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Cataclysmic Variable Stars in the Sloan Digital Sky Survey

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\textbf{ABSTRACT} The purpose of this study is to identify Cataclysmic Variables (CVs) using spectroscopic and photometric data. CVs are useful for studying plasma physics in extreme conditions such as the high temperature and strong magnetic fields seen in CV accretion disks. They are also critical for understanding the evolution of binary stars, both in the field and in globular clusters. This project used photometric and spectroscopic data from the Sloan Digital Sky Survey (SDSS) to identify and classify CVs. Six thousand objects were selected based on multi-color criteria and analyzed using spectral data. Approximately 1\% of these objects in the sample were classified as CVs in the SDSS pipeline. Of these, 11\% were found to have typical spectra while the remaining 89\% had spectra inconsistent with standard CVs.

\textbf{INTRODUCTION}
Cataclysmic variable stars (CVs) are binary stars that are usually made up of a white dwarf and a main-sequence “donor star.” A white dwarf is a hot, dense remnant of a star. Because of its extreme density, the white dwarf’s gravitational force pulls in matter from the donor star creating a hydrogen-rich accretion disk around the white dwarf (see Figure 1).

Cataclysmic variable stars are named for their varying brightness. This variability is largely caused by nova outbursts in the accretion disk and on the surface of the white dwarf. When instability in the accretion disk causes small pockets of fusion, a Dwarf Nova event can be seen as a brief increase in brightness. More sudden and greater increases in brightness are often due to classical novae, which occur when a much larger amount of accretion disk matter undergoes fusion or when accretion disk matter falls onto the surface of the white dwarf (Szkody & Gaensicke, 2012).

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Research Completed in Summer 2017
The objective of this project was to develop an efficient and accurate way of finding and identifying cataclysmic variable stars using data from the Sloan Digital Sky Survey (SDSS) and to test the accuracy of the SDSS data analysis pipeline. This was done in order to create a reliable sample of CVs for use in future plasma physics, accretion disk, globular cluster and other research.

The SDSS is an astronomical imaging and spectroscopic survey that began in 2000 and continues through today to make a 3-dimensional map of the universe. Data are gathered from two telescopes in New Mexico and Chile (Abazajian et al., 2003). The telescopes capture images and spectra at ultraviolet, optical, and infrared wavelengths. In order to obtain their data, SDSS takes images of regions of the sky in five filters: \( u, g, r, i, \) and \( z \) (ultraviolet, green, red, near infrared, and infrared) in order to identify the light sources from which they would like to gather data. Holes are then drilled in a metal plate corresponding to the positions of those light sources. The plate is placed on the telescope and optical fibers are plugged into the holes and connected to a spectroscope in order to gather data (see Figure 2). The data are processed through a standard data analysis pipeline and made publicly available in the SDSS Skyserver database.

The Skyserver has both images and spectral data, and also provides basic instructions on how to access and use the data. Researchers wishing to access specific data can use various search interfaces, including SQL (Structured Query Language), a programming language designed for querying databases.

![Figure 1. Artist representation of a CV (Smale, n.d.).](https://via.library.depaul.edu/depaul-disc/vol7/iss1/13)

The data analysis pipeline uses spectroscopic and imaging data to measure and categorize the observed objects. The pipeline first identifies whether an object is a point source or a galaxy. Then it compares the object’s spectra to known archetypal spectra to classify the object as stars, quasars, or galaxies. It further identifies the subclass of the objects. For stars, this includes classifying single stars in the Morgan-Keenan system, as well as identifying different binary star systems like cataclysmic variable stars (Bolton et al., 2012).

**METHODS**

Because of the extremely high temperatures in CV accretion flows, CVs give off light at shorter wavelengths, notably in the ultraviolet spectrum (Szkody & Gaensicke, 2012). The apparent magnitude of an object is defined as the negative logarithm of the flux, corresponding to how bright it appears from the earth. The lower the magnitude, the brighter the object is (Ostlie & Carroll, 1996). Color can be expressed as a difference of apparent magnitudes of that object at different wavelengths, and this color can often be used to help identify stellar objects including CVs. For example, \( u-g \) is a color defined as the difference between the magnitudes of \( u \) and \( g \). Thus, an object with higher \( u-g \) emits more light in the green part of the spectrum than in the ultraviolet part of the spectrum compared to an object with a lower \( u-g \).
Previous studies have shown that CVs tend to have the colors $u-g<0.4$, $g-r<0.7$, $r-i>0.4$, and $i-z>0.4$, where $u$, $g$, $r$, $i$, and $z$ are magnitudes ranging from ultraviolet to infrared.

A color-color diagram, a graph with a different color plotted on each axis, is a common tool that can be used to compare the color of objects (see Figure 3). Stars with a similar composition and temperature will cluster in the same region of the diagram.

