Cataclysmic Variables From the Sloan Digital Sky Survey

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Abstract In the four years since the Sloan Digital Sky Survey (SDSS) began operation, over 100 new cataclysmic variables (CV) have been found. Among these are many interesting systems, including eclipsing, pulsating, and magnetic CVs. A comparison of the statistics emerging from the observed period distribution of the SDSS compared to past surveys shows many more short period systems, consistent with less selection bias based on brightness. Opportunities for observations with ongoing XMM and HST projects are presented.

1. Introduction

The Sloan Digital Sky Survey (SDSS) is nearing the end of its original five-year plan to map out the North galactic area of the sky with five-color photometry and spectra (see the SDSS web site http://www.sdss.org/ for details). The main part of the survey will be completed in June 2005 but an extension is planned to finish the areas of the sky that were lost to bad weather and to obtain additional data closer to the galactic plane. While the main focus of the survey has been on galaxies and quasars, many stars are also observed, among them cataclysmic variables (CVs). At the current time, there are over one hundred new cataclysmic variables that have been found, and spectra and colors of many previously known systems have also been obtained. The detailed results on these systems are published in Szkody *et al.* (2002a, 2003a, 2004, and 2005).

The primary advantages of the SDSS as compared to previous surveys are that 1) it goes several magnitudes fainter (down to 21st magnitude) so that there are fewer brightness selection effects, 2) it takes both blue and red spectra so that the white dwarf, the accretion disk, and the late type secondary can all be observed, and 3) SDSS obtains so much spectroscopy that a wide variety of CVs are found (see Warner 1995 for an overall review of the kinds of CVs). SDSS is finding CVs containing accretion disks, those that have white dwarfs with large magnetic fields so that no disk forms (Polars), and those with intermediate fields (Intermediate Polars or DQ Her stars). Since SDSS can observe faint sources, which are generally those with low accretion rates (hence low contribution of the accretion disk or column), the underlying stars are often evident in the spectra.

SDSS operates by first taking photometric images on strips of the sky, using the best dark nights with good seeing. From various color selection criteria set up by the research groups within SDSS, galaxies, quasars, and stars are selected for spectroscopic fibers. Plates are drilled so the fibers match the objects in a three-degree field. Approximately one-hour exposures are then taken to obtain 660 spectra at a time. The reduced photometry and spectra are released at regular intervals and are available through the SDSS web site. The next release (Data Release 4 or DR4) is planned for June 2005. Because CVs can show a wide range of colors, it is difficult to uniquely select them from the SDSS photometry alone. But since their colors overlap with those of quasars, and quasars receive a large number of fibers for spectroscopy, most of the CVs are found as QSO "rejects" or through a category called Serendipity which selects very blue or very red objects.

In this paper, we will summarize the results that have emerged in three important areas of CV research: the period distribution, the magnetic CV population, and the pulsating white dwarfs primaries. These results have important implications for the evolution of CVs.

2. The period distribution of CVs

Howell, Nelson, and Rappaport (2001) have taken three million primordial binary models and evolved them (with no nuclear evolution of the secondary star and with secondary mass less than one solar mass) to produce 20,000 CVs. These CVs stretch from orbital periods of 6 hours to the minimum of 65 minutes, with 99% of the objects reaching the minimum period during the lifetime of the galaxy. In contrast, most CVs discovered in previous surveys (with faint limits near 16th magnitude) have orbital periods longer than three hours. Part of this discrepancy is due to selection effects, as the brighter (hence longer period CVs with high accretion rates) are easier to find. However, the other part of the difference between models and observations lies in how fast angular momentum is lost in going from a long period to a short period system. If the loss rate is high, objects quickly move to short period, whereas if it is low, they take a long time to evolve and so we would find most of them at longer periods. Thus, obtaining the period distribution of CVs from SDSS, where one can create a volume-limited sample containing both bright and faint CVs, can give direct clues to the actual angular momentum loss rates.

