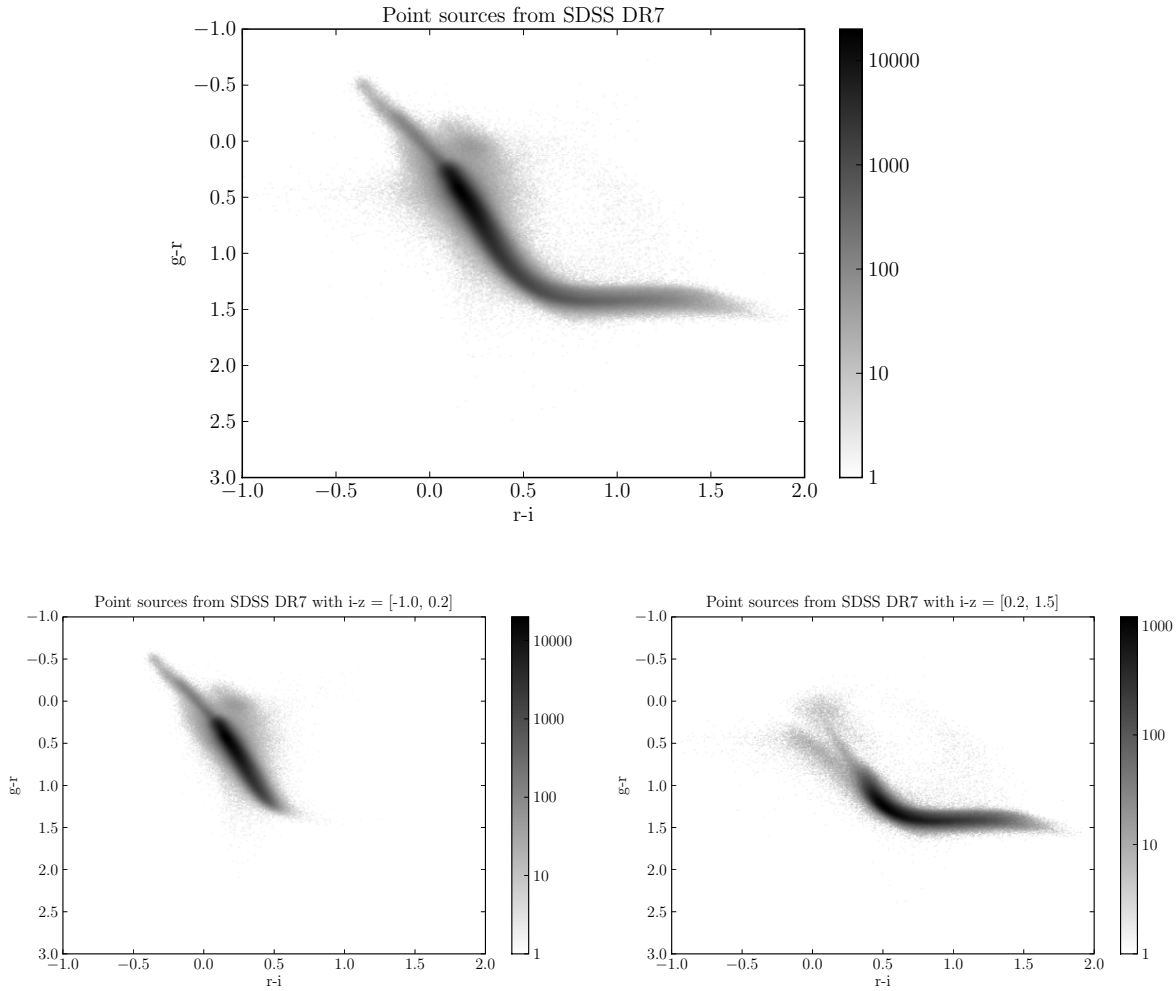

Figure 3.8: *Three different colour-colour projections giving the density of point sources in SDSS through 2-dimensional logarithmic greyscale histograms. The top figure shows the projection onto gri colour space that was shown in the previous section in Fig. 3.2. The two figures at the bottom are made for each of the two parts of the sample after it was cut in two based on a third colour dimension i-z. The one at the left shows objects with an i-z colour between -1.0 and 0.2, the figure at the right shows objects with an i-z colour between 0.2 and 1.5. A summation over the number of objects in both figures at the bottom would result in the figure at the top.*

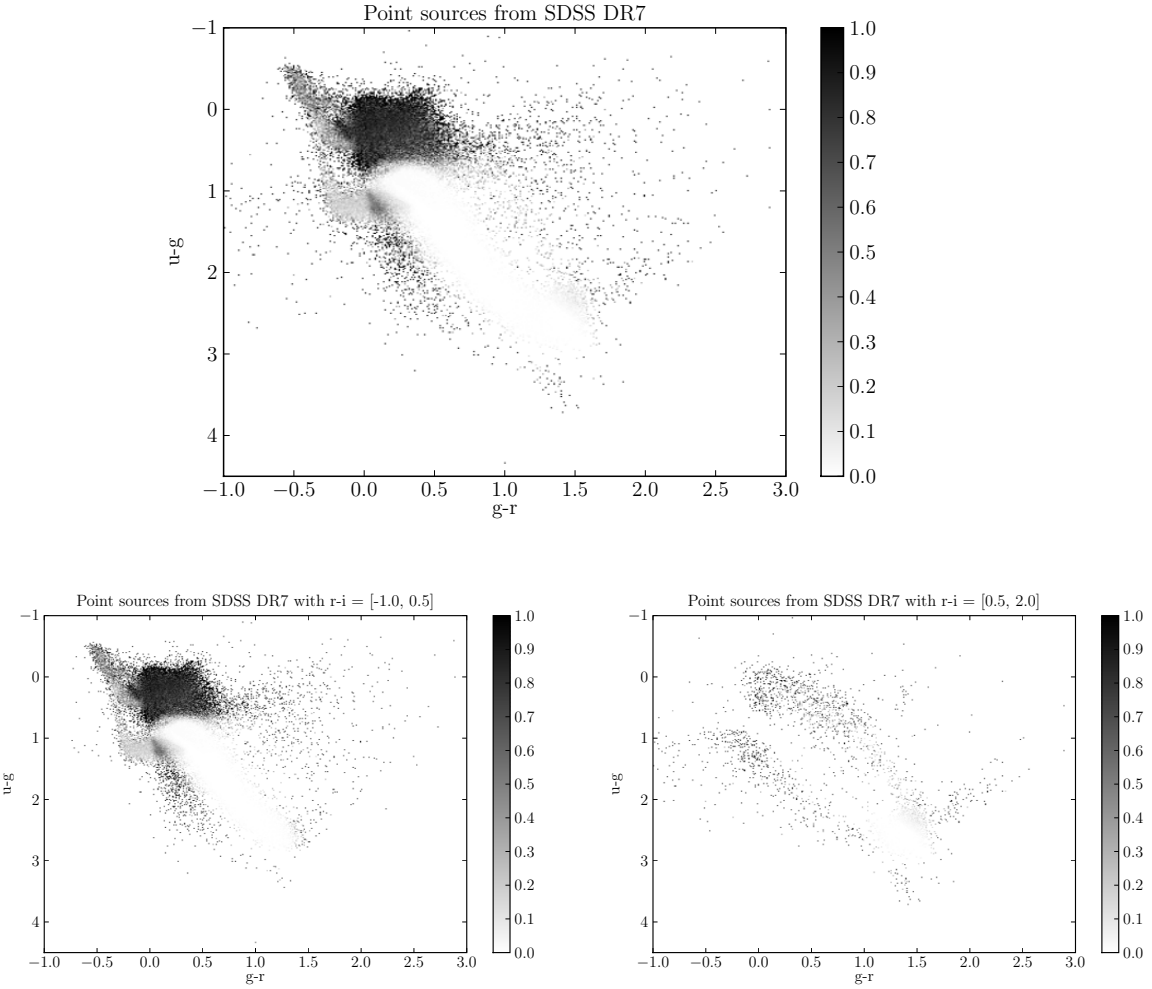

Figure 3.9: *Three colour-colour plots showing the spectral completeness of point sources in SDSS using greyscale histograms. The top figure was shown before in Fig. 3.4. In the two plots at the bottom the sample has been cut according to the value for r-i. For each group a new histogram has been made: the left figure is made for objects with an r-i = [-1.0 , 0.5], the one at the right is for objects with r-i = [0.5 , 2.0]. Summing over all objects with a spectrum in the same grid elements of the left and right figure and taking the ratio of this number to the sum of all objects in these grid elements of both bottom figures, would lead to the spectral completeness histogram as shown in the top figure.*

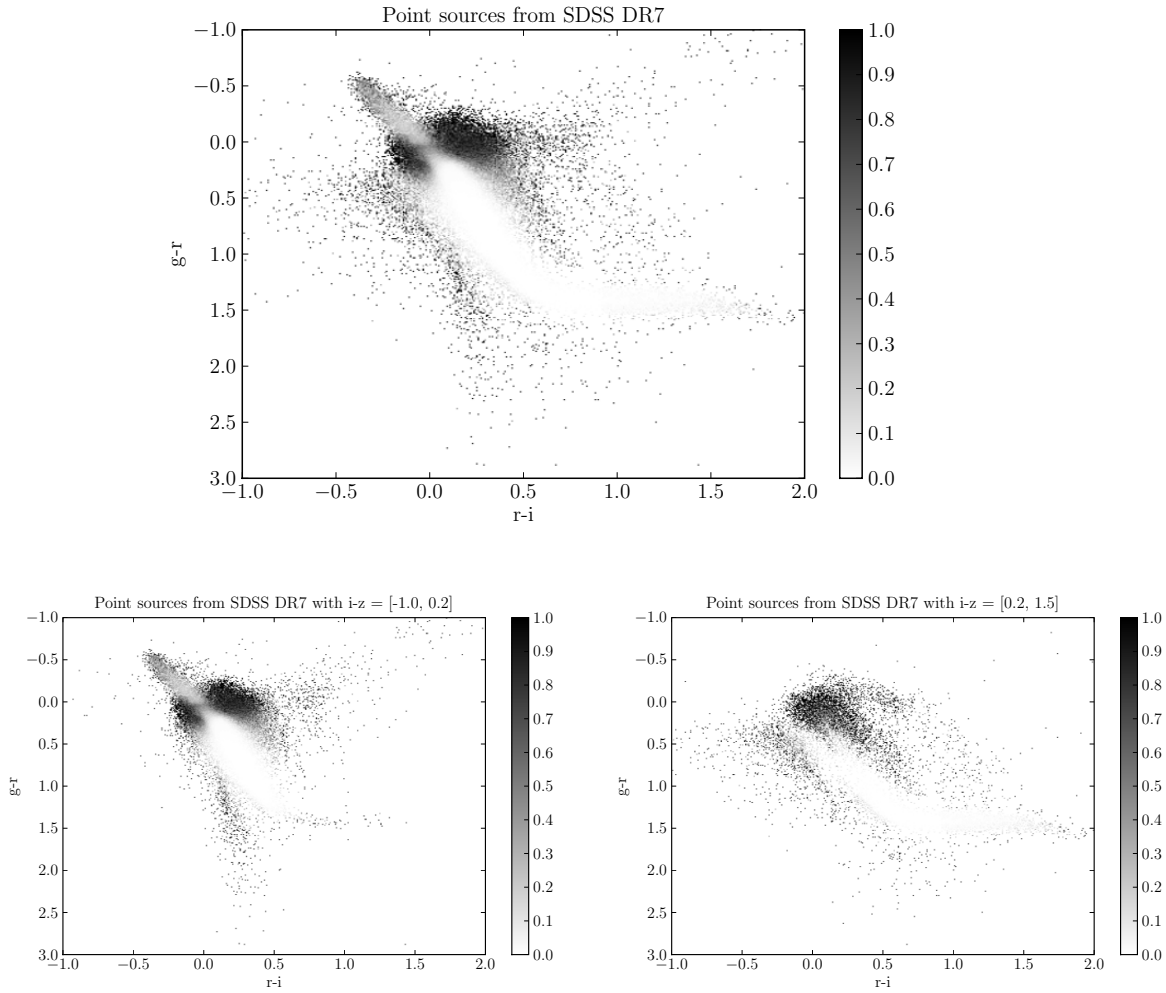

Figure 3.10: *Three colour-colour histograms giving the spectral completeness of the sample of point sources in SDSS. The figure seen at the top is Fig. 3.5. For the two figures below, the i-z colour range (and thus also the whole sample of objects) has been divided in two and for each group of objects a new histogram was made. The histogram at the left shows all objects with i-z = [-1.0 , 0.2] and the one at the right shows all objects with i-z = [0.2 , 1.5]. Dividing the summation of objects with a spectrum from both figures in the same small area by the sum over all objects from both plots in that same area, would give the spectral completeness from the top figure in that area.*

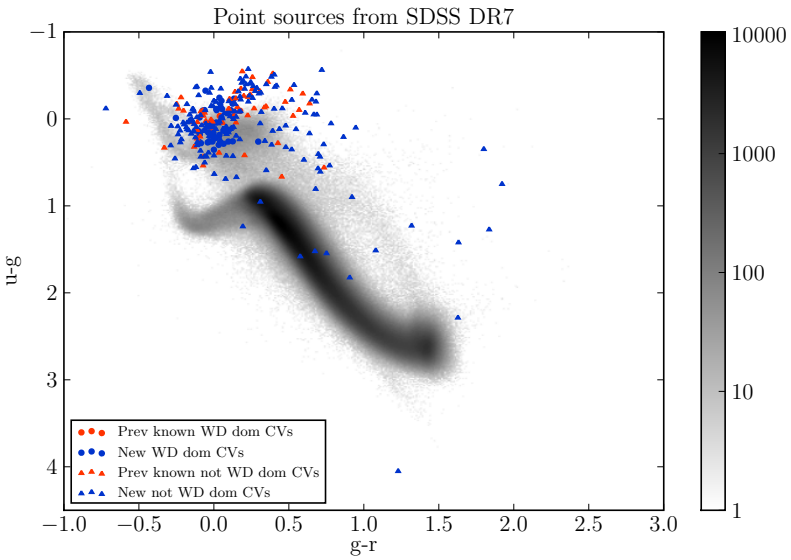

Figure 3.11: *A density colour-colour plot for all point sources imaged by SDSS with all CVs that were targeted by SDSS in different colours and symbols on top of it. It can clearly be seen that most of the CVs are in the low redshift quasar region.*

3.2 Spectral completeness of all CVs in SDSS

3.2.1 All CVs targeted by SDSS

The easiest way to identify a cataclysmic variable is by using the strong hydrogen Balmer and/or helium emission lines in its spectrum. For SDSS, a large part of this has been done by Paula Szkody and coworkers. Almost all CVs they found with a specturm in SDSS were published (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009). The CVs from the last data release are the only ones that have not been published yet. Together with some ten other cataclysmic variables found by other people, a list of 279 CVs with a spectrum in SDSS was available to use and analyse. In Figs. 3.11, 3.12 and 3.13 all these CVs are shown on top of the density histograms from the previous sections. The whole magnitude range was allowed for these CVs, so not only the ones with an i-magnitude lower than 19.1. The colour and symbol code used on these colour-colour density histograms is as follows. Blue CVs are newly discovered by SDSS, red CVs were previously known and rediscovered by SDSS. The spheres represent CVs where the spectrum is dominated by the white dwarf[4], the triangles are all the others where the spectrum is not white dwarf dominated. Examples of different kinds of CVs are given in Appendix A.1.

The distribution of CVs in Fig. 3.11 is quite noticeable. The large majority of cataclysmic variables is situated above the main-sequence in the so called low redshift

[4]These are the so called white dwarf dominated CVs that are believed to populate the period minimum spike that was until recently not observed in the orbital period distribution of CVs.

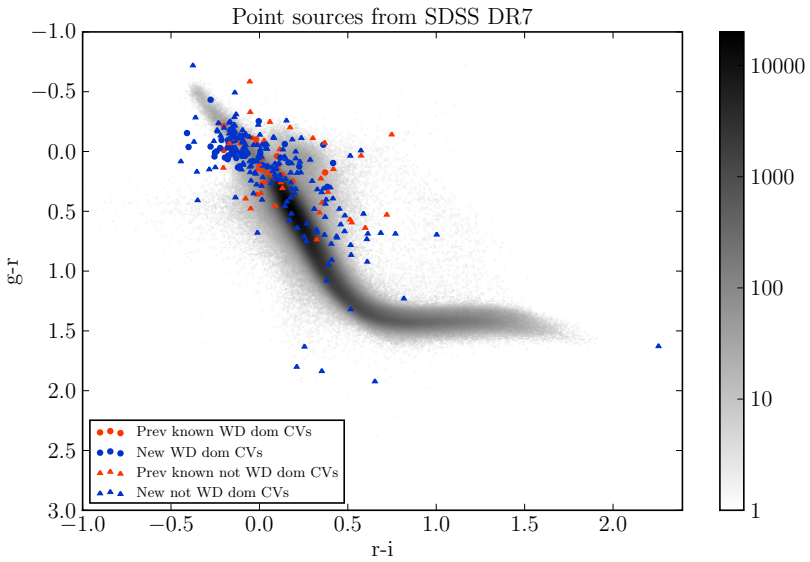

Figure 3.12: *A greyscale density histogram showing all the point sources from SDSS in gri colour space in the background with the CVs found so far in the spectroscopic database of SDSS in blue and red dots and triangles on top of it.*

	Previously known CVs	New CVs
WD dominated CVs	4	44
Not WD dominated CVs	54	177

Table 3.1: *The distribution of CVs with a spectrum in SDSS. The CVs are divided into groups according to whether they were previously known or not and if their spectrum is dominated by the white dwarf or not. 80 % of these CVs are not white dwarf dominated while SDSS increased the sample of white dwarf dominated CVs by a factor of eleven.*

quasar region. All the previously known CVs (shown in red) have colours in this region. SDSS however also discovered CVs outside of this region (shown in blue). Since cataclysmic variables can have a wide range of colours, it is good to see that SDSS increased the colour range of the sample of known CVs. The numbers of CVs in each of the four groups (white dwarf dominated, not white dwarf dominated, previously known and new discovered CVs) are shown in Table 3.1. More than 80 % of these CVs are not white dwarf dominated. This can be understood remembering that the white dwarf dominated CVs populate the lowest periods and these are the intrinsically weak CVs which are not easy to find. With this in mind however, it is remarkable to see that SDSS increased the sample of white dwarf dominated CVs with a factor of eleven. Compared to previous surveys, SDSS was able to select fainter objects for a spectrum (i-mag < 19.1 instead of ~ 17.5 in previous surveys).