Because CVs do not generate light in the same way as main sequence stars, they will generally be separate from the cluster formed by the stars and can therefore be identified as outliers. Thus, the location of an object on a color-color graph can help determine what type of object it is likely to be. However, different types of objects, such as CVs and quasars, can still have similar colors.

Although color-color diagrams are useful for separating CVs from main sequence stars, it is more difficult to differentiate between CVs and other high-energy objects such as quasars.

Spectroscopy measures the flux of an object as a function of wavelength. In a graph of flux vs. wavelength (see Figure 4) emission lines, points where radiation is emitted above the continuum, can be seen as a spike going up at a certain wavelength; absorption lines, points where radiation is absorbed, are seen as a spike going down. Spectra can be used to discern various properties of objects, including the mechanism by which radiation is generated. Because there is overlap in the color-color graphs between quasars, white dwarfs, CVs and other objects, their spectra were used in this study to have a more definitive way of identifying CVs, as their spectra have unique features that separate them.

Figure 3. A color-color graph of CVs (pink) vs. Stars (black).
from other objects with similar colors. Most notably, the large majority of CVs will have strong emission lines in the Hydrogen Balmer series, which is the series of wavelengths associated with transitions between the hydrogen level with \( n=2 \) and higher levels (Szkody et al., 2002).

A two-step process was used to identify CVs. The first step was to query the SDSS database for objects within the previously stated color range to narrow the search parameters. The next step was using spectral features to confirm which objects were CVs. To be able to include CVs that were previously misidentified as quasars or white dwarfs, the color criteria were broadened to include those of quasars and white dwarfs with similar colors to CVs (Bolton et al., 2012). The final color ranges used to identify CV candidates in this study are: \(-1<u-g<0.71, -1<g-r<0.7, -0.27<r-i<0.57, -0.35<i-z<0.7\). The search was also limited to \( g<21 \) in order to avoid complications due to the large photometric errors in fainter objects.

**Figure 4.** The expected CV spectra (top) from object 0592520250601 compared to the “false CV” spectra (bottom) from object 0300519430042 found using data from the SDSS Skyserver (Sloan Digital Sky Survey Science Archive Server, n.d.).
RESULTS

Following Szkody et al. (2002), spectra were analyzed by eye, looking for the spectra with strong emission lines in the Balmer series: Hα(6563 Å), Hβ(4861 Å), Hγ(4341 Å) and Hδ(4102 Å). Using the SDSS spectral query, the entire sky was searched, and 213,688 objects with spectra were found within the chosen color parameters. From these objects, 6,000 were randomly selected and were analyzed by eye. Of the 6,000, 81 were categorized as CVs by the SDSS pipeline. Of the 81 objects, only 9 had the expected spectra for CVs, having strong emission lines in the Balmer series. Interestingly, many of the remaining 72 objects do have strong spectral lines in the Balmer series, but they exhibit absorption lines rather than emission lines. Because they have atypical spectra, these objects were considered to be “false CVs” (see Figure 4).

Further investigation showed that none of the three archetypes used in the SDSS pipeline were consistent with the spectra of the “false CVs” (Abazajian et al., 2003). The eigenspectra shown in Figure 5 represent 3 different typical spectra of CVs. They are shown on a graph of arbitrary units of flux vs. wavelength (Figure 5). This is done to show the shape of the spectra and the spectral lines. Because the spectra of the “false CVs” were not consistent with the eigenspectra in shape or spectral features, it was concluded that these “false CVs” were either misclassified as CVs, possibly due to flaws in the pipeline, or they were CVs at different points in their life cycle. Nova events change the radiation the CV emits and consequently changes their spectral lines (Smale, n.d.). Another factor that could have caused a larger number of “false CVs” to appear in the sample is the magnitude limit used in the query. These objects identified as CVs, which have absorption lines rather than emission lines, may have had a larger presence in the data set because the search criteria was limited to only contain bright CVs. Limiting $g$ to less than 21 makes brighter CVs, ones with the potential to have these atypical spectra, more common than the less bright, quiescent CVs. Most CVs should have emission lines in the Balmer series because CVs spend most of their time at this darker, quiescent state. Considering that it is unlikely that all of the 72 “false CVs” (more than 80% of the sample) found are undergoing nova outbursts, it is believed that the SDSS pipeline has misclassified many of these objects.

DISCUSSION

This study shows that the SDSS pipeline by itself is not a reliable way to identify CV spectra. It is believed that the SDSS pipeline may be identifying objects as a CV based on their photometric variability in addition to its spectral features. Because the spectrum and the images of the same object are taken at different times, the pipeline may classify the object as a CV based on
the assumption that the data were taken during nova and (fainter) quiescent states (Szkody, 2017). As a follow-on study to this work, it would be beneficial to further examine the algorithm used to identify CVs in the SDSS pipeline in order to test this hypothesis. Further insights into the nature of “false CVs” could also be gained by taking additional follow-up spectra.

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