The published papers for SDSS data releases 1–4 list 181 CVs for which we are trying to obtain orbital periods through follow-up photometry (much of it provided by white light observations at USNO) and spectroscopy (mostly from Apache Point Observatory). The light curves provide periods from eclipses, sinusoidal modulations from hot spots, and irradiation effects, as well as some unusual, puzzling variability. Figure 1 shows some of the light curves that have been obtained. For CVs at lower inclinations, radial velocity curves provide the orbital periods. Using the orbital periods that are now available for 72 of the 181 CVs from SDSS, we have found that 51 (71%) are less than two hours, 7 (10%) are in the period gap from two to three hours, and 14 (19%) have periods longer than three hours. Thus, SDSS is primarily finding low mass transfer, short orbital period systems.

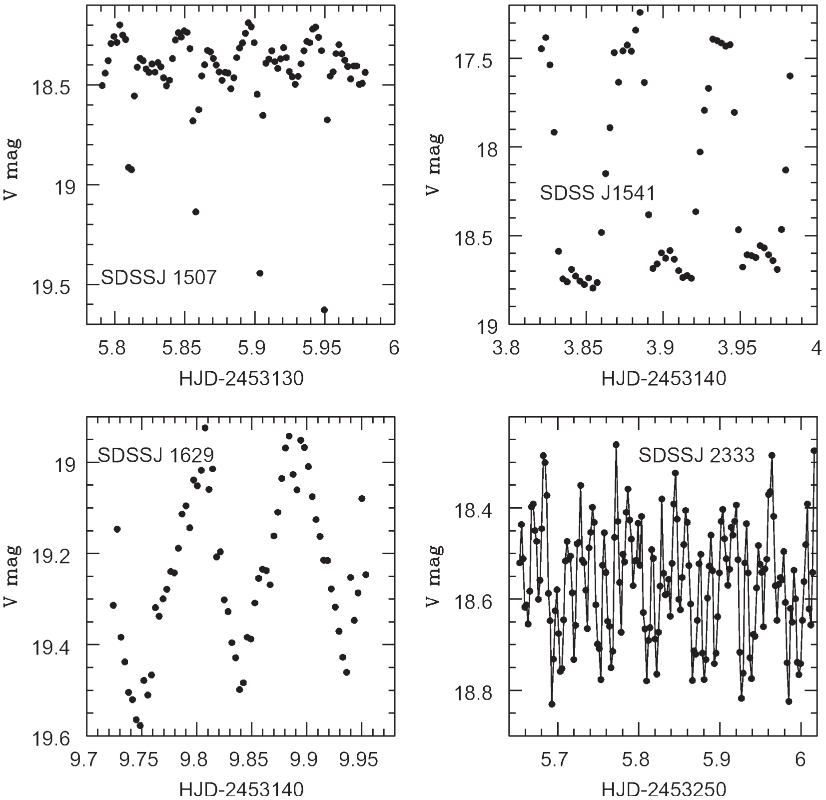

Figure 1. Examples of the SDSS light curves. The eclipsing system SDSSJ 1507 with a period of 67 minutes, the Polar SDSSJ 1541 with a period of 84 minutes, the likely Polar SDSSJ 1629 with period of 122 minutes, and a potential IP, SDSSJ 2333, with an orbital period of 1.4 hours from the radial velocity curve and a 21-minute period in the light curve. Details, including coordinates, can be found in Szkody *et al.* (2005).

3. The magnetic CV population

One of the surprising results from SDSS is the number of extremely low accretion rate magnetic systems that are appearing. This was first noticed with the identification of two objects showing very narrow, large amplitude cyclotron humps in their spectra along with TiO bands from the secondary star (Szkody *et al.*

2003b). The addition of two more from SDSS and two from the Hamburg survey brings the total number of these objects to six (Schmidt *et al.* 2005). All six have magnetic fields close to 60 MG and accretion rates of less than 10^{-13} solar masses per year, which is less than 1% of the normal rate for CVs. The underlying white dwarfs are very cool, implying these systems are old (4 Gyr), but their periods are long (3–5 hours) and their secondaries do not fill their Roche lobes. Follow-up observations with XMM show that the small amount of X-rays coming from these objects are from the M star, not from accretion onto the white dwarf.