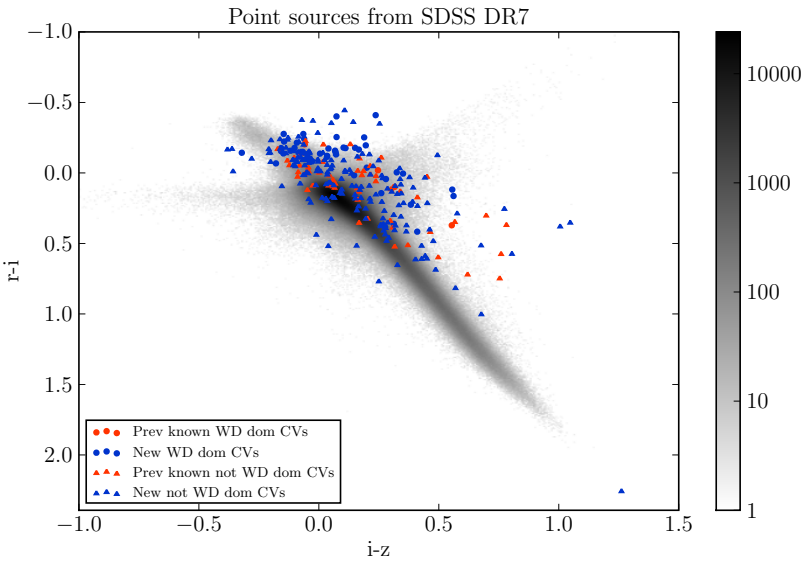

Figure 3.13: *A greyscale colour-colour density plot of all point sources in SDSS with i-z on the x-axis and r-i on the y-axis with the 279 CVs that were targeted by SDSS and found up to now in blue and red shown on top of it.*

3.2.2 Discussing the white dwarf dominated sample of CVs

Fig. 3.14 shows the i-magnitude histogram for all white dwarf dominated CVs with a spectrum in SDSS, Fig. 3.15 shows the i-magnitude histogram for the not white dwarf dominated ones. In both histograms, the i-mag = 19.1 limit used by the quasar survey is indicated with a black dashed line. When comparing the two histograms, several things should be noticed about their shape. First of all, the distribution of the bright CVs (i-mag < 19.1) is totally different for the two groups of CVs. It can be seen that the lower limit of the histogram (the smallest i-magnitudes) differs by about 1 mag between the two groups (16 for the WD dominated CVs, 15 for the not WD dominated ones). This mainly shows that white dwarf dominated systems are intrinsically fainter. The much smaller percentage of white dwarf dominated systems with an i-mag < 19.1 (about 45 % of all WD dominated CVs) compared to the not white dwarf dominated CVs (about 80 % of all not WD dominated CVs) confirms this.

Looking beyond the i-mag = 19.1 limit shows that the number of white dwarf dominated CVs does not decrease as much for i-mag > 19.1 (stays about the same up until an i-mag $\approx$ 20.5) compared to the not white dwarf dominated sample. The decrease in the number of CVs in the latter sample was explained before, using the quasar sample that mainly targeted objects with an i-magnitude smaller than 19.1. Since white dwarf dominated CVs are intrinsically faint objects there are much more faint WD dominated CVs and so it is normal that SDSS targeted more of the WD dominated CVs than the not white dwarf dominated ones. It is however still remarkable to see that SDSS took spectra of so many faint systems. Next to the quasar sample, SDSS used its spare fibers

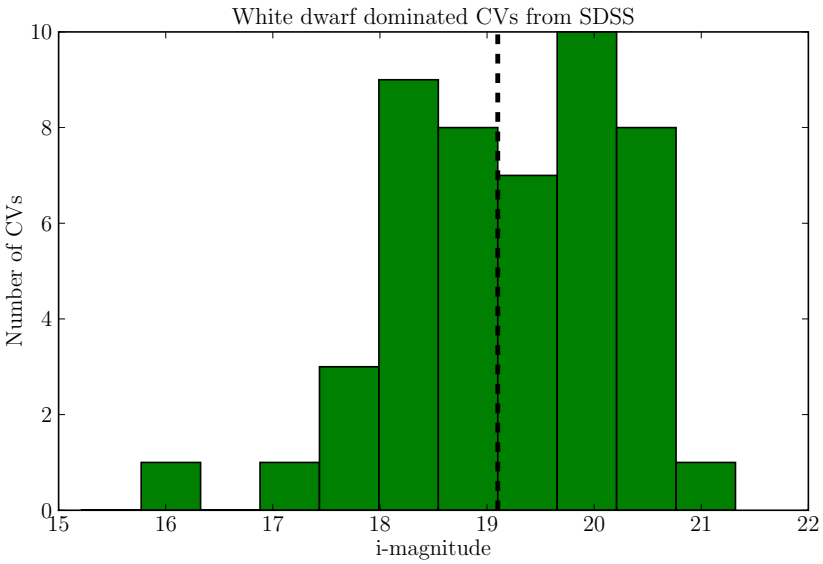

Figure 3.14: *A histogram showing the i-magnitude distribution for all white dwarf dominated SDSS CVs known up to now. The dashed line represents the 19.1 quasar limit. There are still quite a lot of blue CVs at the faint side of this border line and that the histogram ramps up to an i-magnitude around 20.5. Most of these faint CVs were targeted through serendipity criteria.*

to target serendipity objects (extreme blue, red or distant) and quasar targets with an i-mag > 19.1. 26 white dwarf dominated CVs had an i-mag > 19.1 and got their spectrum as faint quasar candidates and serendipitously blue or distant objects.

3.2.3 Focus on a cluster of CVs

The aim of this Chapter is to compute the spectral completeness of all CVs in SDSS. To find this ratio, both the number of CVs with a spectrum and the total number of CVs that have been observed by SDSS are needed (both with and without a spectrum). 279 CVs with a spectrum in SDSS are known up to now, most of them found by Paula Szkody using the detection of hydrogen and/or helium emission lines in the spectra of CVs. There might still be CVs with a spectrum in the spectroscopic database of SDSS that have not been found yet. Apart from that, a number of CVs with no spectrum is needed and there is no way to find the CVs in the photometric database of SDSS that did not get a spectrum. Only an estimate of this number can be made.

To do this, only that part of the 4-dimensional colour space was allowed where the density of CVs is highest, i.e. the low redshift quasar region above the main-sequence as shown in Fig. 3.11. The main reason for this is that an attempt was made to find more cataclysmic variables with a spectrum in SDSS, to make sure that the number of CVs with a spectrum was reliable enough. There was no use in looking for CVs with the spectral emission line method of Paula Szkody. The CVs that are left should be systems that are not easily found with this method. There is no point in looking at random spectra and there is no time to look at all the spectra. For that reason, a search

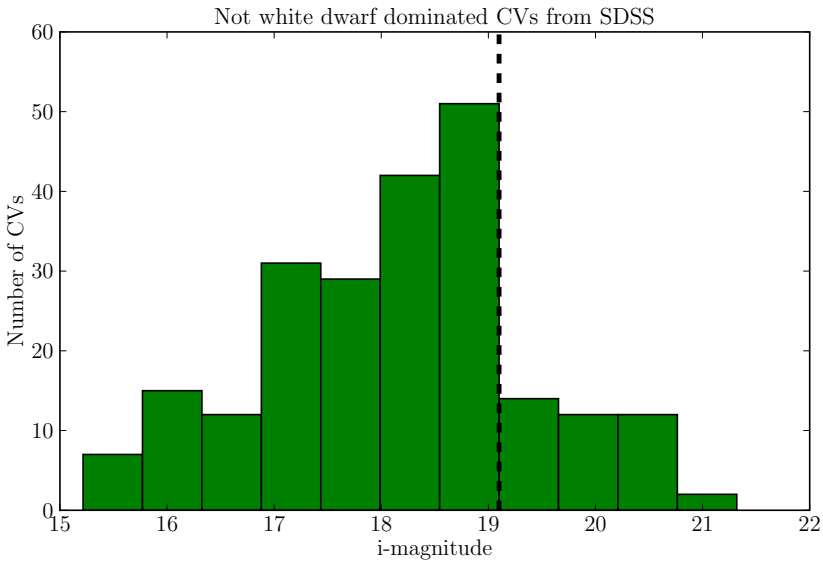

Figure 3.15: *A dereddened i-magnitude histogram made for all the not white dwarf dominated CVs targeted by SDSS. The black dashed line shows the 19.1 border line used by the quasar survey. Less objects with an i-magnitude fainter than 19.1 have been targeted compared to Fig. 3.14. This gradual decrease could indicate a real decrease in number of objects at those distances.*

was started for CVs with similar colours as the ones that had already been found. Since the region of space with the highest density of CVs (the low redshift quasar region) also has a high spectral completeness (see Fig. 3.4), the chance of finding more CVs is highest in this part of 4-dimensional colour space.

The region of 4-dimensional colour space with the highest CV density was created by making 4-dimensional spheres around each CV with an u-g < 0.75 (to exclude the main-sequence). The size of the spheres was adjusted so that each sphere contained an average of 20 objects with a spectrum. Most of the CVs were surrounded by a sphere with a radius of 0.045 mag. For the CVs that had less than 7 objects[5] in the sphere of radius 0.045, a sphere of radius 0.080 was used. The resulting $\sim$ 5000 spectra were looked at by eye to search for new cataclysmic variables. Only 1 new CV was found (SDSSJ093220.93+133122.2). This probably means that most of the CVs have been found with the emission line method and that the list of 279 CVs is reliable enough for the total number of CVs with a spectrum in this region of colour space. Assuming that most of the CVs in the spectroscopic database of SDSS have been found, the next step is to estimate the number of CVs that did not get a spectrum.

To do that, the radius of the spheres was increased. The goal was to create some kind of 4-dimensional cluster of overlapping spheres, containing the majority of CVs in the low redshift quasar region (so not all CVs with u-g < 0.75 were used). The right size

[5]This number was fixed to 7 experimentally, to allow an average of about 20 objects in each sphere.

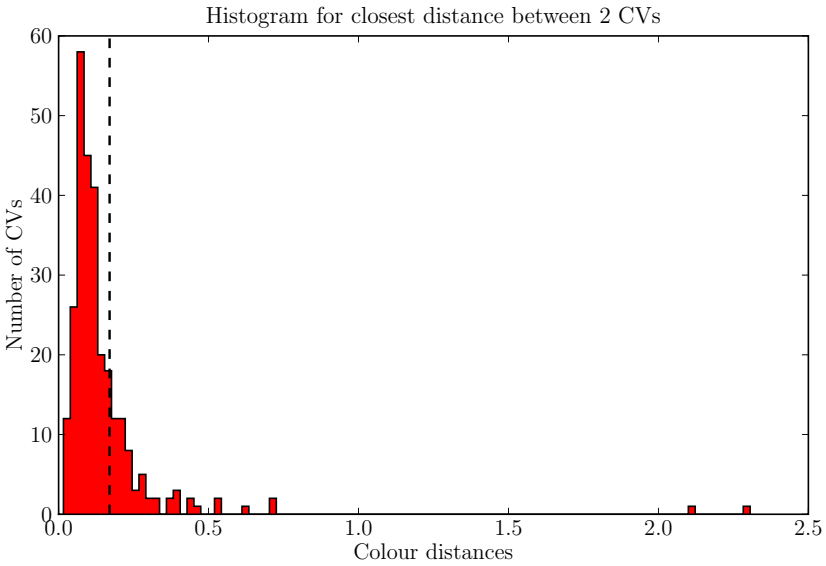

Figure 3.16: *A histogram giving the distribution for each CV of the closest colour distance to another CV. The peak is around 0.1 and at 0.17, 77 % of the binaries have another CV at or closer than that distance to it. At a distance of 0.17 a dashed line is drawn.*

of the spheres had to be chosen. It could not be so big that each sphere would include all other CVs and overlap with all other spheres. It could not be so small that each sphere would only include the CV around which the sphere was created and nothing else either. Something in between was needed. The requirement that was put on the size of the spheres in the end was that it had to contain at least one more CV next to the one at the centre (so at least 2 CVs in a sphere so that the spheres of both CVs overlap) and that it had to be big enough so that the majority of the CVs in the quasar region was included in the cluster. The histogram in Fig. 3.16 shows the distribution for each CV of the closest colour distance[6] to another CV. It can be seen that at a distance of 0.17, most of the CVs have a neighbour at or closer than that distance. This is the radius that was used for the spheres in the big 4-dimensional cluster. It means that all CVs that had a second CV in a sphere of radius 0.17 mag, were used to compute the spectral completeness of CVs in the region of high CV density in SDSS. The result was a cluster around 216 CVs (which is about 77 % of the number of CVs in my list) containing 49280 spectroscopic objects.

Figs. 3.17 (ugr colour space), 3.18 (gri colour space) and 3.19 (riz colour space) show all the CVs with a spectrum in SDSS in red and blue on top of the density histograms, surrounded by coloured spheres. The ones with a yellow sphere were part of the big cluster, the ones with a green sphere were not. The size of the spheres in these figures is smaller than the value that was used in reality. If they would have been drawn in

[6]Colour distance refers to the difference in colour (all 4 colours, u-g, g-r, r-i and i-z) between two objects in 4-dimensional colour space.

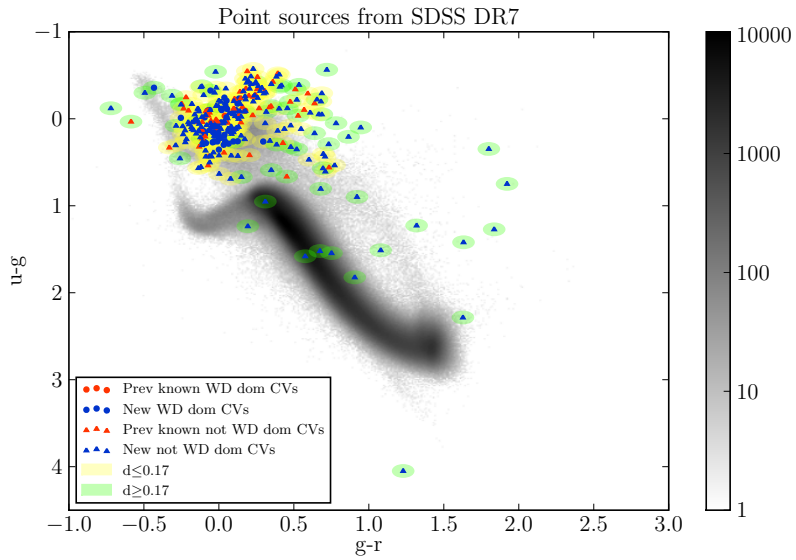

Figure 3.17: *A greyscale colour-colour plot for all the point sources of SDSS in ugr colour space with the CVs targeted by SDSS on top of it in red and blue, surrounded by coloured spheres. The yellow spheres point to CVs that have been included in the cluster of objects that were used to find the spectral completeness, the green ones were not used.*

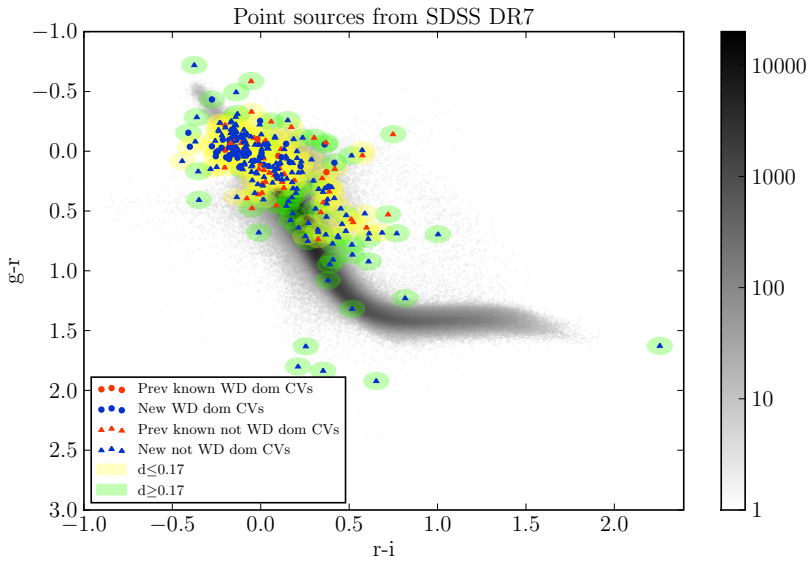

Figure 3.18: *A 2-dimensional colour-colour density histogram for all point sources in SDSS in the background and the CVs targeted by SDSS shown in blue and red on top of it. The CVs surrounded by yellow spheres were included in the cluster used to find the spectral completeness of CVs in SDSS, the ones with a green sphere were not.*

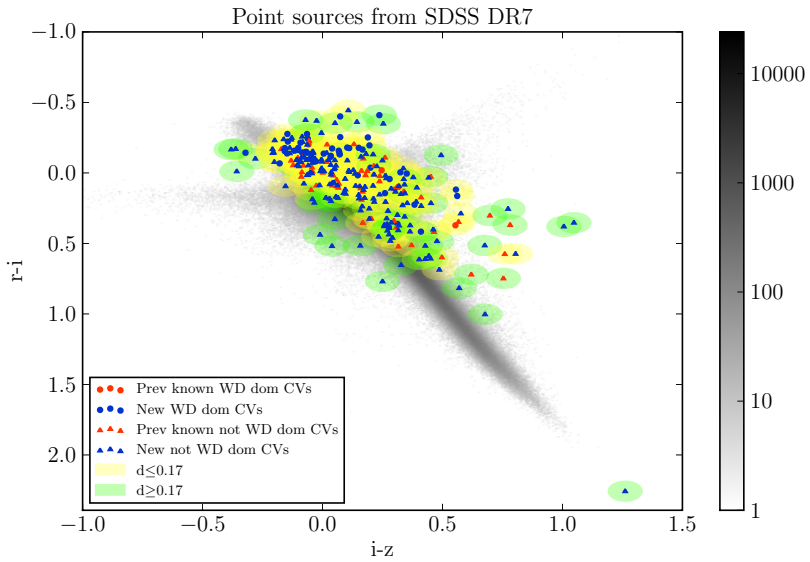

Figure 3.19: *A greyscale histogram showing all point sources imaged by SDSS in riz colour space and the CVs from SDSS plotted on top of it in red and blue, surrounded by coloured spheres. The CVs with a yellow sphere have been used to calculate the spectral completeness, the ones in green not.*

the right size, it would have been even less clear what the colour was of each sphere. This cluster of CVs and other objects are now used to give an estimate of the spectral completeness of all CVs in SDSS. Allowing the whole magnitude range, the total number of photometric objects in this cluster is 388 642 of which 49 280 have a spectrum. 216 of this last group are CVs. The percentage of CVs in the spectroscopic database is 216 divided by 49 280, which equals 0.0044. This means that 0.44 % of all objects with a spectrum in this colour region is a CV. For the following reasons it is allowed to extrapolate this number to the photometric database and say that the same percentage of objects in the photometric database is a CV. SDSS did not target any objects on purpose, which means that all objects had the same possibility of being targeted as long as they were in the right colour region. Since SDSS made exclusion boxes and did not allow main-sequence stars, white dwarfs and white dwarf main-sequence binaries to be targeted, there will be more of these objects in the photometric database than in the spectroscopic one. However, the 4-dimensional cluster that was created is situated outside these exclusion boxes, so that it is allowed to say that all objects inside the cluster had the same possibility of being targeted. This means that about 0.44 % of all objects in the photometric database of SDSS with colours in this cluster is a CV. 388 642 objects were imaged by SDSS and are part of the cluster. 0.44 % leads to 1703 CVs. This sample also contains the 216 CVs with a spectrum, so that it is expected that about 1487 CVs in this cluster were imaged by SDSS but did not get a spectrum. In terms of spectral completeness, this means that 12.7 % of all CVs in the 4-dimensional cluster

Number of photometric objects	388 642
Number of CVs in the photometry	1 703
Number of these CVs with a spectrum	216
Number of these CVs with no spectrum	1487
Spectral completeness (in %)	12.7

Table 3.2: *A table giving the number of photometric objects in the cluster, the total number of CVs in there and the number of these CVs with and without a spectrum.*

situated in the low redshift quasar got a spectrum. All these numbers are summarized in Table 3.2.

