A Brief Introduction to Cataclysmic Variables and Polars

Cataclysmic Variables, CVs, are a special type of binary Star System in which there is a main sequence star and a white dwarf. As in all binary star systems the two
stars orbit around a common center of mass with a fairly constant separation. In CV systems the white dwarf is close enough to the main sequence star to gravitationally pull gas away from the star at its Inner Lagrangian Point (L1). The angular momentum of the stream causes it to spiral around the white dwarf while slowly being pulled closer in a whirlpool motion. This process is called accretion and the stream is now called an accretion disc.

Polars are different from other CVs, because the white dwarf has a strong magnetic field approximately a hundred million times the Earth's magnetic field. This strong field disrupts the gravitationally bound flow of the gas stream. The accretion disc is not able to form because the stream is forced to follow the magnetic field lines. This results in some unusual structure in the stream.

The first important point is the L1 point or point at which the gas is first drawn to the white dwarf. At this critical juncture the lowest density gases begin to follow the magnetic field and flow onto the magnetic pole of the white dwarf. This stream is called the L1 stream and is labeled on figure1. The higher density gases move from the L1 point on a ballistic or gravitational trajectory towards the white dwarf. The ballistic stream reaches another critical juncture called the coupling region where the magnetic field becomes the most influential force. The two streams then rapidly gain momentum as they approach the white dwarf. Their high energy collision with the white dwarf is energetic enough to produce UV and x-rays. This collision region is called the hot spot.
Figure 1 is a visualization of a Polar stream. The stream itself is red and the white dwarf is blue. As the system rotates the unusually shaped stream can eclipse the white dwarf or more specifically the hot spot on the white dwarf. If the stream is relatively dense optically speaking, an observer will see the flux from the hot spot drop dramatically. If the stream is not relatively dense, the flux will remain constant to an observer or perhaps drop only a little. For this reason the observational data of Polars is very complex.

**This Summer's Research**

The focus of research on this project has been to model the line of sight column densities of the gas stream so that we can have a better understanding of how this affects
the observational data currently available on Polars. In order to do this, we will model the stream at different phases and inclinations to see how and when it will eclipse the hot spot on the white dwarf.

In order to model this a combination of Fortran and Interactive Data Language (IDL) will be used. IDL is a high level language with many strong visualization tools. In IDL programs can be written or the command line interface can be used to make simple calculations or run programs line by line (for debugging purposes). Fortran is a much older language with a more strict syntax and no visualization tools. It's is mainly used because of its ability to handle many calculations quickly.

There are many important steps in calculating the column densities of a Polar's gas stream. The forces generating the internal behavior of the stream must be taken into account. If this is accurately modeled, the structure of the stream can be determined (most importantly the density). When the density of the stream is determined this data has to be manipulated such that the material between us and the hot spot can be determined. This measurement is called a column density and is the ultimate goal of my research.

Dr. Cash has pioneered a Fortran program to model the internal behavior of the stream. It uses a method called Smooth Particle Hydrodynamics, SPH, to model the individual atoms and molecules in the stream as a group with a density that decreases along the radius of the SPH pseudo particle. This Fortran program was designed to incorporate the thermal, gravitational, and magnetic processes within the stream. It outputs the position, velocity and density (in dimensionless units) of the roughly 30,000 particles.

The information provided by Dr Cash's Fortran code has to be manipulated for better analysis. I used IDL to convert the output of the code into a three dimensional
array where the position in the array represented position in space and the values of the array represented density.

What can make further analysis difficult is the fact that the whole system rotates and each system might be at a different inclination compared to the observer. In other words, the column density for a particular Polar will change depending on the system inclination and phase at the time of observation. Because of this, any attempt to measure the column densities of a polar model must allow the model to rotate along a vertical and horizontal axis giving us a line of sight column density.

In order to rotate the array of density values, I created an IDL program which transformed the x,y,z coordinates to the line of sight coordinates an observer might see. The formulas needed to do this transformation are:

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\begin{align*}
    s &= x \cdot \sin(\text{ph}) + y \cdot \cos(\text{ph}) \\
    t &= -x \cdot \cos(\text{i}) \cdot \cos(\text{ph}) + y \cdot \cos(\text{i}) \cdot \sin(\text{ph}) + z \cdot \sin(\text{i}) \\
    u &= x \cdot \sin(\text{i}) \cdot \cos(\text{ph}) - y \cdot \sin(\text{i}) \cdot \sin(\text{ph}) + z \cdot \cos(\text{i})
\end{align*}
\]

\(\text{ph}\) is the phase or rotation about the vertical axis and \(\text{i}\) is the inclination or rotation about the horizontal axis. The \(s, t,\) and \(u\) terms are the new coordinates for the rotated system.

The program that uses these formulas takes three coordinates for a single point or an array of coordinates as input and gives the rotated coordinates or coordinate system as output.

The rotated grid now has the values of the densities in their respective positions in an array for a given line of sight. The task now becomes adding up the column densities along that line of sight. I did this with another IDL program called cdloops that adds up the values for the line of sight axis pointing toward an observer. Unfortunately, the values of the densities could not be extracted directly because, in a computational array
there are only integer points to determine the location of a value. The points for adding up the densities did not necessarily coincide with one of these integer coordinates on the grid. The built in IDL function Interpolate averages the surrounding points to determine what a value will be in between those points. Interpolate was used in my program to determine the values not on an integer coordinate.

Figure 2 above is a surface plot of an array created by the cdloops script. The data was taken for phase of .23 or about 83 degrees of orbit and 72 degrees of inclination. The big spike on the right is the L1 point on the main sequence star. This is the most dense region of the stream. The L1 stream can also been seen behind the ballistic stream.

We now have a model that gives us many column densities over the whole system at a particular phase and inclination as show in figure 2. This can give us some interesting detail such as the density gradient along the stream (density decreases rapidly as the stream leaves the main sequence star). This however does not tell us what the column
density is between the hot spot and an observer over all the phases of the system which would better explain observational data. A small modification was needed in the cdloops script to make this change. The modified script, cdloopstar, calculates the column density over one orbit of the system and outputs an array that gives the column density as a function of phase. Figure 3 shows the types of results that can be obtained by the cdloopstar program. Figures 4 and 5 is a visualization of what the system would like in the higher column densities phases.

Figure 3 is from the cdloopstar Its data was recorded at an inclination of 72 degrees. As you can see there are two spikes. The first spike is from the magnetically influenced remnant of the ballistic stream. The second spike is from the L1 stream.
Figures 4 left and 5 right give us a visualization of the magnetic stream (figure 4) and the L1 stream (figure 5) eclipsing the hot spot on the white dwarf.

To make the process of analysis faster, a way to automatically read in parameters of the modeled system generated by Dr Cash's code was needed. I did this by writing a Fortran program that creates a log file of the parameters used by Dr. Cash's code. I modified my IDL data manipulation programs to read and extract the parameters from the log file.

**Future Steps**

Further work is needed to complete the analysis of this data. Because the data that Dr Cash's generates is in dimensionless units it is difficult to determine whether the column densities are dense enough to eclipse the white dwarf. To do this, small adjustments will need to be made in either the log files used or the IDL programs that manipulate the data.
The ultimate goal of all models of physical systems is to compare to the observations of that physical system. To do this we will need to use the column densities of the system to determine what kind of light and how much light can escape that stream.