These characteristics imply that these objects are pre-magnetic CVs that will ultimately become Polars. The strong magnetic field likely captures the wind from the secondary so the angular momentum losses are very low compared to normal CVs, and they remain at long periods for a long time. Since the four systems found from SDSS comprise nearly half the number of magnetic CVs found in SDSS, the total number of pre-Polars may be quite large. These systems are easy to identify from photometry since the changing view of the magnetic pole causes a large variation in the cyclotron features over the orbit, resulting in a large (1–2 magnitude) sinusoidal variation in the light curve.

4. Pulsating white dwarfs in CVs

About 15% of the spectra of CVs from SDSS show broad absorption lines flanking the Balmer emission. The broad absorption is a signature of the underlying white dwarf which contributes a substantial amount of optical light when the accretion rate is low so that the disk does not dominate. The low accretion rate is also inferred by the short (near 80 minutes) orbital periods evident in all of these systems. Surprisingly, most of the systems with detailed high time-resolution photometry reveal pulsating white dwarfs (ZZ Ceti stars). At this time, there are eight known pulsators in CVs: GW Lib (van Zyl *et al.* 2004), four from SDSS (Woudt and Warner 2004; Warner and Woudt 2004), one from the Hamburg survey (Araujo-Betancor *et al.* 2004), and two recent discoveries (Vanlandingham, Schwarz, and Howell 2005; Patterson, Thorstensen, and Kemp 2005). A study of the UV spectrum of GW Lib with HST (Szkody *et al.* 2002b) showed a massive white dwarf with 63% of the dwarf surface at a temperature of 13,300K and the remaining 37% at 17,100K. It is unclear if the two temperatures are a result of the accretion or the pulsation. The questions of whether all ZZ Ceti stars in CVs have dual temperatures and if the instability strip is different for accreting CVs as compared to single ZZ Ceti stars are currently being explored with HST observations of 3 more of the pulsating SDSS CVs scheduled for the summer of 2005.

5. Conclusions

The period distribution of SDSS CVs with measured periods (72 of 181 objects) shows that 71% have periods below two hours. This is in contrast to the Hamburg

Survey (that only reaches to 18th magnitude), in which 37 periods are known for 53 new objects (Gänsicke 2005). The Hamburg results show that only 22% are less than 2 hours.

Thus, the SDSS data removes some of the selection bias on brightness and produces a period distribution that is closer to that predicted by the Howell, Nelson, and Rappaport (2001) evolution models. However, the percentage of old systems found at the period minimum does not match the model estimate of 99%, indicating that we still do not totally understand the angular momentum loss rate and the selection biases.

Among the 181 CVs (of which 152 are new discoveries), eight are new confirmed Polars, with four among the extreme lowest accretors (and likely to be magnetic pre-CVs) and another with an extremely deep eclipse. At least three high mass transfer systems above the gap are known, while 28 (15%) show absorption lines from the white dwarf. Continuing follow-up studies of these systems with XMM and HST are helping to delineate the physical structure of these CVs, how magnetic fields alter angular momentum losses, and how accretion affects the instability strip.

While investigations are underway, there is still much to be done. If we want a complete study of the population characteristics of the SDSS CVs, we will need to find all their orbital periods. The AAVSO observers can help this effort by observing systems at outburst for superhumps (which are related to the orbital period) and just determining if outbursts occur, thus defining an object as a dwarf nova. Because XMM and HST programs often need to take place at a specific state, coordinating ground-based observations with HST or XMM times is also especially important. There are many peculiar systems among the SDSS set and the answers to many questions remain to be explored.

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