In the previous table the calculations were made allowing the whole magnitude range in the cluster. Since most CVs were found in the quasar survey and it only allowed objects with i-mag < 19.1, it can be useful to calculate the spectral completeness of the sample of CVs with an upper i-magnitude limit of 19.1. 45 323 objects with an i-magnitude lower than 19.1 were imaged by SDSS and are part of the big cluster. 29 993 objects got a spectrum and 166 of them are CVs. This means that 0.55 % of all objects in the spectroscopic database are CVs. Extrapolating this percentage to the photometric objects in the cluster results in about 250 CVs that were imaged compared to a total number of 45 323 photometric objects. 166 of these CVs have a spectrum. The spectral completeness of CVs with an i-mag < 19.1 in the 4-dimensional colour cluster then equals 66.4 %. All the numbers are shown in Table 3.3. The percentage of objects in the photometric database that turn out to be CVs for this limited magnitude range is somewhat higher (0.55 %) than for the full magnitude range (0.44 %). The reason could be that in the full magnitude range the number of quasars keeps increasing at large i-magnitudes because of the increasing volume one looks at (which makes the objects look fainter) whereas the number of CVs drops at some point when the volume becomes larger than the height of the Galactic disc.

Number of photometric objects with i_mag < 19.1	45 323
Number of CVs with i_mag < 19.1 in the photometry	250
Number of these CVs with a spectrum and i_mag < 19.1	166
Number of these CVs with no spectrum but with i_mag < 19.1	84
Spectral completeness (in %)	66.4

Table 3.3: *A table showing the number of objects from the photometric database under the quasar limit that are part of the cluster, the number of these objects that are CVs and the number of these CVs with and without a spectrum.*

3.2.4 Spectral completeness comparison

In Chapter 2 the spectral completeness of all previously known CVs was computed using CVs from the Ritter & Kolb catalogue and the Catalina Real-Time Transient Survey. All these objects were looked at by eye and the ratio of the number of CVs with a spectrum to the total number of CVs was calculated. This was done in a very wide spread area in colour space for individual point sources. It resulted in a spectral completeness of 65 %. In this Chapter a cluster was created in a very specific area in colour space that contained about 75 % of all CVs with a spectrum in SDSS. All objects in this cluster were used to compute the spectral completeness, based on an extrapolation from the CVs from the spectroscopic database to the CVs from the photometric database of SDSS. Surprisingly this resulted in a spectral completeness around 66 %. These two numbers were found in totally different ways but still agree very well. However, it was noticed in Chapter 2 that for the previously known CVs this spectral completeness might be a lower limit because there were probably also CVs that were imaged by SEGUE but did not get a spectrum in SEGUE. Since the Sloan Legacy Survey targeted the most uniform sample of objects in the Universe, it is better to focus on this part of SDSS alone. The same effect of SEGUE needs to be taken into account for the spectral completeness calculations of this chapter. The objects in the Galactic disc were already cut out, but unfortunately SEGUE also imaged the sky at other latitudes. Even though this part of the sky that was imaged by SEGUE outside the galactic disc is much smaller, it could still be lowering the spectral completeness here. So taking this into account, both spectral completeness measurements (for the sample of previously known CVs and for the full sample of SDSS CVs) are probably lower limits.

3.2.5 CVs from SDSS in 3 colour dimensions

In Section 3.1.4, density and spectral completeness histograms were made for 3 colour dimensions. This was done by dividing the whole sample of objects into different groups according to the value of the third colour and then creating the histograms for these smaller samples. The same has been done here for the density histograms alone, but now with the CVs from the spectroscopic database of SDSS on top of them. This is shown in Figs. 3.20 (ugri colour space) and 3.21 (griz colour space). From Fig. 3.20 it can be seen that most of the CVs are in the region of r-i = [-1.0 , 0.5] (shown in the left subfigure). This is also visible in Fig. 3.18 where the majority of objects is at the left side of the figure. Fig. 3.21 shows that most of the CVs from the cluster have an i-z = [-1.0 , 0.5].

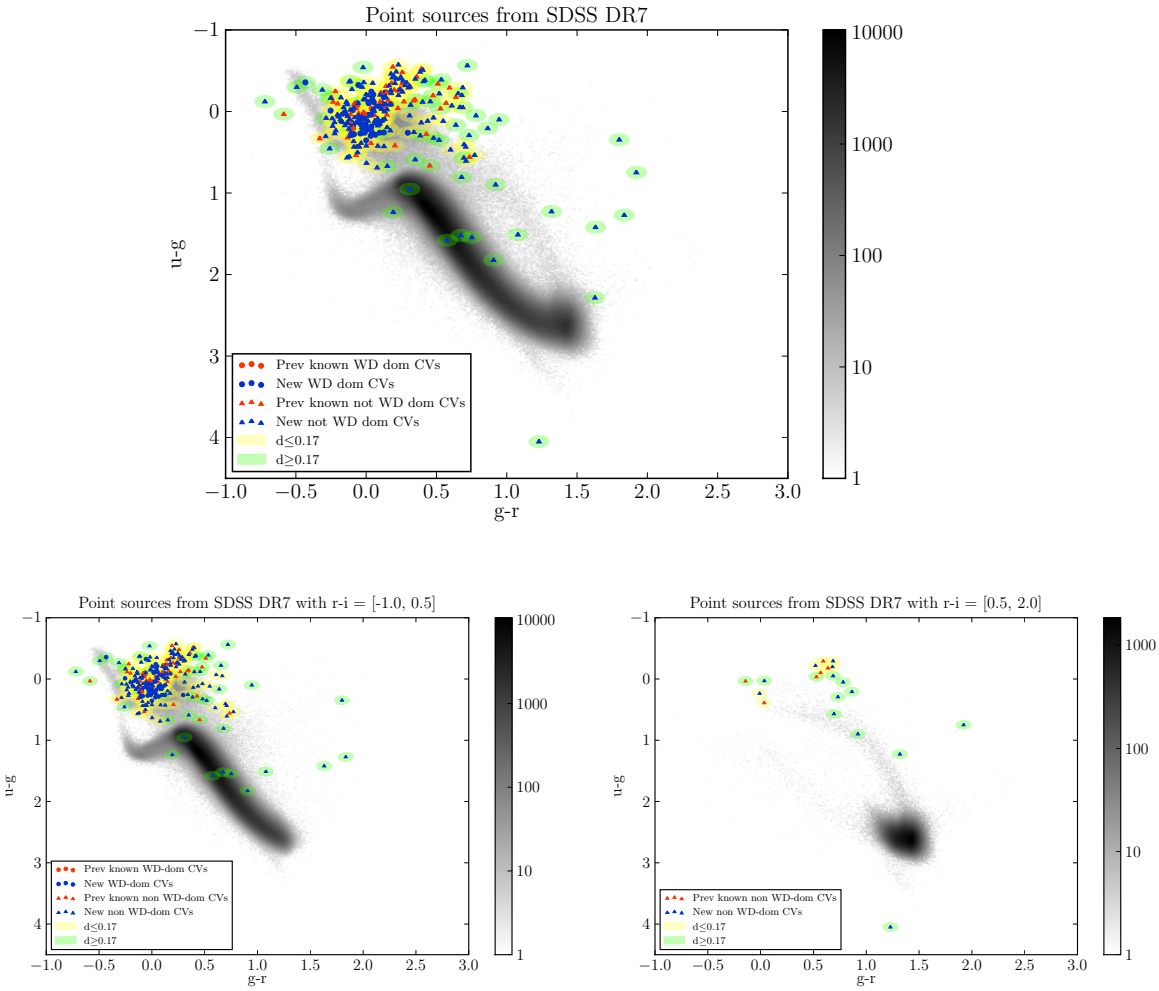

Figure 3.20: *Three 2-dimensional projections of the 4-dimensional colour space onto (g-r) - (u-g) of all point sources from SDSS with the CVs from the spectroscopic database of SDSS on top of it, surrounded by yellow and green spheres. The ones with a yellow sphere are part of a cluster that has been used to find the spectral completeness of CVs in SDSS. The figure at the top is Fig. 3.17. The two figures at the bottom are cuts in a third colour r-i: the objects in the region [-1.0 , 0.5] are part of the figure at the bottom left, the ones in the region [0.5 , 1.0] by the figure at the bottom right. It can be seen that most CVs have an r-i colour in the range [-1.0 , 0.5].*

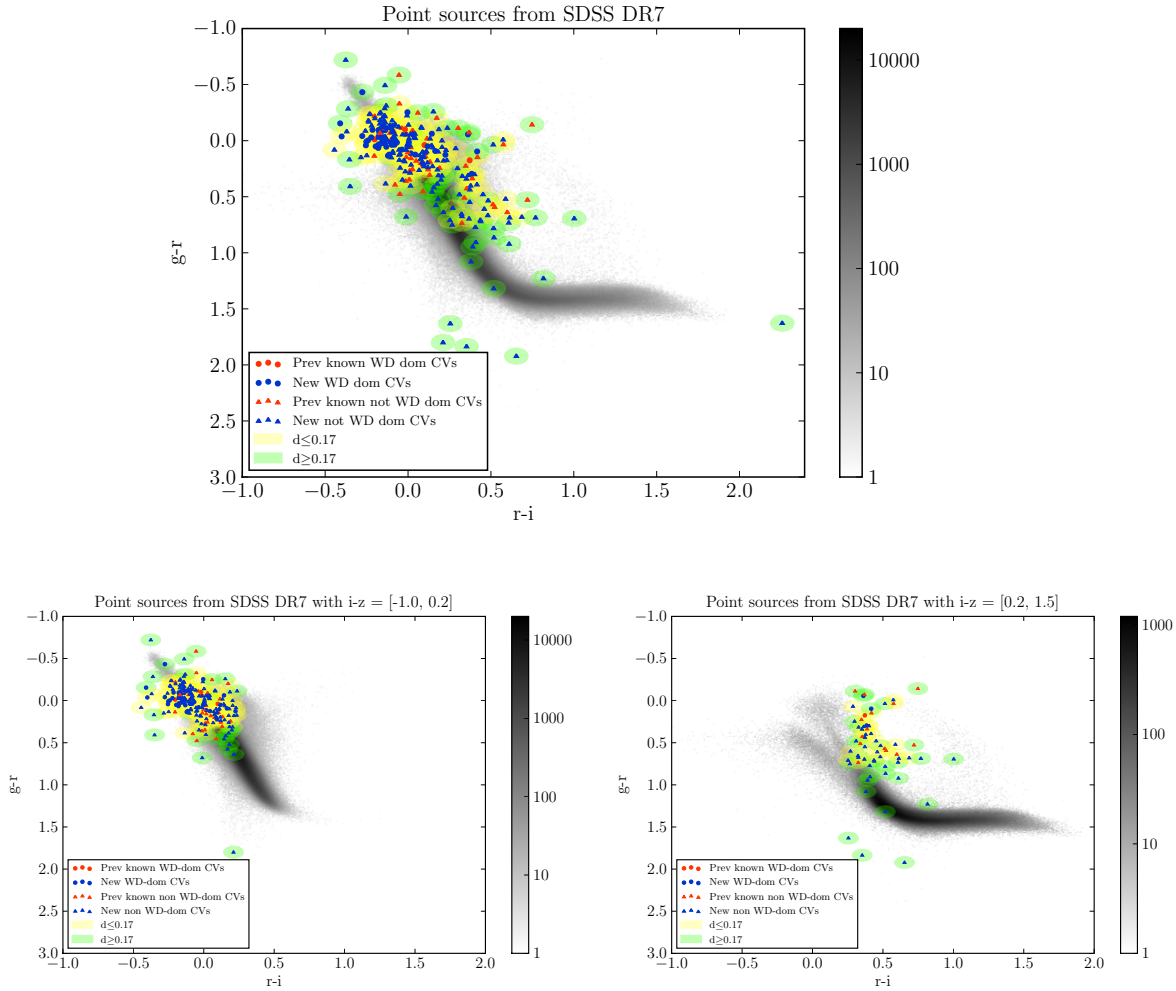

Figure 3.21: *Three colour-colour density histograms for different samples of point sources in SDSS with the CVs in different colours on top of them. The one at the top is a projection of the 4 different SDSS colours onto (r-i) - (g-r) colour space and shows the SDSS CVs on top of it. They are surrounded by spheres which indicate if they had been used in the cluster of CVs to compute the spectral completeness of CVs in SDSS (yellow ones) or not (green ones). The two figures below show the same objects but this time divided into two groups based on their i-z colour. The ones with an i-z = [-1.0 , 0.2] are shown in the figure at the left bottom, the ones with i-z = [0.2 , 1.5] are shown in the figure at the right bottom. The CVs with the coloured sphere are again plotted on top of the density histograms.*

Chapter 4

Selecting CVs as future targets

It is now known that more than 60 % of the CVs with a dereddened i-magnitude in the range [15.0 - 19.1] that were imaged by SDSS got a spectrum. Once beyond the i-mag = 19.1 limit, the spectral completeness of CVs drops dramatically. The ones that were found so far in SDSS turned out to be a quite uniform sample. CVs with different colours have been targeted while previous surveys found mostly CVs with colours in the low redshift quasar region. Both white dwarf dominated CVs and others were found, increasing the sample of white dwarf dominated CVs with more than a factor of ten. The CVs are spread over the largest and deepest area of the sky ever. Nothing else but colour exclusions were used to select the objects that would get a spectrum. The result from all this is that the sample of CVs with a spectrum in SDSS has not been biased to variability, X-ray emission or only blue colours which was the case before. From the calculations that were done in Chapter 3, it was assumed that there are still a lot of CVs in the photometric database of SDSS that did not get a spectrum. The majority of these have an i-mag > 19.1, which was shown in both Chapter 2 and 3. Remembering the lack of white dwarf dominated CVs that should populate the period minimum spike, it could be very useful to find a way to target CVs that are still in the photometric database of SDSS.

This chapter shows a way to select these CVs with no spectrum in the photometric database of SDSS. Section 4.1 explains how it helps to make use of objects with proper motion measurements in SDSS. In Section 4.2 it is shown that by selecting those objects from the spectroscopic database of SDSS that have proper motions and also have been found by GALEX, the number of quasars in any random sample can be largely diminished. Section 4.3 proves that SDSS has been uniform over the years by showing that the results from the previous sections are valid for objects from different data releases. In Section 4.4 it is explained how all this could be used on the photometric database of SDSS to target more CVs.

4.1 Objects with proper motions in SDSS

The Sloan Digital Sky Survey took more than a million spectra of quasars and galaxies as these were the targets of the two main surveys. When querying for objects in the database of SDSS in the previous chapter, only point sources were asked for, no extended sources (which are objects like galaxies with a wider luminosity spread at the sky). With these point sources, both CVs as quasars came in (and main-sequence stars, but these were left out with a colour cut). Because quasars are galaxies, one would expect to see them as extended objects at the sky. This is not the case since the luminosity comes from the centre of the galaxy where the black hole is accreting matter. Since there are so many quasars, a large part of the objects in the database of SDSS are expected to be quasars and any random sample of objects would give 90 % of quasars (after the main-sequence stars were cut out). The goal is to find the CVs that were observed by SDSS but did not get a spectrum, by taking a sample of objects from the photometric database which have passed some selection criteria (that are going to be defined in this chapter), get spectra of these objects and see that a lot of them are CVs. Since it is not known which objects exactly are the quasars and which ones are the CVs (because there are no spectra of these objects), the most important thing is to decrease the number of quasars in such a sample. To be able to see the effect of certain selection criteria on the population of these quasars, the spectroscopic database was used for which the spectra identify the objects.

The CVs that can be observed are nearby objects in the Milky Way Galaxy. Since the Milky Way is a spiral galaxy, everything in it rotates around the centre at a different velocity, depending on the arm of the galaxy it is in and on the distance from the centre. Apart from that, objects in the disc also seem to move at random velocities. For these two reasons, all objects in the Milky Way Galaxy around us move at different velocities. The projection of these velocities onto our 2-dimensional view of the sky can be measured and are called the *proper motion* of an object. SDSS measured proper motions for a whole lot of objects during the imaging phase. Since quasars are not a part of our Galaxy, their proper motion will be much lower and it should be possible to distinguish between CVs and quasars by only allowing objects with a significant proper motion measurement.

A second query was done, this time for all objects with a detected proper motion in the spectroscopic database of SDSS and u-g < 0.75. The colour cut was done to eliminate all the main-sequence stars that are present in the Milky Way Galaxy which also have a detectable proper motion. 98 524 objects were selected through this query. The errors on these proper motion measurements were also given and had to be taken into account since it does not make sense to allow objects with proper motion errors of the same order as the proper motion measurements. In a first test, only objects with a 3σ-proper motion measurement were allowed (which means that only a proper motion that was 3 times as big as its error was used). 6612 objects had a 3σ-proper motion in the spectroscopic database of SDSS. A quick look at the spectra of these objects showed that there were still a lot of quasars in that sample. Fig. 4.1 shows the right ascension

Object	3σ-PM		4σ-PM		5σ-PM	
	(#)	(%)	(#)	(%)	(#)	(%)
Cataclysmic Variables	128	1.9	103	2.4	87	2.7
Quasars	3480	52.6	1583	37.3	920	28.8
White dwarfs	2045	30.9	1760	41.5	1536	48.0
WDMS binaries	816	12.4	700	16.5	590	18.4
Rest	143	2.2	97	2.3	67	2.1
Total	6612	100	4243	100	3200	100

Table 4.1: *A table giving all objects from SDSS that got a spectrum and proper motion measurements. Both absolute numbers and percentages of the different objects in the 3, 4 and 5σ-proper motion samples are shown here in the different columns.*

(RA) and declination (dec)[1] values of the proper motions of CVs and quasars from this 3σ sample. Most of the quasars seem to occupy a uniform region with RA and dec between -100 and 100 which might indicate that the proper motion measurements of these quasars are probably errors[2]. As a result, also a 4σ and a 5σ-proper motion sample were made, in an attempt to get more quasars out. 4243 objects had a 4σ-proper motion, 3200 had a 5σ-proper motion. It can be seen from Table 4.1 that indeed relatively more quasars were cut out in the 5σ-proper motion sample, compared to the 3σ sample. This table shows the numbers of all the different kinds of objects that were in these samples with 3, 4 and 5σ-proper motion measurements (with 3 new CVs in the 5σ-proper motion sample). The classifications of all these objects were based on their spectra. Examples of spectra of these different groups of objects are given in Appendix A. Taking into account that initially 120 000 quasars were targeted by SDSS, after selecting all the objects that got proper motion measurements and only the ones with a 5σ-proper motion it is not too bad still to have 920 quasars left. In the rest of this chapter, only the 5σ-proper motion sample will be used.

Even though the relative number of quasars was cut down with almost 25%, the difference between the percentages of quasars and CVs is still too large. This means that not the whole the sample of 5σ-proper motion objects should be allowed and something extra needs to be found to cut out more quasars. It is already known that CVs have the same colours as quasars in the optical range. What can be done now is to check if this is still the case in the other ranges of the electromagnetic spectrum.

[1]Right ascension and declination are the coordinates of the equatorial coordinate system used to describe the position of objects at the sky. This system is the most related to the geographic coordinate system. Imagining that the Earth is the centre of a sphere and the sky is the surface of this sphere, than the right ascension of an object at the sky corresponds to the longitude of an object that is measured on Earth (and so on each sphere-like surface) and the declination to the latitude.

[2]Normally the proper motion of objects is calculated using distant quasi-stationary objects as reference frame. It might be that for these quasars the stationary objects were the ones moving at a certain velocity while the quasar was standing still so that the quasar got the proper motion value of the "stationary" objects.

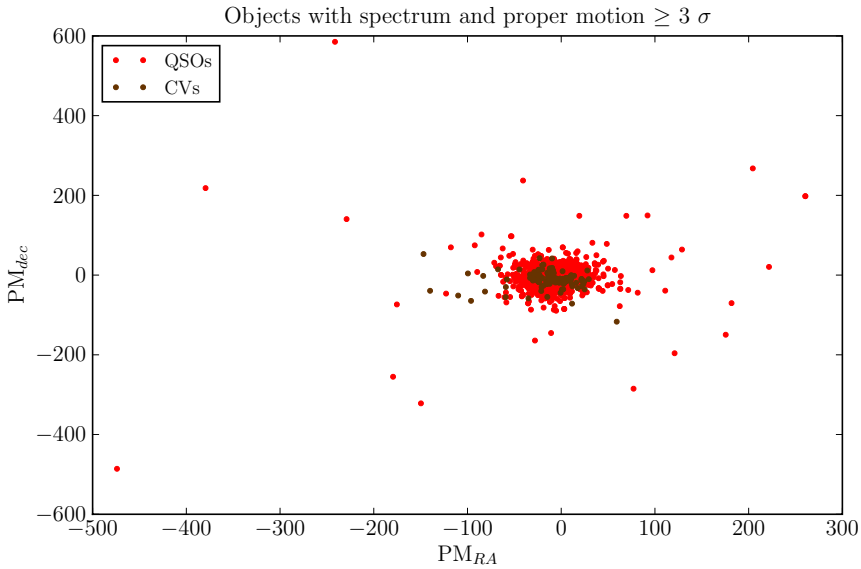

Figure 4.1: *The proper motion coordinates of the 3σ-proper motion sample of QSOs and CVs. It can be seen that the quasars are distributed quite uniformly with absolute proper motions smaller than 100.*

4.2 Photometry from GALEX

The Galaxy Evolution Explorer (GALEX) is a space telescope orbiting the Earth and taking images of the ultra-violet sky. Near UV as well as far UV images are obtained with the goal to explain how galaxies evolve and change. All objects form the spectroscopic database of SDSS with a 5σ-proper motion were cross checked with the objects from the last data release of GALEX (DR6). From the initial 3200, there were 1109 objects with both far and near UV magnitude measurements in GALEX. The numbers of all the different kinds of objects that were found in this sample are shown in Table 4.2, in the first column of numbers which shows all objects.

In Fig. 4.2 these objects are shown in a colour-colour plot with g-r (optical SDSS colour) on the x-axis and fUV-nUV (UV GALEX colour) on the y-axis. The different kinds of objects are shown in different colours: the green dots represent the white dwarfs, the yellow ones are the quasars, the red ones show the CVs and the brown dots are the white dwarf main-sequence stars. From this plot it can be seen that the white dwarfs occupy a very distinct region with only few other objects. Because there are so many white dwarfs left in the sample and they are not of interest for this research, a cut was made based on this plot to get most of them out of the sample. The region in this colour-colour plot where the majority of white dwarfs are situated, is shown with a blue line: all objects at the left side of this line were rejected. Mostly white dwarfs were eliminated this way but also some quasars and white dwarf main-sequence binaries were lost. The cut was made in such a way that no CVs were rejected. With this so called *white dwarf cut (WD cut)*, 72 % of the white dwarf population was successfully

Object	All	WD cut	WD & QSO cut	% of final objects
Cataclysmic Variables	60	60	56	12.3
Quasars	284	279	66	14.6
White dwarfs	440	122	76	16.7
WDMS binaries	306	281	239	52.6
Rest	19	18	17	3.8
Total	1109	760	454	100

Table 4.2: *A table showing the number of different kinds of objects in the spectroscopic database of SDSS with a 5σ-proper motion and measurements of the far and near-UV magnitudes from GALEX. In the second column all objects are shown, the third column shows the ones that were left after the white dwarf cut, and the fourth column shows the ones left after the white dwarf and quasar cut. The percentages of the final sample are shown in the fifth column.*

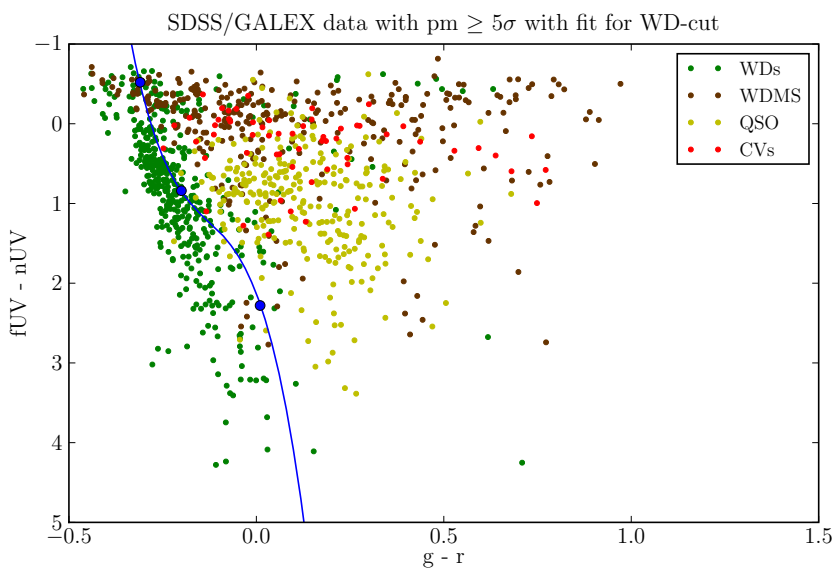

Figure 4.2: *A colour-colour plot of all objects from the spectroscopic database of SDSS with a 5σ-proper motion measurement and GALEX magnitude measurements. They are plotted for g-r against fUV-nUV. The blue line is the border used to cut out most of the white dwarfs. All objects at the left side of this line were eliminated from the sample.*

eliminated. The number of objects that are left afterwards are shown in Table 4.2 (in the second column which shows the WD cut).

The white dwarf cut was made based on a colour-colour plot with g-r as optical SDSS colour. Some other colour-colour combinations were tested to see if there were figures where the quasars could be cut out the same way as the white dwarfs were eliminated. Plotting u-g on the x-axis instead of g-r for all objects that were left after

the WD cut, leads to Fig. 4.3. It can be seen that the quasars are now in a quite specific region on the colour-colour plot which is not too much overlapping with the region of cataclysmic variables. All objects below the blue line were cut out with the *quasar cut (QSO cut)*. This eliminated 76 % of the quasar sample, but again some other objects were lost too. The number of different kinds of objects that were left after both cuts are shown in Table 4.2 (in the column that shows the QSO-cut). The sample that is left after the two colour-colour cuts were done, is shown in Fig. 4.4 with g-r on the x-axis again. From both the table and the figure it is clear that the majority of white dwarfs and quasars have been eliminated from the sample.

The final percentages of all the objects are shown in the last column of Table 4.2: 12.3 % of the objects left are CVs, 14.6 % of the objects are still quasars, 16.7 % are white dwarfs, the majority, 52.6 %, of the objects are white dwarf main-sequence binaries and 3.8 % are main-sequence stars and other objects that are not interesting for this research (and which have for this reason not been included in the colour-colour plots). The group of white dwarf main-sequence binaries is still a very large part of the sample (about half of it). An attempt could have been made to cut out most of them too. This however has not been done because it can be useful to find more of these objects. Since white dwarf main-sequence binaries are the progenitors of CVs, these systems could give answers to some big questions concerning the evolution and origin of CVs. The sample of white dwarf main-sequence binaries in the Galaxy is not at all complete yet, so it is good to find a way to get more spectra of these systems too. The most striking thing to see however is that after both cuts the percentage of quasars is about the same as the percentage of CVs, whereas before the cuts were made there were about 5 times as many quasars as CVs (10 times as many before the GALEX objects were selected). This means that it should be possible to get a sample of objects from SDSS with much less quasars than initially present and with still quite some CVs in it. Selecting objects with a 5σ-proper motion, with magnitude measurements for near as well as far UV from GALEX that went through both the WD and the QSO cut, can lead to a sample of objects with a high percentage of white dwarf main-sequence binaries and cataclysmic variables.

4.3 Independent check of uniformity of SDSS

It was said that over the years SDSS did not change too much about the selection algorithms that chose the objects that would get a spectrum. Based on the percentages that came out of the previous section, an independent check was done of the uniformity of SDSS between DR6 and DR7. 142 objects that had a 5σ-proper motion detection, GALEX magnitude measurements and were not in the WD cut or in the QSO cut, were targeted extra in DR7 compared to DR6. These 142 objects were classified again (based on their spectra) and the results of this are shown in Table 4.3. Comparing this with Table 4.2 reveals that the numbers are quite similar. The white dwarf main-sequence binary sample is still the largest one with more than 50 % of the total and even though the number of CVs is smaller than the number of quasars, it is still of the same order. This means that SDSS has indeed been targeting its objects uniformly.

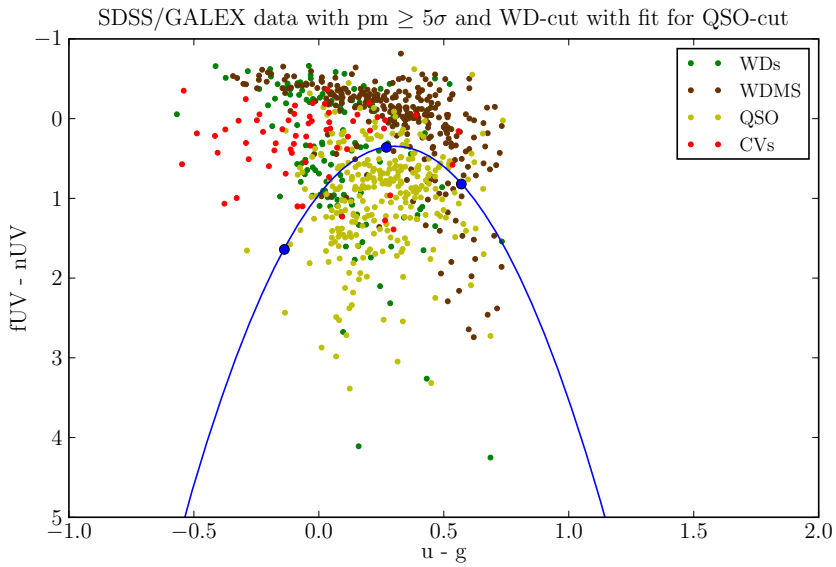

Figure 4.3: *A colour-colour plot showing all the objects from the spectroscopic database of SDSS with a 5σ-proper motion and GALEX magnitudes that were left after the white dwarf cut. All the objects under the blue fit line were eliminated in the quasar cut because this is the region where most of the quasars are.*

Object	Number	% of objects
Cataclysmic Variables	11	7.8
Quasars	18	12.7
White dwarfs	32	22.5
WDMS binaries	81	57.0
Rest	0	0.0
Total	142	100

Table 4.3: *A table giving the number of cataclysmic variables, quasars, white dwarfs and white dwarf main-sequence binaries that were part of a sample of 142 objects from the photometric database of SDSS. The percentages of all the objects are in the same order as for the whole spectroscopic database of SDSS as was shown in Table 4.2*

4.4 Targeting CVs in the photometric database of SDSS

In the previous sections, objects from the spectroscopic database of SDSS were used to obtain a sample of objects with as few quasars and as many CVs as possible. This was found by using proper motions and GALEX colours. These results could now be used to extend the spectroscopic database of CVs by targeting the CVs that were observed but did not get a spectrum in SDSS. Using the methods from the previous section on the photometric database, should lead to more CVs that were observed by SDSS.

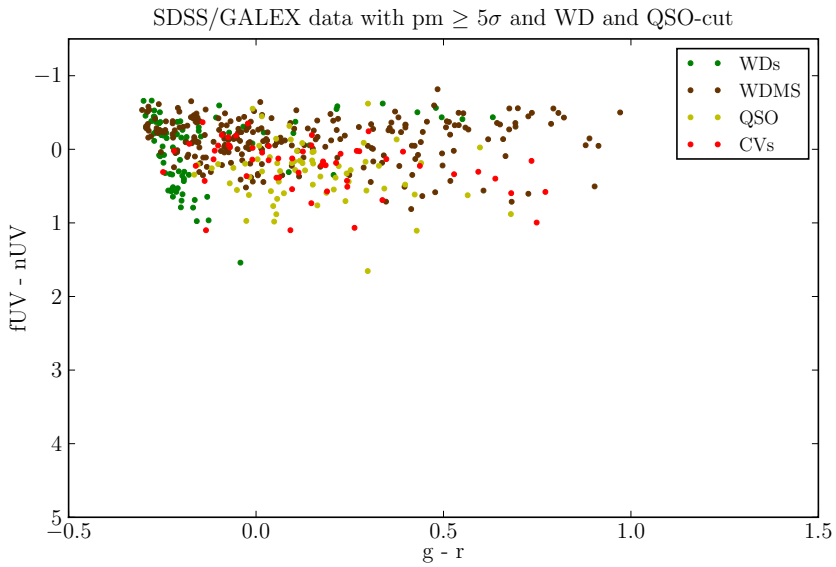

Figure 4.4: *A colour-colour plot for all the objects from the spectroscopic database of SDSS with a 5σ-proper motion and with GALEX measurements that were left after both the white dwarf cut and the quasar cut were done. 12.3 % of the objects left are CVs, 14.6 % are quasars, 16.7 % are white dwarfs and 52.6 % are white dwarf main-sequence binaries.*

The same query that was done on the spectroscopic database was now done on the photometric database of SDSS: all objects that were observed by of SDSS, had a 5σ-proper motion and u-g > 0.75 were allowed into the sample. 15 029 objects followed these criteria and did not have a spectrum. An i-magnitude histogram is made for this sample of objects in Fig. 4.5. It can be seen here that there are a lot of objects in SDSS with an i-magnitude larger than 19.1 that have not been targeted. Finding these faint CVs in the photometric database of SDSS could also help to push up the faint magnitude limit to larger i-magnitudes. The next step then was to get GALEX data for this sample of 15 029 objects and do the same colour-colour cuts as was done on the spectroscopic database of SDSS. All object were cross checked with the GALEX database: 2 967 of them had magnitudes in both far UV and near UV. This sample was plotted on colour-colour plots with optical SDSS colours on the x-axis and UV GALEX colours on the y-axis and went through the WD and the QSO cut. First assuming that the same percentage of objects will be eliminated in each of the cuts in the photometric database as was done in the spectroscopic database, about 72 % of the white dwarfs would be cut out in the white dwarf cut and about 76 % of the quasars would be eliminated by doing the quasar cut. This leads to the Figs. 4.6, 4.7 and 4.8. In the first one (Fig. 4.6) all objects are shown on a colour-colour plot with g-r on the x-axis and fUV-nUV on the y-axis. The blue line is the same as was used for the spectroscopic database and indicates the border line for the WD cut: all objects at the left side of this line are eliminated. The second figure (Fig. 4.7) shows the objects after the WD cut was made. 2 323

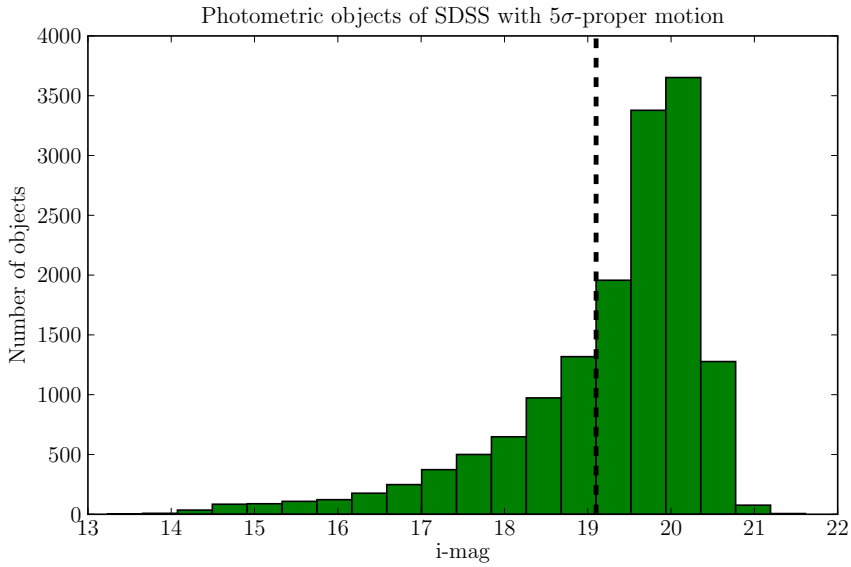

Figure 4.5: *An i-magnitude histogram for all the objects from the photometric database of SDSS that have a 5σ-proper motion detection and did not get a spectrum. It is clear that there are a lot of objects fainter than i-magnitude 19.1. The black dashed line indicates this 19.1 limit.*

objects are left here. The blue line again indicates the border line for the QSO cut. All objects under the line were eliminated, leaving another 1 359 objects. Now if the same percentages of objects as was calculated for the spectroscopic database are in this sample, about 12 % would be CVs, 14 % quasars, 17 % white dwarfs, 53 % white dwarf main-sequence binaries and 4 % would be occupied by other objects, less interesting for this research work.

The problem now is that it is not known which objects without a spectrum are present in the photometric database because they cannot be classified in the same way as the ones with a spectrum. This means that it is not sure that the percentages of objects in the spectroscopic database are the same as the percentages of those same objects in the photometric database. The problem for the group of objects with an i-mag < 19.1 is the following. Most of the systems that got a spectrum were targeted by the quasar survey, which made use of exclusion boxes. This means that white dwarfs and white dwarf main-sequence binaries were excluded on purpose. Compared to the other objects that were targeted by the quasar survey, much less of these systems got a spectrum but they are still in the photometric database. The result is that the percentage of white dwarfs and white dwarf main-sequence binaries that come out of the GALEX colour cuts must be higher in the photometric database because more of these objects are present there. How big the effect of these exclusion boxes is however still needs to be explored. It could be that the effect is larger for the white dwarf main-sequence binaries than for the white dwarfs, because a large percentage of white dwarfs are eliminated with the WD cut. For the group of objects with an i-mag > 19.1,

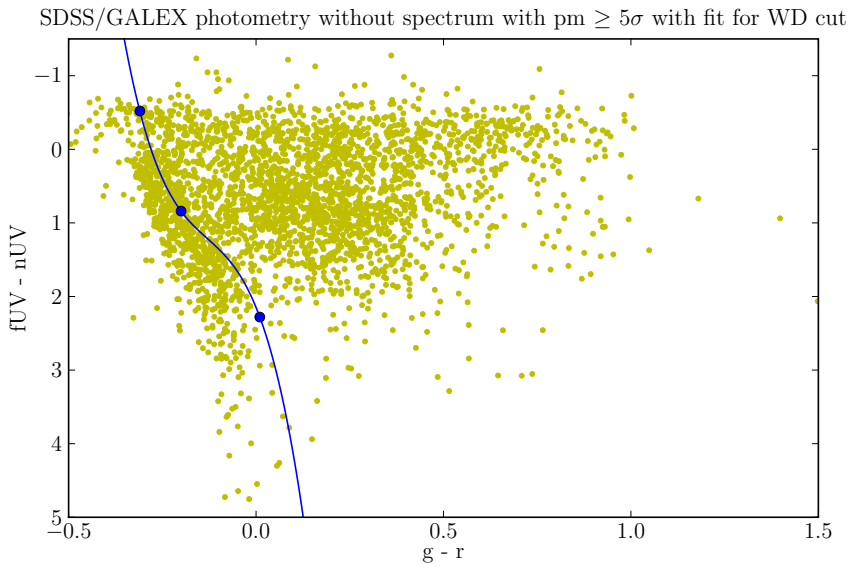

Figure 4.6: *A colour-colour plot for all objects from the photometric database of SDSS that did not get a spectrum in SDSS, that have a 5σ-proper motion measurement and that have values for the GALEX magnitudes. The blue line indicates the border of the white dwarf cut and all objects at the left side (where is assumed that most of them are white dwarfs) are cut out of the sample.*

the biggest problem is the group of quasars in the photometric database. Up to an i-mag ≈ 20 the percentages of objects in the photometric database should be quite similar to the spectroscopic database (taking the exclusion boxes into account). When the sample moves up to higher i-magnitudes however, the number of quasars ramps up (because the volume in which the quasars are seen, increases) while the number of CVs decreases (due to the limited height of our disc as explained before). Next to that, proper motion measurements of faint objects are not precise enough anymore. These things together put a limit on how far the faint limit can be pushed upwards. One could say however that this effect should be minor because the objects are selected in a totally different way, using different colours and using proper motion measurements (where this last one already cuts out a lot of quasars). This however cannot be said for sure until further research has been done. Assume that the exclusion boxes do have an effect, then the final sample of objects will contain much more white dwarf main-sequence stars, more white dwarfs and probably also more CVs because part of them also got into exclusion boxes.

The ultimate goal now is to get spectra for these 1359 objects. This would be a check for the percentages and would allow to increase the sample of known cataclysmic variables. An ESO-proposal has been written for XShooter to get spectra for a first small sample of 24 objects. If this will be successful, a larger program can be started and it would be possible to get a more complete sample of CVs (and WDMS binaries).

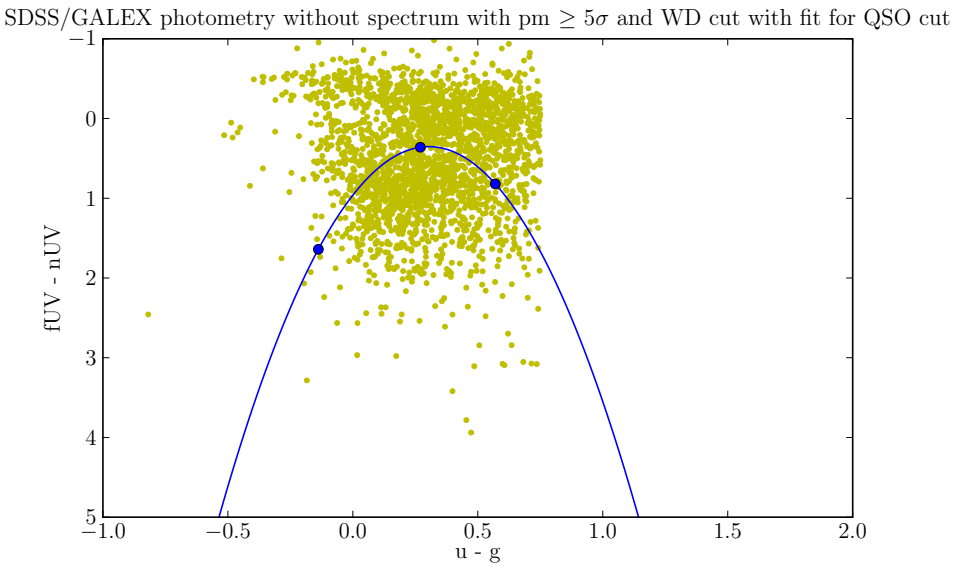

Figure 4.7: *A colour-colour plot showing all the objects from the photometric database of SDSS without a spectrum in SDSS but with a 5σ-proper motion and magnitude measurements from GALEX after the white dwarf cut was done on the sample. Based on this figure, all objects under the blue line will be eliminated in the quasar cut. The u-g = 0.75 cut that was done on the sample in the beginning to eliminate main-sequence stars can clearly be seen.*

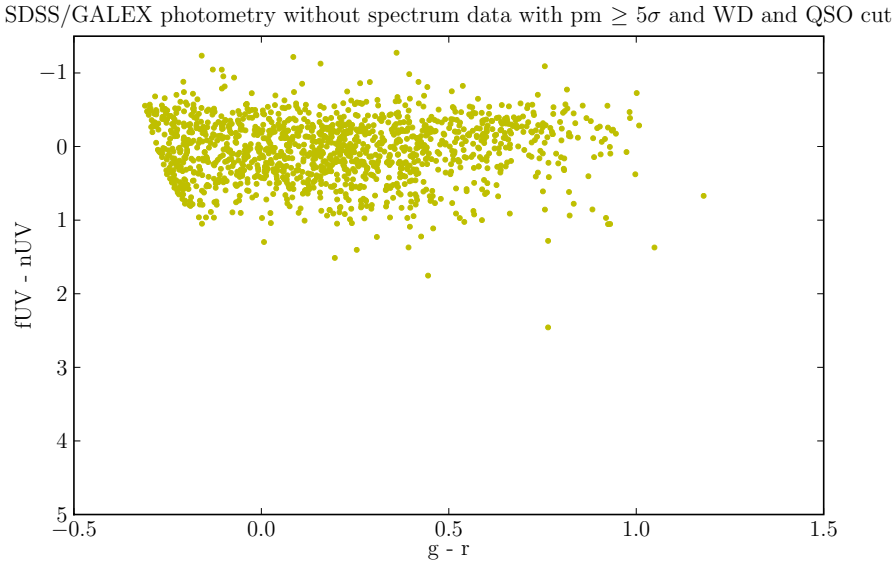

Figure 4.8: *A colour-colour plot giving all the objects from the photometric database of SDSS that did not have a spectrum in SDSS, that have a 5σ-proper motion measurement and that have values for GALEX magnitudes after both the white dwarf and the quasar cut were done.*

Chapter 5

Conclusions and future prospects

5.1 Conclusions

Before the Sloan Digital Sky Survey started observing, cataclysmic variables were found by searching for variability, X-ray emission and/or only blue colours. This sample was not at all uniform and missed e.g. the CVs with low accretion rates and thus faint X-ray emissions. SDSS should give the must unbiased sample of CVs ever because it did not select its objects based on specific colours or characteristics. The only thing that was done was eliminating all objects in small areas of colour space.

Looking at the sample of CVs detected by previous surveys and programs, it was immediately clear that SDSS targeted mainly cataclysmic variables with a dereddened i-magnitude between 15 and 19.1 where this faint border line is the faint upper limit used to take spectra by the quasar survey. The spectral completeness of this sample of CVs in SDSS was about 65 % which is pretty good for a survey that did not target CVs on purpose. Once beyond the 19.1 limit however the completeness drops dramatically. This is understandable since most CVs were found in the quasar sample but it shows that a lot of faint cataclysmic variables are left out, which makes the full sample quite incomplete towards high magnitudes.

Generalizing to the whole sample of CVs found thus far in SDSS, shows that it is quite uniform in the i-magnitude range 15 - 19.1. Not only CVs with quasar colours but also very blue or very red ones were given a spectrum. SDSS also increased the small number of previously known white dwarf dominated CVs with a factor of eleven (because SDSS was able to target the faintest CVs ever). Using a specific region in colour space, the number of CVs in the photometric database that did not get a spectrum, was estimated. Based on this number, the spectral completeness was calculated. For the sample of CVs with an i-magnitude between 15 and 19.1 the spectral completeness was 66 %, which matches surprisingly good with the percentage of previously known CVs with a spectrum.

Since there are still a lot of cataclysmic variables in the photometric database of SDSS without a spectrum, it would be interesting to find them and get spectra of these systems in other ways. By using all objects with a 5σ-proper motion measurement that have been imaged by GALEX, it was possible to decrease the number of quasars (with 76 %) and the number of white dwarfs (with 70 %) from any random sample of objects from the spectroscopic database of SDSS. Using this method on a sample of objects from the photometric database of SDSS could lead to about 12 % of cataclysmic variables, 15 % of quasars, 16 % of white dwarfs, 53 % of white dwarf main-sequence binaries and 4 % of other different objects if it can be assumed that the same percentage of objects from the spectroscopic database is present in the photometric database with no spectrum. Future research should however give more information about this. In any case, the majority of objects would be WDMS binaries (the progenitors of CVs) and the percentage of quasars would be about the same as the percentage of CVs.

5.2 Future prospects

Several things are still to be done and investigated in the coming months to complete this work and prepare for publication. First of all a big check needs to be made on SEGUE. It is known that SEGUE imaged big parts of the sky, mostly the galactic disc and that it took spectra of objects using totally different criteria compared to the Sloan Legacy Survey. The spectral completeness calculations should be repeated without the objects used and targeted by SEGUE. This is the case both for the previously known CVs as for the 4-dimensional colour cluster of CVs.

A second important thing to do is checking how much influence the exclusion boxes have on the proper motion sample. If the percentage of objects without a spectrum that are in the area of the exclusion boxes would be larger than the percentage of objects with a spectrum in this area, then this would have to be taking into account. This would mean that after doing the proper motion selections and colour cuts, much more white dwarf main-sequence binaries would be occupying any random sample of objects.

For all the objects in the photometric proper motion list it would be nice to get spectra. The discovery of more white dwarf dominated CVs would help in the research of B.Gänsicke et al. in populating the period minimum spike.

One thing that has not been used to find more CVs with a spectrum in SDSS is variability. The Sloan Supernova Survey took repeated images of the so called Stripe 82. CVs could be found in here because they are variable objects. This would only help to find the few missing CVs with a spectrum in SDSS (if there are any).

Appendix A

Spectral classification

A.1 Cataclysmic variables

Cataclysmic variables can be recognized from quite broad double peaked hydrogen Balmer and/or helium emission lines. These emission lines originate from the hydrogen (and helium for helium-rich donor stars) in the accretion disc around the white dwarf. Through collisions of atoms in the disc and radiation from the white dwarf, the hydrogen atoms are excited to higher energy levels, fall immediately back to their ground level and emit photons. When the disc is optically thin these photons will escape and will be visible as emission lines in the spectrum of a cataclysmic variable. The fact that these lines are mostly quite broad and double peaked is due to the mass in the accretion disc that rotates at high velocities close to the white dwarf. This mass will emit light at a redshifted frequency. Averaging over all mass particles with different velocities in the disc then results in one broader emission line around the rest wavelength. Since half of the disc in average moves away from the observer and the other part moves towards the observer, half of the disc is in general redshifted and the other part is blueshifted. This explains the double peaked emission lines. Fig. A.1 shows a general spectrum of a blue CV where the continuum of the spectrum is dominated by the hot white dwarf or accretion disc. These hot components of the CV are visible at the left side of the figure as a steep ramp up to shorter wavelengths (and thus higher energies). In Fig. A.2 the cooler secondary is visible at longer wavelengths (and thus lower temperatures) through the molecular absorption bands. An example of a white dwarf dominated cataclysmic variable is shown in Fig. A.3. In a younger system the hydrogen in emission from the accretion disc dominates over the absorption of hydrogen from the white dwarf and only the emission is visible. In these older systems the emission from the accretion disc is less strongly which results in broad absorption lines with narrow emission in the middle. Fig. A.4 nicely shows the double peaked emission lines which are not always as visible as for this particular cataclysmic variable. The CV shown in Fig. A.5 is an example of a helium cataclysmic variable, or AM CVn. This system contains a helium-rich extremely low mass main-sequence star that lost a lot

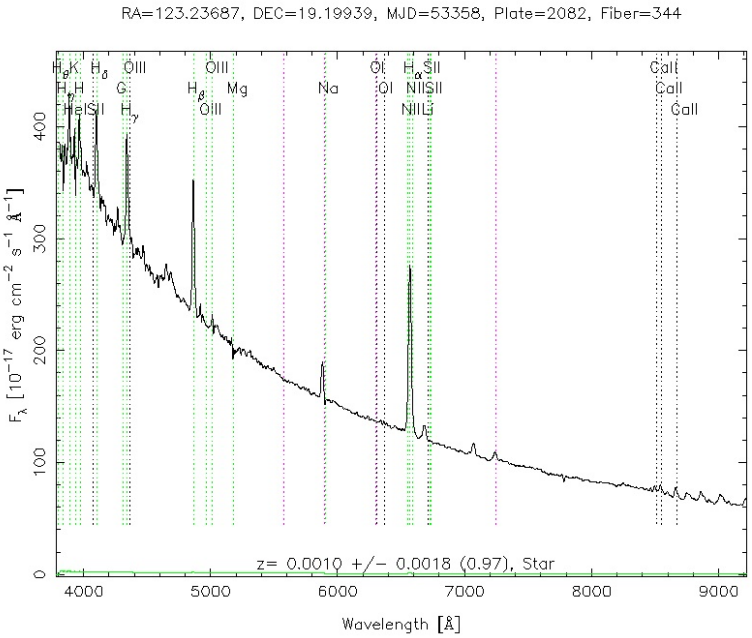

Figure A.1: *The spectrum of a blue cataclysmic variable in its most common appearance. The continuum of the spectrum is dominated by the white dwarf and the accretion disc at the short wavelengths, where at the longer wavelengths the red main-sequence star is barely visible. The broad emission lines are situated at the wavelengths for the Balmer lines indicated by H_α, H_β, H_γ and H_δ.*

of helium to the accretion disc around the white dwarf which is visible in the broad double-peaked helium emission lines.

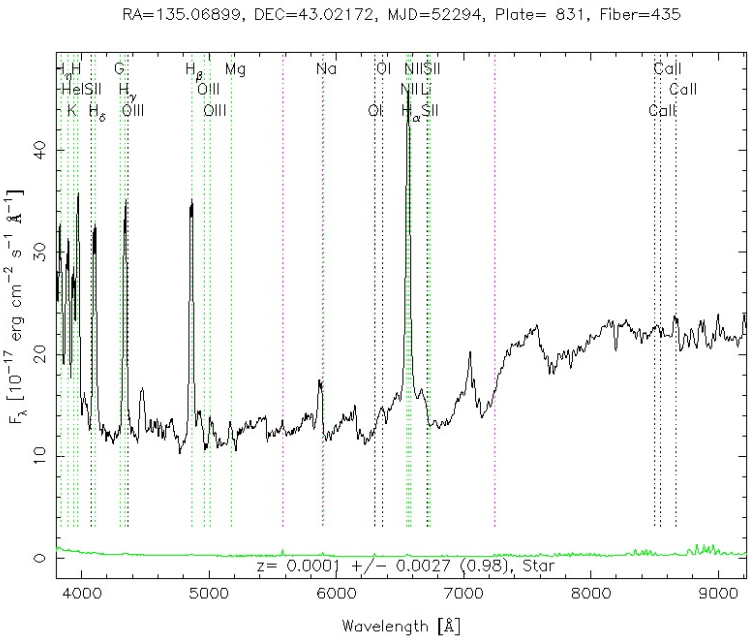

Figure A.2: *The spectrum of a cataclysmic variable where the continuum is dominated by the cool secondary. It nicely shows the broad Balmer lines at shorter wavelengths and broad molecular absorption bands at longer wavelengths.*

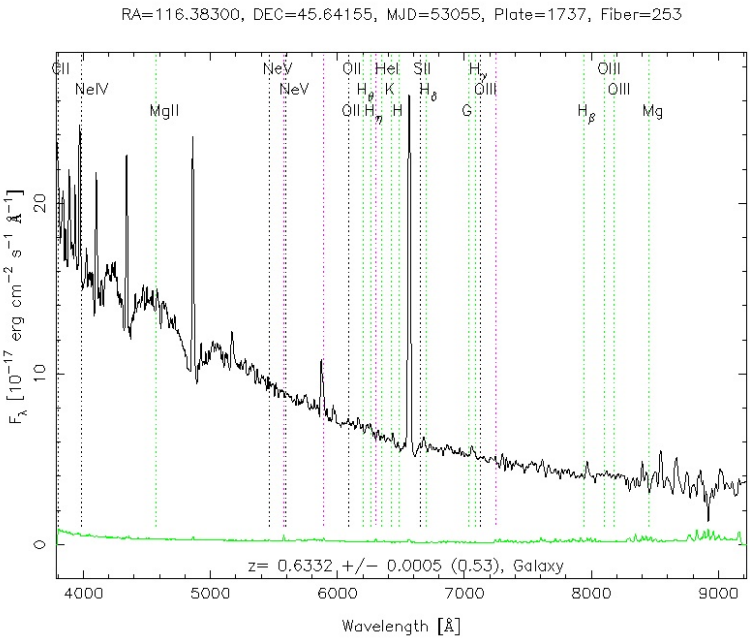

Figure A.3: *The spectrum of a white dwarf dominated cataclysmic variable. The broad hydrogen absorption lines from the white dwarf are visible together with the narrow hydrogen emission lines from the accretion disc.*

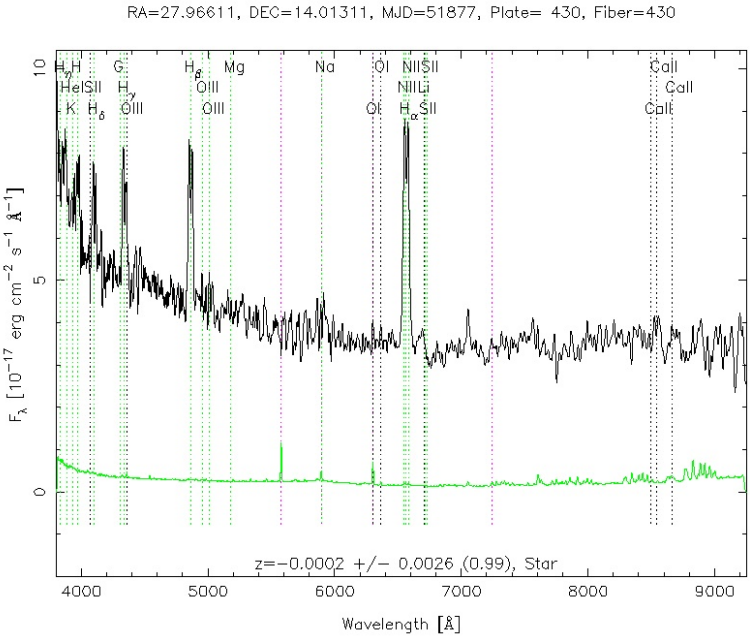

Figure A.4: *The spectrum of a cataclysmic variable where the double peaked hydrogen Balmer emission lines are very clear. The continuum is not dominated by any of the two components. Only the strong hydrogen emission lines from the accretion disc are visible.*

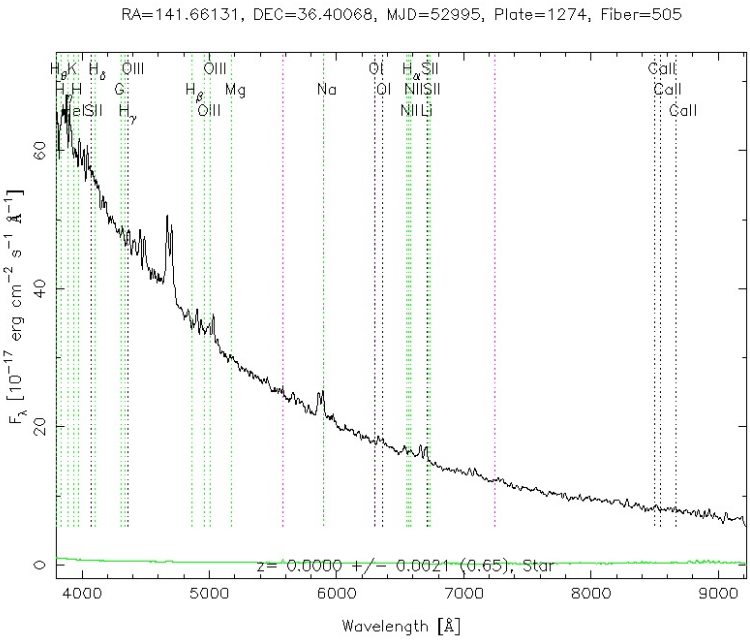

Figure A.5: *The spectrum of an AM CVn or a helium cataclysmic variable. Instead of hydrogen emission lines, helium emission lines are visible because in these systems the white dwarf is accreting mass from a low-mass helium-rich secondary star.*

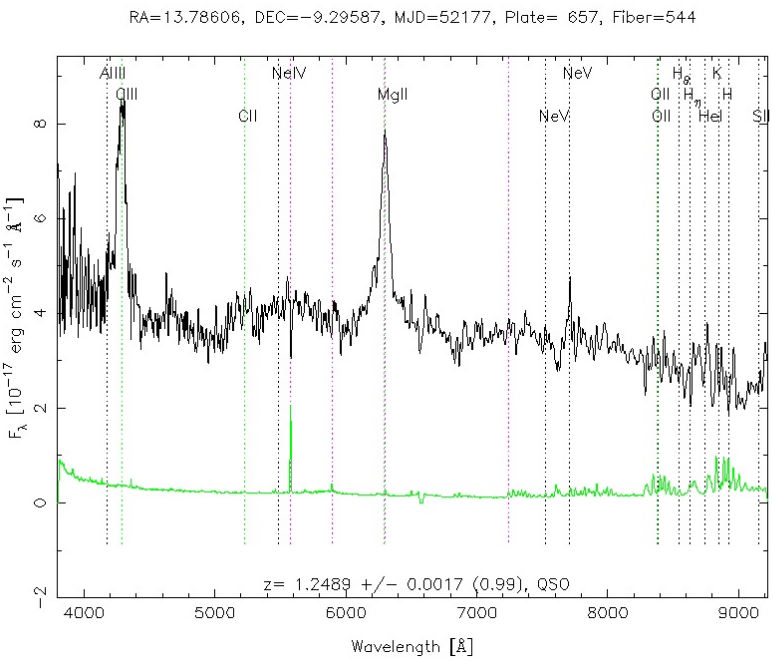

Figure A.6: *The spectrum of a quasar. The broad emission lines are typical for quasars and originate from the large disc around the black hole in quasars from which the black hole accretes matter.*

A.2 QUASARS

A quasar is a distant and extremely luminous galaxy with a very bright centre which is believed to host an accreting black hole. In optical light quasars look like point sources, by eye indistinguishable from normal stars. Since they are so luminous, quasars belong to the most distant objects that have ever been observed. The spectrum of a quasar shows very broad emission lines which originate from the matter in the accretion disc that rotates at very high velocities close to the black hole. The two big differences between the accretion discs in CVs and quasars are that the accretion disc is much larger for quasars and that the velocity at which objects are rotating at the centre of the disc is much larger. This results in much broader emission lines for quasars compared to CVs. Since quasars are very distant objects their spectrum is always reddened by a huge amount because of the scattering of its light on dust and gas. In Fig. A.6 a typical spectrum of a quasar is shown where the very broad emission lines due to the accretion onto the black hole are visible.

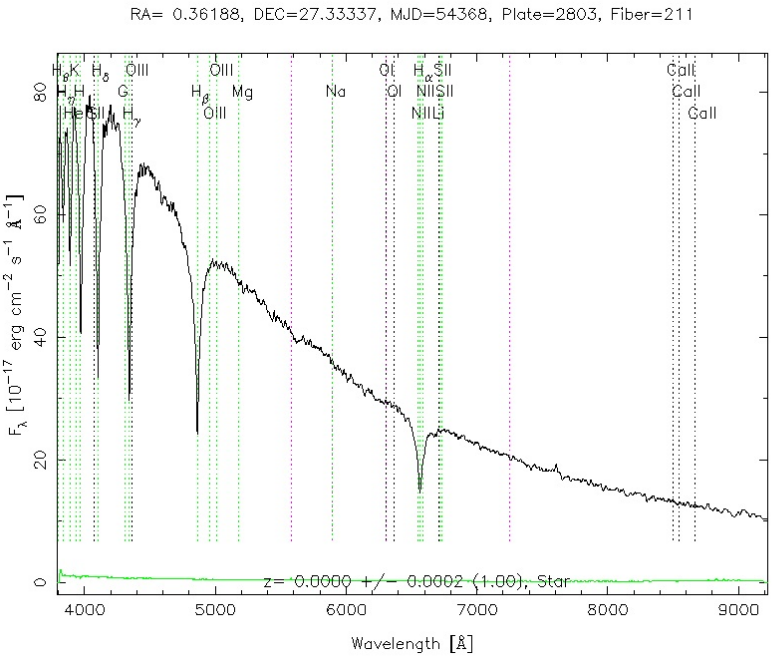

Figure A.7: *The spectrum of a dA white dwarf with broad absorption Balmer lines indicated by H_α, H_β, H_γ and H_δ.*

A.3 WHITE DWARFS

When a main-sequence star with a mass in the range of 0.08 - 8 $M_\odot$ has no more hydrogen to burn in its core, it will go through several evolution steps and eventually end up as a helium-rich compact small object with a mass comparable to the mass of our Sun and a size comparable to the size of the Earth: a white dwarf. The spectrum of these objects is dominated by absorption lines from elements in the outer atmosphere the white dwarf. The most common white dwarfs have hydrogen in their outer layers which is visible in their spectrum as broad hydrogen absorption lines as shown in Fig. A.7. These white dwarfs are called dA white dwarfs. When other metal lines are visible it is called a dB white dwarf with a spectrum shown in Fig. A.8. A dZ white dwarf has the typical Ca II absorption lines visible in Fig. A.9 at the short wavelengths at 3933 and 3969 Å. The last important group of white dwarfs are the dQ white dwarfs which show very prominent absorption bands of molecular carbon, the so called Swan bands. A spectrum of a dQ white dwarf is shown in Fig. A.10.

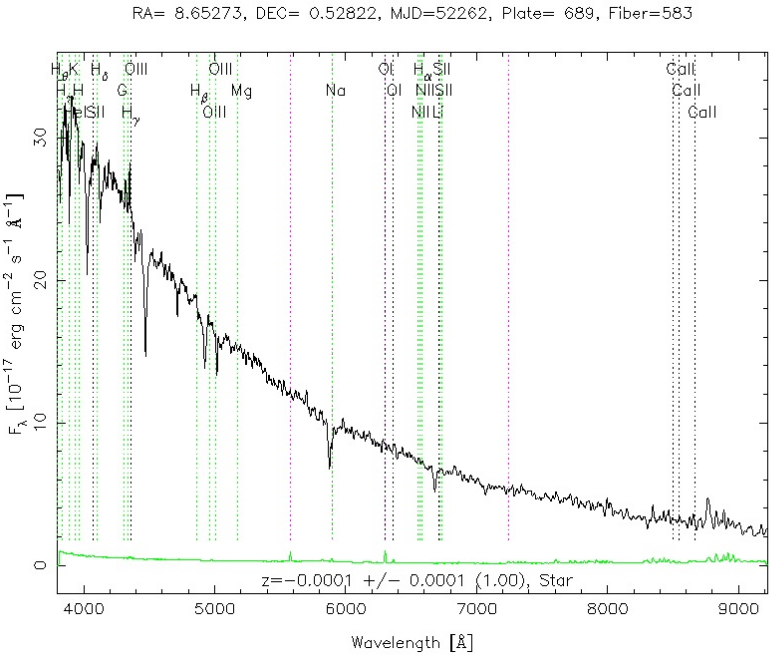

Figure A.8: *This spectrum of a dB white dwarf with metal absorption lines. This white dwarf is clearly not dominated by hydrogen because no hydrogen absorption lines are visible. On the other hand a lot of other elements are seen in absorption as for example Na and OIII.*

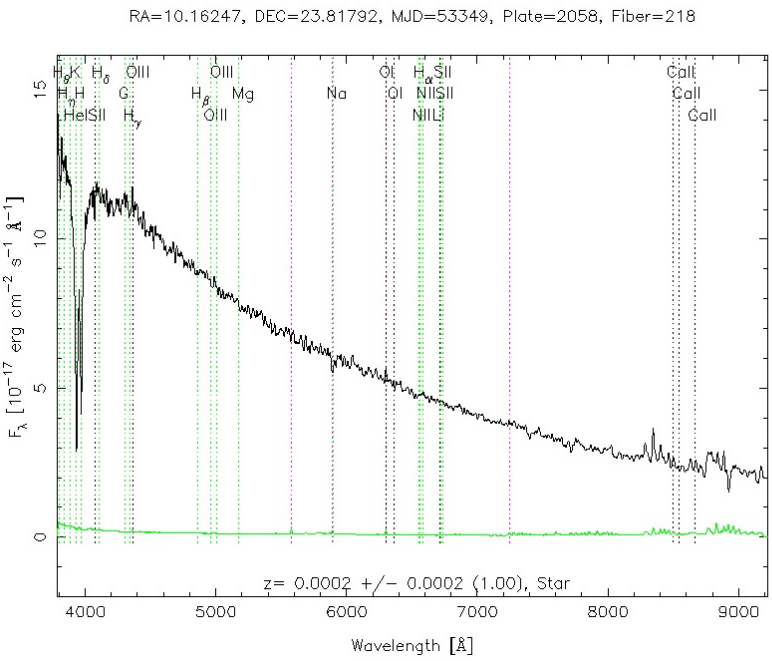

Figure A.9: *The spectrum of a typical dZ white dwarf with steep absorption lines for the CaII doublet at wavelengths of 3933 and 3969 Å.*

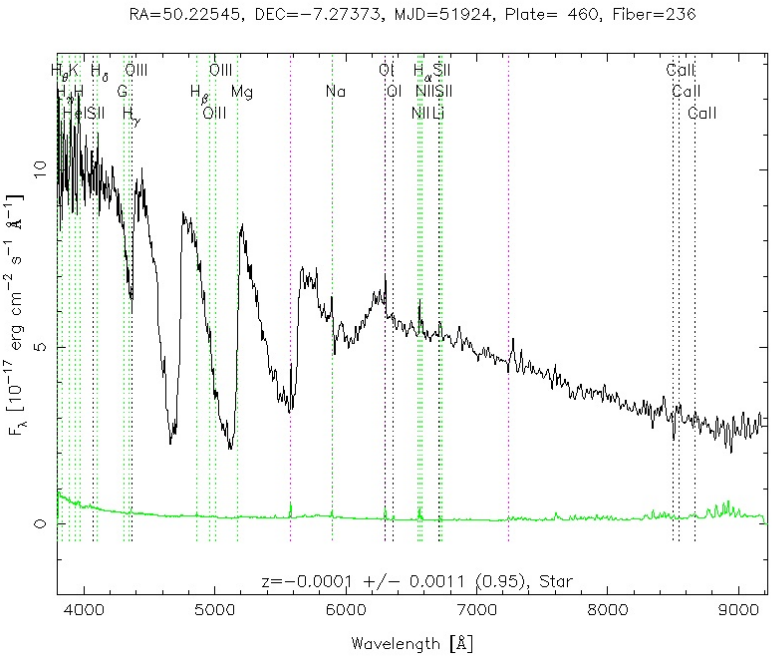

Figure A.10: *The spectrum of a cool dQ white dwarf. These stars show atomic and/or molecular carbon absorption bands, the so called Swan bands.*

A.4 WHITE DWARF MAIN-SEQUENCE BINARIES

White dwarf main-sequence binaries consist of a white dwarf and a detached (not mass transferring) main-sequence star. These systems are the progenitors of cataclysmic variables and are very closely related to them. Since WDMS binaries do not transfer mass, there is no accretion disc around the white dwarf and so no broad emission lines will be visible on the spectrum of WDMS binary. Sometimes however mass can be accreted onto the white dwarf through the magnetic field lines. In this case emission lines will be visible in the spectra but they will be very narrow. Fig. A.11 shows a typical spectrum of a white dwarf main-sequence binary. At shorter wavelengths the continuum is dominated by the hot white dwarf and at larger wavelengths it is dominated by the cooler secondary. The broad hydrogen absorption lines at the left side of the figure originate from the white dwarf while the broad molecular absorption bands at the right side come from the secondary. Fig. A.12 shows a WDMS system that is dominated by the white dwarf and has a much fainter secondary. The white dwarf main-sequence binary in Fig. A.13 on the other hand is dominated by the secondary: the white dwarf cannot be seen in the continuum, it can only be seen because of the broad hydrogen absorption lines at shorter wavelengths (and thus higher energies). In this example a narrow emission line for H_α is visible.

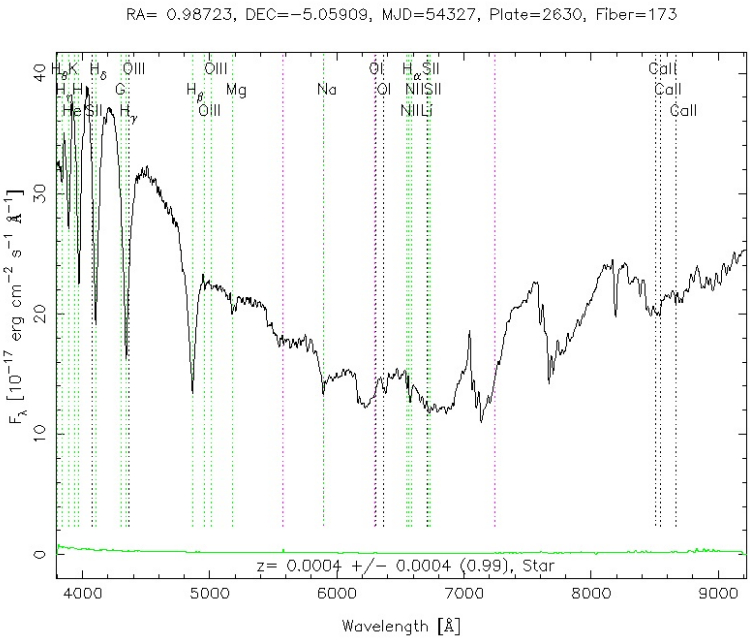

Figure A.11: *The spectrum of a white dwarf main-sequence binary where the white dwarf is visible at shorter wavelengths and the secondary at the larger wavelengths, both in the continuum as in the absorption lines.*

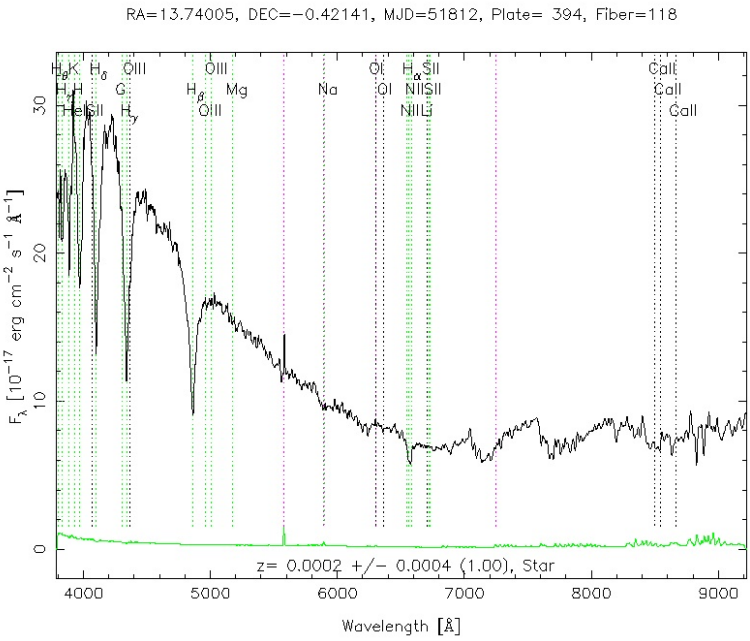

Figure A.12: *The spectrum of a white dwarf dominated WDMS binary. The secondary is not visible in the continuum of the spectrum. Its presence is only seen through the broad molecular absorption bands.*

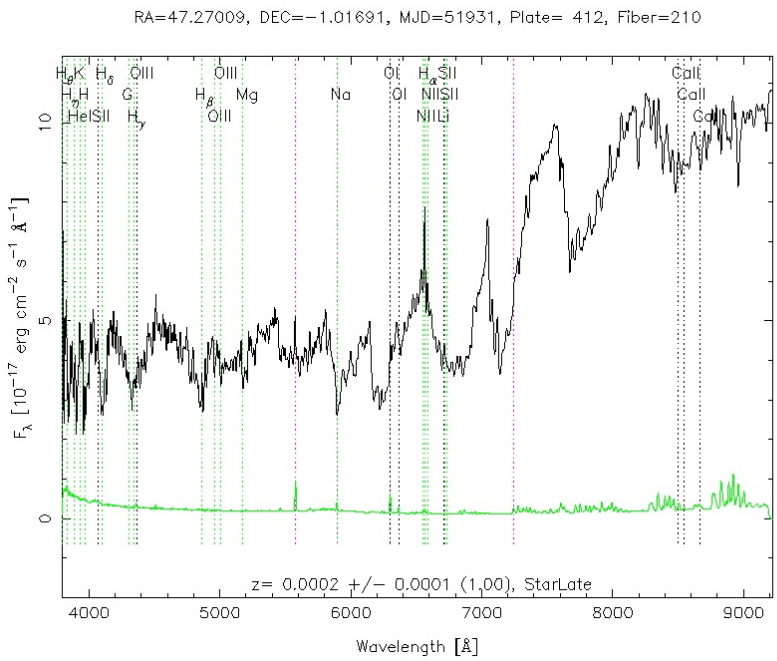

Figure A.13: *The spectrum of a white dwarf main-sequence binary that is dominated by its secondary. The faint white dwarf is only visible through the broad hydrogen absorption lines at shorter wavelengths, while the continuum is purely dominated by the cooler but brighter main-sequence star.*

A.5 REST

The spectra that are shown here are objects that are either not interesting enough for this research or were unrecognisable from just one spectrum. Fig. A.14 shows the spectrum of a typical main-sequence star. The largest part of the main-sequence stars was eliminated from the CV sample because there are a lot of these stars in our Galaxy and if all of them would be allowed, this would be a large contamination to spectroscopic samples. A hydrogen dominated main-sequence star looks a lot like a dA white dwarf by only looking at its spectrum except for the fact that main-sequence stars have much narrower hydrogen Balmer absorption lines. Figs. A.15 is an example of an unclassifiable object. Fig. A.15 could be a white dwarf with no apparent absorption lines but it is not possible to be sure from just one spectrum. For some objects things just went wrong while taking a spectrum. Such an example is shown in Fig. A.16 where something seems to be broken or at least not correct at all.

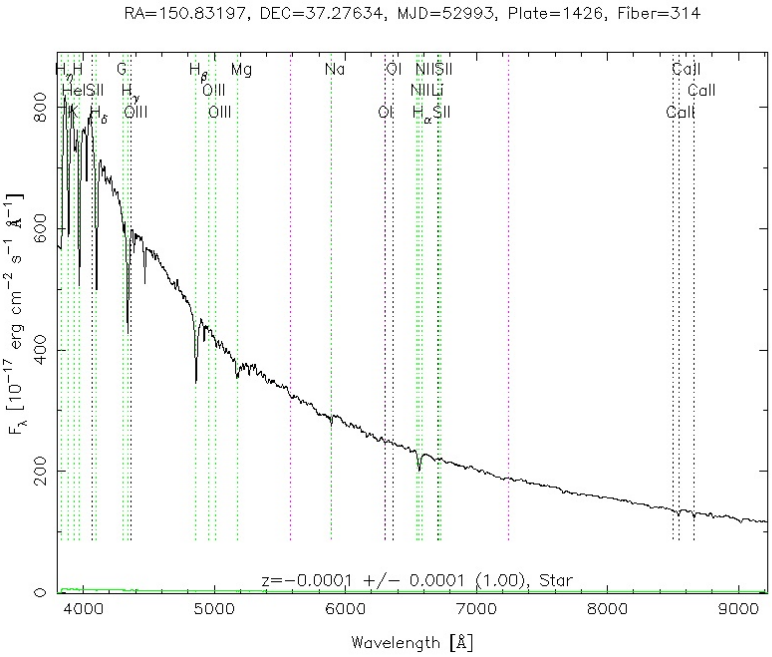

Figure A.14: *The spectrum of a main-sequence star. Since these stars burn hydrogen in their core, hydrogen and helium will be the biggest contributors to absorption of light. This is visible in the spectrum through the hydrogen Balmer absorption lines.*

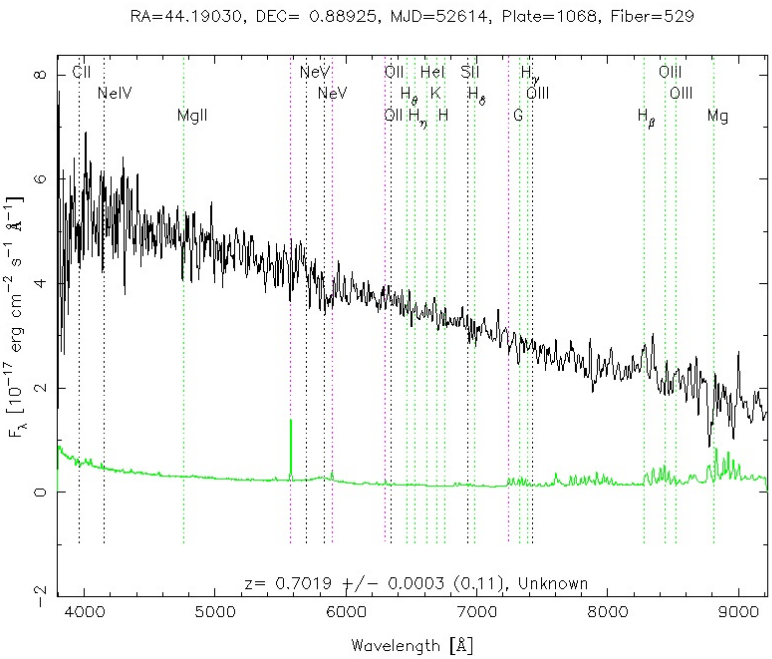

Figure A.15: *The spectrum of some unknown object. It could be the spectrum of a white dwarf with no evident absorption lines, but it is not clear enough.*

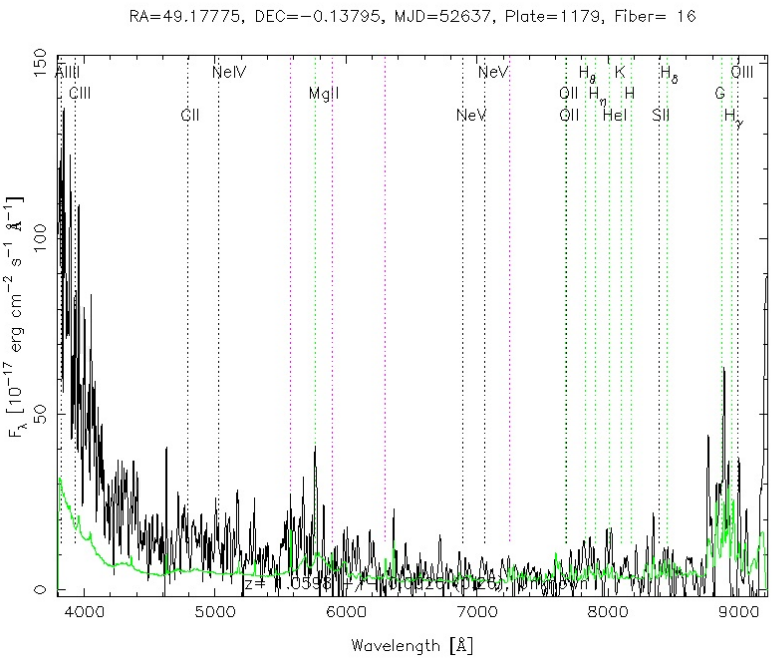

Figure A.16: *The spectrum of some unknown object. Something seems to have gone wrong while taking this spectrum. This could in other words be anything at all, but what it is exactly is not possible to say.*

Samenvatting

S.1 Cataclysmische Variabelen

Wanneer twee sterren gravitationeel aan elkaar gebonden zijn, spreekt men van *dubbelsterren*. De twee componenten in deze systemen draaien in een vlak rond een gezamelijk massacentrum. Meer dan de helft van alle sterren in ons Universum behoren tot een dubbelster. Het is echter maar bij vijf tot tien procent van alle dubbelsterren mogelijk de beide componenten te onderscheiden met het blote oog of met behulp van optische camera's of telescopen. Bij meer dan 90 % is de afstand tussen de twee sterren zo klein dat de systemen als één enkele puntbron waargenomen worden. Dubbelstersystemen die twee sterren bevatten die niet met behulp van zichtbaar licht te onderscheiden zijn, noemt men *nauwe dubbelsterren*. Zo'n systemen kunnen verschillende soorten sterren bevatten: normale waterstofverbrandende *hoofdreekssterren* (zoals onze zon), verder geëvolueerde *rode reuzen* of de uiteindelijk eindproducten van sterren. Deze laatste noemt men compacte sterren en hiertoe behoren witte dwergen, neutronensterren en zwarte gaten.

Nauwe dubbelsterren kunnen op verschillende momenten in hun leven massa verliezen. Op kleinere schaal gebeurt dit door sterrenwinden, op grotere schaal via het principe van *Roche-lobe massaverlies*. Het is geweten dat de afstand tussen de twee objecten in een dubbelster kleiner wordt naarmate het systeem ouder wordt. Op een gegeven ogenblik kunnen de twee sterren zich zo dicht bij elkaar bevinden dat de gravitatiekracht van één van beide sterren zo groot wordt dat ze massa van de andere ster aantrekt. Het grootst mogelijke volume dat een ster in een dubbelstersysteem kan aannemen zonder massa te verliezen aan de andere ster noemt men het *Roche-lobe volume*. Dit volume bevat de grootste hoeveelheid massa die de ster gravitationeel kan vasthouden. Hoe dichter beide sterren bij elkaar komen, hoe kleiner het Roche-lobe volume wordt en hoe moeilijker het wordt voor de ster om de volledige massa vast te houden. Na verloop van tijd zal de Roche-lobe van de ster kleiner worden dan haar volume. Op dat moment begint de ster massa te verliezen aan de andere ster en ondergaat ze Roche-lobe massaverlies.

Cataclysmische variabelen (CV's) zijn nauwe dubbelsterren die bestaan uit een witte

dwerg (WD) en een lage massa hoofdreeksster. Aangezien een witte dwerg het eindproduct is van een hoofdreeksster met een massa tussen 0.08 en 8 $M_\odot$ (zonsmassa's), moet de voorganger van de CV een dubbelster geweest zijn, bestaande uit twee normale lage massa hoofdreeksterren. Tijdens de evolutie van een hoofdreeksster naar een witte dwerg, wordt het volume van de hoofdreeksster groter dan zijn Roche-lobe en verliest ze massa aan de andere component van het systeem. Op het ogenblik dat de hoofdreeksster een veel kleinere witte dwerg wordt, stopt de massa-overdracht. Naarmate de dubbelster ouder wordt, verkleint de afstand tussen de witte dwerg en de hoofdreeksster omwille van draaimoment verlies. De dubbelster wordt echter pas een cataclysmische variabele genoemd op het ogenblik dat de separatie zo klein geworden is dat de Roche-lobe van de hoofdreeksster kleiner wordt dan de ster zelf en zij massa verliest aan de witte dwerg. De witte dwerg in een CV heeft typisch een massa van 0.6 $M_\odot$ (zonsmassa's), de hoofdreeksster een massa van 0.3 $M_\odot$. Beide componenten vervolledigen een volledige rotatie rond het massacentrum (één periode) in typisch in enkele dagen tot enkele uren tijd.

S.2 De Sloan Digital Sky Survey

De *Sloan Digital Sky Survey (SDSS)* onderzocht gedurende 8 jaar meer dan een kwart van de hemel. 357 miljoen objecten werden in 5 verschillende magnitudebanden[1] (u, g, r, i, z) geobserveerd. Hiervan kregen meer dan een miljoen quasars[2], galaxies en interessante objecten in de Melkweg een spectrum. SDSS maakte gebruik van een telescoop met een spiegeldiameter van 2.5 meter die zich in het Apache Point Observatorium in New Mexico bevindt. Deze telescoop werd enkel en alleen hiervoor gebruikt en was uitgerust met een *CCD-camera* en twee *spectrografen* die elk een verschillend deel van het gewenste golflengtegebied voor hun rekening namen. Aan de hand van de beelden van de CCD-camera werden objecten geselecteerd die een spectrum zouden krijgen. De spectrografen maakten gebruik van optische fibers om per observatie, van 640 objecten een spectrum te kunnen maken.

SDSS had als doel een 3-dimensionaal beeld van ons Universum te maken. Met behulp van spectra kan men de 2-dimensionale beelden van de camera uitbreiden naar een derde diepte-dimensie. Aangezien men wou weten hoe de grote structuren er diep in het heelal uitzien, heeft SDSS vooral naar sterrenstelsels (galaxies) en quasars gezocht. De galaxy en de quasar survey hadden elk eigen selectiecriteria aan de hand van dewelke ze hun objecten selecteerden voor een spectrum. In dit werk is de quasar survey van zeer groot belang omdat deze een zeer breed kleurengebied en i-magnitude gebied toeliet (i-magnitude van 15 tot 19.1). Het is immers zo dat de kleuren van CV's overlappen met het kleurengebied dat in de quasar survey toegelaten

[1] De magnitude van een object drukt de zichtbare helderheid van een object uit op een logaritmische schaal waarbij een helder object een lagere magnitude heeft dan een zwak object. De magnitude van een object kan uitgedrukt worden in verschillende golflengtegebieden.

[2] Quasars zijn galaxies met een zeer zwaar zwart gat in het centrum. Dat zwart gat trekt massa rondom zich aan en de enorme hoeveelheid gravitationele potentiële energie die hierbij vrijkomt, wordt uitgestraald.

werd. Dit betekent dat niet enkel quasars geselecteerd werden maar ook veel andere objecten met gelijkaardige kleureigenschappen, zoals cataclysmische variabelen. Wanneer er optische fibers over waren tijdens een observatie, werden er naast quasars en sterrenstelsels ook nog andere interessante objecten geselecteerd. Onder interessant werd bijvoorbeeld erg rode, erg blauwe of erg verre objecten verstaan. Door deze bijkomende fibers kregen nog veel extra CV's een spectrum.

Eén beperking op het CV sample zou het gebruik van *exclusie-boxen* kunnen zijn. De quasar survey heeft immers geprobeerd zoveel mogelijk niet-quasars te vermijden door in bepaalde kleurenregio's geen objecten te selecteren. Er werden exclusie-boxen gedefinieerd voor standaard hoofdreekssterren, witte dwergen en wijde dubbelsterren met een witte dwerg en een hoofdreeksster die geen massaverlies ondergaan zoals CV's. Hoewel geen regio's gedefinieerd werden om CV's te vermijden, zouden er toch een aantal cataclysmische variabelen in deze gebieden terecht kunnen gekomen zijn. Ondanks deze beperking verwachten we toch nog veel CV's met een spectrum te vinden in de databank van SDSS.

De gemakkelijkste manier om CV's terug te vinden in de grote spectroscopische databank van alle objecten met een spectrum, is zoeken naar spectra met prominente waterstofemissielijnen. Deze emissie is afkomstig van de materie die de hoofdreeksster (die voornamelijk uit waterstof bestaat) aan de witte dwerg verliest. Deze massa komt in een accretieschijf rond de witte dwerg terecht en is zichtbaar in emissie. In totaal werden er tot nu toe 279 CV's gevonden in de spectroscopische databank van SDSS. De overgrote meerderheid van deze systemen werden door Paula Szkody et al. (Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009) ontdekt met behulp van deze emissielijnmethode.

S.3 Cataclysmische variabelen in SDSS

Cataclysmische variabelen maken een aantal belangrijke fenomenen mee in hun leven, zoals Roche-lobe massaverlies, variabiliteit, vorming van accretieschijven en emissie van X-stralen door de massa-accretie. Sommige CV's bevatten zeer magnetische witte dwergen die geen vorming van accretieschijven toelaat en waar de massa-accretie op een geheel andere manier verloopt. Om de oorsprong en het verloop van al deze fenomenen te kunnen verstaan, moeten er genoeg CV's voor handen zijn. Een zoektocht naar objecten die zeer sterk variëren in lichtkracht zou veel CV's kunnen opleveren maar zou diegene die minder sterk variëren, missen. Observaties in het X-stralenregime zouden de oudere CV's vergeten die naar het einde van hun leven toe aan een veel lagere snelheid massa aantrekken en dus veel minder X-stralen uitsturen. Om die redenen is het belangrijk een uniform groep van cataclysmische variabelen te verkrijgen. Dit laat toe om uitspraken te kunnen doen over verschillende soorten CV's, zowel de sterk als minder sterk variërende, zowel de sterke als zwakkere X-stralers.

Er zijn verschillende redenen om te geloven dat SDSS de meest uniforme groep aan CV's ooit geleverd heeft. In de quasar survey zijn er geen restricties gemaakt op eigenschappen zoals variabiliteit, X-stralenemissie of enkel blauwe kleur zoals veel vroegere survey's wel deden. Dit heeft als resultaat dat niet alleen de objecten die regelmatig

(op tijdschaal van maanden of weken) explosies ondergaan, geobserveerd zullen worden. Niet alleen de sterke X-stralers waarbij de hoofdreeksster aan een hoge snelheid massa verliest, zullen gevonden worden. Naast de heel blauwe objecten moet SDSS ook de rodere CV's kunnen vinden waarbij het spectrum niet door de hete witte dwerg of accretieschijf gedomineerd wordt (zoals bij de blauwe tegenhangers) maar door de koudere hoofdreeksster. SDSS is ook de eerste survey die objecten kan selecteren tot en met een i-band magnitude van 19.1. Vroegere survey's haalden amper de grens van 17.5. Dit breder magnitude-gebied laat toe om de intrinsiek zwakkere en oudere CV's in ons Melkwegstelsel te vinden.

Deze thesis heeft als doel te onderzoeken hoe volledig SDSS geweest is in het selecteren van deze groep uniforme CV's om er een spectrum van te nemen. Er wordt eerst gewerkt vanuit de groep CV's die reeds ontdekt waren vóór SDSS zijn observaties begon. Daarna worden alle 279 CV's met een spectrum in SDSS als één groep beschouwd en onderzocht. Deze bevat dan zowel de eerder als nieuw ontdekte CV's. Uiteindelijk wordt er nagegaan of het mogelijk is CV's te vinden in de fotometrische databank van SDSS die geen spectrum kregen. De conclusies van deze thesis besluiten deze samenvatting.

S.3.1 Catalogen met eerder ontdekte CV's

Om de eerder ontdekte CV's die in SDSS geobserveerd werden te onderzoeken, wordt gebruik gemaakt van 2 verschillende groepen CV's: CV's in de Ritter & Kolb-cataloog en CV's die gevonden zijn door de Catalina Real-Time Transient Survey.

H. Ritter & U. Kolb catalogiseren alle CV's met een gekende periode die in publicaties vermeld worden in de zogenaamde *Ritter & Kolb-cataloog*. De meest recente lijst bevat meer dan 700 cataclysmische variabelen, waaronder ook diegene die in SDSS ontdekt werden en een gekende periode hebben. Deze laatste werden verwijderd, samen met alle CV's die niet in het juist gebied aan de hemel lagen om door SDSS te kunnen worden geobserveerd. Van de uiteindelijke groep van 122 CV's bleken er 57 een spectrum gekregen te hebben, 65 niet. Van deze laatste groep cataclysmische variabelen zonder spectrum, lag 50 % buiten het toegelaten i-magnitude gebied voor de quasar survey (15 - 19.1). Van de overige 50 % kwamen een aantal CV's in een exclusie-box terecht. Bij een aantal anderen zijn er problemen geweest met de spectrograaf tijdens het nemen van de spectra. Voor de overige CV's is het niet geweten waarom ze geen spectrum kregen.

In november 2007 begon de *Catalina Real-Time Transient Survey (CRTS)* zijn zoektocht naar variabiliteit aan de hemel aan de hand van drie verschillende telescopen met een spiegeldiameter van 0.5 tot 1.5 meter. Onder variabiliteit verstaan we zowel voorbij vliegende meteorïden of kometen, sterren die variabel zijn in lichtkracht, uitbarstingen op of rond een ster (wat bij CV's het geval is), als supernova's. De CRTS vond tot nu toe (april 2009) 82 cataclysmische variabelen in het gebied dat geobserveerd werd door SDSS, waarvan 16 CV's een spectrum kregen. Ongeveer 70 % van de CV's zonder spectrum was te zwak, 15 % werd geselecteerd voor een spectrum maar kreeg er uiteindelijk toch geen. De overige 15 % kwam terecht in een exclusie-box, kreeg geen spectra omwille van problemen met de spectrografen of kreeg voor een

ongekende reden geen spectrum.

Om te weten hoeveel CV's SDSS geselecteerd heeft voor een spectrum, wordt de spectroscopische volledigheid berekend. Deze waarde drukt uit welk percentage cataclysmische variabelen een spectrum kreeg in een bepaalde groep CV's. Als de CV's die door CRTS gevonden werden met de CV's uit de Ritter & Kolb cataloog vergeleken worden, is het duidelijk dat minder CRTS CV's geselecteerd werden voor een spectrum ($\sim$ 20 %) dan Ritter & Kolb CV's ($\sim$ 45 %). De reden hiervoor moet gezocht worden bij de aard van de cataclysmische variabelen die gevonden worden door de Catalina Real-Time Transient Survey. CRTS observeert objecten die variabiliteit vertonen aan de hemel. In het geval van CV's gaat dit om perioden van explosies rond of op de witte dwerg. Op zo'n ogenblikken kan de CV plots 5 tot 6 magnituden helderder worden. Als we rekenen met het magnitudegebied van de quasar survey van SDSS (15 - 19.1), dan kan een CV in rust met een i-magnitude van 22 plots in een goed observeerbaar magnitudegebied (16 - 17) terechtkomen wanneer ze een explosie ondergaat. CRTS heeft deze objecten geobserveerd in explosieve toestand, maar op het ogenblik dat ze door SDSS geobserveerd werden, was de meerderheid van deze dubbelsterren in een rusttoestand en waren ze te zwak (i-mag > 19.1) om geselecteerd te worden voor een spectrum door SDSS. Aangezien 70 % van de CV's in de Catalina Survey lijst die geen spectrum kregen in SDSS te zwak zijn (i-mag > 19.1), is de lage spectroscopische volledigheid van de CRTS CV's in SDSS op deze manier verklaard.

Een i-magnitude histogram van alle eerder ontdekte CV's (zowel CRTS als Ritter & Kolb CV's) toont enerzijds dat 75 % van de CV's zonder spectrum buiten het helderheidsgebied liggen dat gebruikt werd door de quasar survey (15 - 19.1) en anderzijds dat meer dan 80 % van de CV's met een spectrum binnen het toegelaten quasar gebied ligt. De spectroscopische volledigheid is de verhouding tussen het totaal aantal CV's (190) en het aantal CV's met een spectrum in SDSS (65). Voor het volledige helderheidsgebied geeft dit dus een spectroscopische volledigheid van 34 % voor alle eerder gekende CV's. Het grootste aantal CV's in SDSS komt echter uit de quasar survey die zijn limieten binnen het 15 - 19.1 gebied gelegd heeft. Hier zou het percentage van CV's met een spectrum dus hoger moeten liggen. 84 CV's hebben een i-magnitude binnen de grenzen (15 - 19.1) waarvan er 55 een spectrum kregen. Dit resulteert in een spectroscopische volledigheid van alle eerder gekende CV's van 65 % voor i-magnituden tussen 15 en 19.1. Dit is inderdaad een hoger percentage dan wat gevonden werd voor het totale i-magnitudegebied.

Deze waarden moeten echter ietwat genuanceerd worden omwille van twee redenen. SDSS werd gedurende de laatste 4 jaren opgedeeld in 3 verschillende surveys. De Sloan Legacy Survey deed observaties over bijna 20 % van de hemel en nam meer dan 90 % van alle spectra, als een vervolg van het werk van de eerste 5 jaren van SDSS. SEGUE (Sloan Extension for Galactic Understanding and Exploration) deed observaties en nam spectra van objecten in de Melkweg. De Sloan Supernova Survey zocht herhaaldelijk in eenzelfde beperkt stuk aan de hemel (de zogenaamde Stripe 82) naar variabiliteit, als een vervolg van het werk van de eerste 5 jaren van SDSS. Zowel de galaxy en quasar survey als de extra zoektocht naar extreem blauwe, rode of verre objecten voor de extra fibers behoorden tot de Sloan Legacy Survey. De Sloan Supernova

Survey werd uitgevoerd op een klein gebied dat tot het observatiegebied van de Sloan Legacy Survey hoorde en hier werden geen spectra genomen. SEGUE deed dit echter wel en gebruikte hiervoor zijn eigen selectiecriteria. Het is geweten dat de kans dat SEGUE CV's gevonden heeft met deze selectie-algoritmen zeer klein is omwille van de eisen die gesteld werden aan de te selecteren objecten. Het is echter moeilijk onderscheid te maken tussen de objecten die door Legacy en door SEGUE geobserveerd werden. Een manier om dit te doen is door het gebied dat de melkweg bevat niet toe te laten. Zo wordt al een groot stuk van de fotometrie van SEGUE vermeden. SEGUE heeft echter een groter gebied dan alleen deze strook geobserveerd. Dit betekent dat het totaal aantal eerder ontdekte CV's die in het juiste gebied aan de hemel lagen om geobserveerd te kunnen worden door SDSS zowel CV's bevat die door Legacy als door SEGUE geobserveerd werden. De CV's die een spectrum kregen werden waarschijnlijk allemaal geselecteerd door Legacy. Daarom zouden de CV's die door SEGUE geobserveerd werden eerst moeten verwijderd worden. Dit zou de werkelijke spectroscopische volledigheid iets groter maken dan de waarde die hier berekend werd.

Een tweede reden waarom de waarde van 65 % spectroscopische volledigheid waarschijnlijk een ondergrens is, heeft te maken met de exclusie-boxen. De quasar survey heeft regio's geselecteerd met objecten die een gelijkaardige kleur hebben om op deze manier witte dwergen, hoofdreekssterren en wijde dubbelsterren met een witte dwerg en een hoofdreeksster in de selectieprocedure te vermijden. Hoewel de meest courante CV's niet in deze gebieden liggen, zijn er toch een aantal CV's in deze boxen terechtgekomen die waarschijnlijk een spectrum zouden gekregen hebben moesten deze regio's niet afgescheiden geweest zijn.

S.3.2 Alle CV's

In een tweede stap wordt de groep van vroeger ontdekte CV's uitgebreid met de nieuwe CV's die door SDSS ontdekt werden gedurende de voorbije 8 jaar. Een eerste aspect dat onderzocht wordt, is de positie van deze 279 CV's op kleur-kleur diagrammen. De assen drukken de kleur van een object uit aan de hand van het verschil tussen de magnituden in verschillende magnitudebanden (u, g, r, i, z). Dit creëert een 4-dimensionale kleurenruimte met kleuren (u-g), (g-r), (r-i) en (i-z) die op drie verschillende 2-dimensionale projecties kan afgebeeld worden. Op zo'n projecties kunnen alle fotometrische objecten getoond worden aan de hand van een *dichtheidshistogram* dat toont in welke gebieden het meeste objecten liggen. Een logisch gevolg is dan het tonen van de spectroscopische volledigheid als een *volledigheidshistogram* dat toont in welke gebieden relatief het meeste objecten een spectrum gekregen hebben. In dit laatste soort histogrammen zijn de exclusie-boxen zeer duidelijk zichtbaar.

Gebruik makend van deze histogrammen kunnen alle CV's die door SDSS een spectrum kregen, afgebeeld worden in de 4-dimensionale kleurenruimte. Een groot aantal CV's zijn zeer blauw en liggen dicht bij elkaar in het gebied waar veel nabije quasars liggen (quasars die nog niet te sterk roodverschoven zijn omwille van Dopplereffecten). Een onderscheid tussen de nieuwe ontdekte en reeds eerder gekende CV's toont aan dat de eerder gekende CV's allemaal in dit blauw gebied liggen. SDSS heeft het aantal CV's in deze groep verder verhoogd maar heeft daarnaast ook de minder

vaak voorkomende CV's gevonden die niet in dit gebied liggen. De groep CV's kan ook opgesplitst worden in twee groepen gebaseerd op de sterkte van de witte dwerg (of eerder de zwakte van de begeleiderster). Een CV waarvan het spectrum gedomineerd wordt door de lichtkracht van de witte dwerg is een oud systeem waarbij de hoofdreeksster reeds zoveel massa verloren heeft dat ze nog nauwelijks zichtbaar is ten opzichte van de witte dwerg. Deze systemen zijn vaak intrinsiek zwakke objecten en werden in vroegere surveys amper gevonden (omwille van de te lage magnitudegrens). Doordat SDSS de magnitudegrens heeft kunnen verhogen zodat zwakkere CV's ontdekt werden, is het aantal witte dwerg-gedomineerde cataclysmische variabelen verelfvoudigd (van 4 naar 44). Het percentage van witte dwerg-gedomineerde CV's was voordien minder dan 10 % is maar is nu gestegen tot 20 %.

Gebruik makend van alle CV's die een spectrum kregen in SDSS is het mogelijk om een schatting te maken van de spectroscopische volledigheid van alle CV's in SDSS. Hiervoor werd een compact 4-dimensionaal kleurengebied geselecteerd dat 77 % van alle CV's bevat. Voor een kleine random geselecteerde groep van objecten met een spectrum in deze cluster werd nagegaan of er nog meer CV's te vinden waren die nog niet ontdekt werden door Paula Szkody et al. met behulp van de emissielijnen methode. Eén nieuwe CV werd hierdoor ontdekt, waardoor er verder vanuit gegaan wordt dat zo goed als alle CV's die SDSS een spectrum gegeven heeft in deze cluster reeds gevonden zijn. In de vorige sectie werd het probleem in verband met de fotometrie die door SEGUE uitgevoerd werd aangehaald. Om dit effect hier te verkleinen, werden alle objecten die geobserveerd werden in het gebied van de galactische schijf niet toegelaten tot de groep van fotometrische objecten in de kleurencluster. Aangezien SDSS geen specifieke objecten geselecteerd heeft maar eerder specifieke objecten geëlimineerd heeft, kan er gezegd worden dat het percentage aan CV's in de spectroscopische databank ongeveer gelijk is aan het percentage aan CV's dat geen spectrum kreeg in de gebieden buiten de exclusie-boxen.

Aangezien de 4-dimensionale kleurencluster geen exclusie-boxen bevat kunnen we een schatting maken van het aantal CV's dat door SDSS geobserveerd is maar geen spectrum gekregen heeft. Voor het volledige magnitudegebied kregen 49 280 objecten in deze cluster een spectrum waarvan 216 CV's. Dit betekent dat 0.44 % van alle objecten met een spectrum een CV is en dus ook 0.44 % van alle fotometrische objecten een CV zou moeten zijn. SDSS observeerde 388 642 objecten in deze cluster en 1 703 hiervan zouden CV's zijn. Hier zitten ook de 216 CV's met een spectrum in. De spectroscopische volledigheid wordt geschat door de verhouding te nemen van het totaal aantal CV's dat geobserveerd werd (1703) met het aantal hiervan dat een spectrum kreeg (216): 12.7 % van alle CV's kreeg een spectrum in SDSS.

De quasar survey heeft zijn selectiegebied beperkt tot een i-magnitude tussen 15 en 19.1. Zoals in de vorige sectie het geval was, wordt de spectroscopische volledigheid verwacht hoger te zijn binnen deze grenzen. 29 993 objecten in deze cluster hadden een i-magnitude tussen 15 en 19.1 en kregen een spectrum, waarvan 216 objecten als CV herkend werden. Dit toont dat een iets hogere 0.55 % van alle spectroscopische objecten een CV is in deze cluster. Deze waarde extrapoleren naar de 388 642 objecten die door SDSS geobserveerd werden, geeft een totaal van 250 CV's die in deze

kleurencluster geobserveerd werden door SDSS. Dit geeft een specroscopische volledigheid van 66.4 %. Deze waarde leunt verbazingwekkend goed aan bij de waarde die bekomen was aan de hand van enkel de eerder gekende CV's, maar die op een totaal verschillende manier berekend was.

S.3.3 Onderzoek van de overige CV's zonder spectrum

De vorige secties hebben getoond dat ongeveer 65 % van alle CV's een spectrum kregen in SDSS. De overige 35 % werd geobserveerd, maar kreeg om één of andere reden geen spectrum. In deze sectie wordt getoond op welke manier het mogelijk zou kunnen zijn om uit een willekeurige groep fotometrische objecten zonder spectrum een zo groot mogelijk aantal CV's te vinden en een zo klein mogelijk aantal quasars.

Cataclysmische variabelen hebben een eigenbeweging (proper motion) aan de hemel, enerzijds veroorzaakt door verschillende afstanden tot het centrum van de Melkweg, anderzijds door willekeurige beweging van de CV's in het galactisch vlak. Deze eigenbeweging wordt in beide gevallen veroorzaakt door het feit dat ze in onze Melkweg liggen. Quasars daarentegen liggen ver buiten het Melkwegstelsel en hebben een veel kleinere eigenbeweging dan CV's. Aangezien de Melkweg zeer veel hoofdreeksterren bevat die dus ook een observeerbare eigenbeweging hebben, werden deze geëlimineerd. Door dan enkel objecten toe te laten met een significante eigenbeweging is het mogelijk een zeer groot aantal quasars kwijt te raken. Omdat we echter wel spreken over miljoenen quasars tegenover een paar duizend CV's, is slechts een klein percentage quasars nog steeds een groot aantal quasars in absolute waarden.

Om die reden werd gekozen naast de significante eigenbeweging nog een extra voorwaarde op te leggen aan de fotometrische objecten uit SDSS die geen spectrum gekregen hebben. Data van de Galaxy Evolution Explorer (GALEX) werd gebruikt naast de data van SDSS. GALEX heeft objecten in het ultraviolet (zowel ver als nabij UV) geobserveerd. Samen met de optische kleuren van SDSS laat dit toe de kleurenruimte uit te breiden met een extra fUV - nUV (far-UV en near-UV) kleur. Het doel is om een 2-dimensionale kleurenprojectie te vinden waarin de quasars duidelijk te onderscheiden zijn van de andere objecten. Gebruik makend van de objecten met een spectrum waarvan geweten is welk soort objecten het zijn, werd een manier gevonden om 76 % van de quasars en 72 % van de witte dwergen te elimineren.

Als er verondersteld kan worden dat dezelfde verdeling aan objecten aanwezig is in de groep objecten die een spectrum kreeg in SDSS als de groep die geen spectrum kreeg, dan zouden we na de vorige selecties en eliminaties de volgende objecten overhouden: 15 % CV's, 15 % quasars, 15 % witte dwergen, 50 % wijde dubbelsterren met een witte dwerg en een hoofdreeksster en 5 % aan andere objecten. De veronderstelling dat dezelfde verdeling aan objecten aanwezig is in de groep objecten met een spectrum als in de groep zonder spectrum is echter niet volledig geldig. Het probleem zit in de objecten die niet toegelaten werden door de exclusie-boxen (vooral de witte dwergen en de wijde dubbelsterren met een witte dwerg en een hoofreeksster aangezien de gewone hoofdreekssterren hier reeds in het begin weggelaten werden). Er zijn zeer weinig witte dwergen en wijde dubbelsterren met een witte dwerg en een hoofdreeksster die een spectrum kregen in SDSS. Dit heeft als resultaat dat het percentage aan

witte dwergen en wijde dubbelsterren in een willekeurige groep van objecten die geen spectrum kregen in SDSS hoger ligt dan voor een groep willekeurige objecten met een spectrum. Het effect hiervan zou aan de andere kant niet zeer groot mogen zijn aangezien het aantal objecten in de exclusie-boxen minder dan 1 % is van het totaal aantal fotometrische objecten. Dit effect moet echter nog onderzocht worden vooraleer met meer zekerheid kan gezegd worden dat dit een goede manier is om CV's te vinden.

S.4 Conclusies en toekomstplannen

Het was reeds geweten dat SDSS een uniformere groep aan CV's zou leveren dan ooit voordien uit een survey gekomen was, doordat geen specifieke selectiecriteria opgelegd werden door SDSS. De veel hogere magnitudelimiet heeft gezorgd voor een uitbreiding van de groep oude, intrinsiek zwakke, witte dwerg-gedomineerde CV's welke voordien amper gevonden werden. SDSS heeft ook bewezen een veel breder kleurengamma toegelaten te hebben voor CV's, waardoor veel nieuwe blauwe CV's ontdekt werden maar ook de rodere varianten gevonden zijn.

De groep CV's die uit SDSS gekomen zijn, is uniform binnen de magnitudegrenzen (15 - 19.1) en is volledig willekeurig gekozen. Het percentage aan CV's met een spectrum ten opzichte van het totaal aantal geobserveerde CV's berekend worden. Dit werd eerst gedaan aan de hand van de eerder gekende cataclysmische variabelen en later op de volledige groep CV's die een spectrum gekregen hebben in SDSS. De spectroscopische volledigheid werd berekend op twee verschillende manieren voor deze twee groepen, maar gaf voor beide groepen een percentage van $\sim 65\,\%$. Hoewel er een aantal redenen zijn om deze waarde te nuanceren, is het goed te merken hoe goed de waarden voor beide groepen aansluiten. Dit is overtuigend genoeg om te geloven dat de groep CV's die door SDSS gevonden werd, een uniforme groep is.

Uit de spectroscopische volledigheid is af te leiden dat nog meer dan 30 % van de geobserveerde CV's geen spectrum gekregen heeft. Gebruik makend van hun eigenbeweging en GALEX data is het mogelijk om een willekeurige groep objecten te selecteren die geen spectrum kreeg in SDSS en het aantal quasars hierin drastisch te verminderen. Op die manier zou het mogelijk moeten zijn CV's te vinden die geen spectrum kregen in SDSS.

In de toekomst zal enerzijds onderzocht worden hoe groot het effect is van de exclusie-boxen op de resultaten bekomen in dit werk. Daarnaast zullen ook observaties gedaan worden van willekeurige groepen objecten die de selectiecriteria ondergingen die in de laatste sectie uitgelegd werden. Dit zou moeten toelaten enerzijds het aantal CV's in het quasar-magnitudegebied (15 - 19.1) uit te breiden en anderzijds te proberen de limiet van 19.1 naar grotere magnitudewaarden te verleggen.

Bibliography

Abazajian, K. & Sloan Digital Sky Survey, f. t. 2009, ArXiv e-prints

Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559

Dillon, M., Gänsicke, B. T., Aungwerojwit, A., et al. 2008, MNRAS, 386, 1568

Drake, A. J., Djorgovski, G., Graham, M., et al. 2006, in Bulletin of the American Astronomical Society, Vol. 38, Bulletin of the American Astronomical Society, 1002–+

Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2008, ArXiv e-prints

Frieman, J. A., Bassett, B., Becker, A., et al. 2008, AJ, 135, 338

Gänsicke, B. T. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 330, The Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota, 3–+

Gänsicke, B. T., Dillon, M., Southworth, J., et al. 2009, MNRAS

Gänsicke, B. T., Rodríguez-Gil, P., Marsh, T. R., et al. 2006, MNRAS, 365, 969

Hellier, C. 2001, Cataclysmic Variable Stars, ed. C. Hellier (Praxis Publishing Ltd)

Hilditch, R. W. 2001, An Introduction to Close Binary Stars, ed. R. W. Hilditch (Cambridge University Press)

King, A. R. 1988, QJRAS, 29, 1

King, A. R., Schenker, K., & Hameury, J. M. 2002, MNRAS, 335, 513

Kolb, U. & Baraffe, I. 1999, MNRAS, 309, 1034

Larson, S., Beshore, E., Hill, R., et al. 2003, in Bulletin of the American Astronomical Society, Vol. 35, Bulletin of the American Astronomical Society, 982–+

Littlefair, S. P., Dhillon, V. S., Marsh, T. R., & Gänsicke, B. T. 2006, MNRAS, 371, 1435

Littlefair, S. P., Dhillon, V. S., Marsh, T. R., et al. 2007, MNRAS, 381, 827

Peters, C. S. & Thorstensen, J. R. 2005, PASP, 117, 1386

Pyrzas, S., Gänsicke, B. T., Marsh, T. R., et al. 2009, MNRAS, 394, 978

Richards, G. T., Fan, X., Newberg, H. J., et al. 2002, AJ, 123, 2945

Ritter, H. 1984, A&AS, 57, 385

Ritter, H. 1987, A&AS, 70, 335

Ritter, H. 1990, A&AS, 85, 1179

Ritter, H. & Kolb, U. 1998, A&AS, 129, 83

Ritter, H. & Kolb, U. 2003, A&A, 404, 301

Smolčić, V., Ivezić, Ž., Knapp, G. R., et al. 2004, ApJ, 615, L141

Southworth, J., Gänsicke, B. T., Marsh, T. R., et al. 2006, MNRAS, 373, 687

Southworth, J., Marsh, T. R., Gänsicke, B. T., et al. 2007, MNRAS, 382, 1145

Southworth, J., Townsley, D. M., & Gänsicke, B. T. 2008, MNRAS, 388, 709

Szkody, P., Anderson, S. F., Agüeros, M., et al. 2002, AJ, 123, 430

Szkody, P., Anderson, S. F., Hayden, M., et al. 2009, AJ, 137, 4011

Szkody, P., Fraser, O., Silvestri, N., et al. 2003, AJ, 126, 1499

Szkody, P., Henden, A., Agüeros, M., et al. 2006, AJ, 131, 973

Szkody, P., Henden, A., Fraser, O., et al. 2004, AJ, 128, 1882

Szkody, P., Henden, A., Fraser, O. J., et al. 2005, AJ, 129, 2386

Szkody, P., Henden, A., Mannikko, L., et al. 2007, AJ, 134, 185

Warner, B. 1995, Cataclysmic variable stars, ed. B. Warner

Wolfe, M. A., Szkody, P., Fraser, O. J., et al. 2003, PASP, 115, 1118

Yanny, B., Rockosi, C., Newberg, H. J., Knapp, G. R., & for the SDSS-II SEGUE collaboration. 2009, ArXiv e-prints

York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579