Method for Finding an Upper Limit on the Annihilation Cross Section of Dark Matter Using Cherenkov Telescopes

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Abstract
Using data taken from VERITAS we will be able to find an upper limit for the Dark Matter annihilation cross section by analyzing gamma ray sources. The next generation of Cherenkov Radiation telescopes, the CTA will be able to probe a higher range of energies further enhancing our understanding of the makeup of Dark Matter and lowering the upper limits on the annihilation cross section.

1 Introduction

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array system consisting of 4 telescopes that can detect gamma rays with energies ranging from 50 GeV to 50 TeV. VERITAS is an atmospheric Cherenkov telescope that takes advantage of Cherenkov radiation to make its measurements. Cherenkov radiation in air, the type that VERITAS looks at, is produced when a gamma ray enters the atmosphere. The gamma ray will interact with a nucleus in the air breaking off and pair producing an electron-positron pair. This electron-positron pair will encounter more nuclei in the air and undergo bremsstrahlung radiation producing more gamma rays which will then produce more electron positron-pairs and the process will continue until the gamma rays run out of energy. This process is referred to as an air shower, where a cascade of particles are being created and moving towards earth. The speed of their creation and
movement is greater than the speed of light in our atmosphere therefore giving off Cherenkov radiation.

Our telescopes picks up on the characteristic blue glow of the light pool emitted from the radiation. The placement of the telescopes and their design facilitates the reconstruction of the arrival direction and can trace the γ-ray shower back to it’s source, this can be seen in Figure 1.

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**Fig. 1.** Illustration from VERITAS detailing a gamma ray shower incident upon our telescopes. On the right the figure shows the feature of the telescopes that allows the tracing back of the gamma ray to its source.

VERITAS at Columbia University uses the information gathered from these air showers in the search for Dark Matter. Scientists are aware of the existence of DM through it’s gravitational interactions with the universe but we have no knowledge of it's makeup. The theory for the particle makeup of DM with the most support behind it is that of the weakly interacting massive particle (WIMP). We can find out more about the particle nature of DM through the detection of secondary particles, such as photons, neutrinos, or charged cosmic rays, that are produced by DM. The processes that would most likely lead to this occurrence would be DM annihilation or DM decay [3]. WIMPs are theorized to undergo either pair annihilation or decay into standard model particles, that would then give rise to gamma rays. These high-energy gamma rays that interact with our atmosphere as described above and are then detectable by our telescopes.

The VERITAS group at Columbia is involved in building the Cherenkov Telescope Array (CTA) which will be a successor to the VERITAS telescopes. The concept for the CTA calls for low, mid and high energy range telescopes with an aperture of 23m, 12m and 6m respectively. With this type of design the array will be able to observe γ-rays in the range of 10 Gev to 100
TeV. The range and the sensitivity of the telescopes will both be a tenfold increase from VERITAS. CTA will be made up of, like VERITAS, multiple mirrors lined up to create the semblance of a bigger mirror. In order to preserve the quality of the data it is very important for these mirrors to be aligned to one another.

2 Finding an Upper Limit on the Cross Section of Dark Matter Annihilation

The WIMPs we are searching for with VERITAS are theorized to have a mass \( m_x \) that can range from about 10 GeV to TeV. VERITAS looks at the creation of gamma rays from DM pair annihilation or decay by probing the galactic center. The galactic center, through simulations like those of the Aquarius project, is believed to be one of the most promising areas to search for DM. Our galactic center is believed to be shrouded in a DM halo, given this and its proximity to earth it is an optimal place for our search. However, because of it’s proximity to us, it has a lot of noise caused by an strong astrophysical background. Before any data can be taken and analysed it must first go through a type of noise reduction.

The astrophysical background of our galactic center is filled with cosmic-ray and non-\( \gamma \) ray induced showers [2]. VERITAS uses an ON/OFF method with extended emission (Figure 2). ON/OFF method refers to taking measurements on source and off source. By doing this you can then look at the events present in ON source and OFF source (basically an empty field of the sky) and subtract away the OFF events that will be considered as background [2]. Once we have our data we can use it to place an upper limit on the annihilation cross section of dark matter annihilation. The flux of DM annihilation products can be written as

\[
\Phi_{\gamma}(\psi,E) = \sigma_{\mu} dN_{\gamma}/dE \int d\rho^2 (r(s, \psi)) \text{ line of sight} \quad (1)[3]
\]

where the factors that depend on the halo profile can be separated out to produce

\[
J(\psi) = \frac{1}{8.5kpc} (\frac{1}{6.3 GeV/cm})^2 [ds * p^2 (r(s, \psi))] \quad (2)[3]
\]

with \( r \) being equivalent to

\[
r = (s^2 + R_\odot^2 - 2sR_\odot \cos l \cos b)^{1/2} \quad (3)[4]
\]

and \( \rho \) is defined by two different profiles, the NFW profile and the Einasto profile (Eq 4 & 5). Figure 3 is from the HESS collaboration and shows the profiles plotted as a function of \( r \), the
galactocentric distance \[1\]. This graph demonstrates that the profiles do not differ greatly and as a result won’t affect our calculations above.

\[
\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)^(1+\alpha_s)} \quad (4)[4]
\]

\[
\rho_{\text{Einasto}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha_E}\left[(r/r_s)^{\alpha_E} - 1\right]\right\} \quad (5)[4]
\]

From the equations above we can get upper limits on the velocity-weighted zero-temperature thermally averaged pair annihilation cross-section, Figure 4. When a null measurement is received a new upper limit will be established. Anything that is not a null measurement will be regarded as a candidate for a DM annihilation signal.

4 CTA

VERITAS, HESS and other Cherenkov radiation telescopes have all reached a peak in regards to the sensitivity of their data. As can be seen from Figure 4 however, we still haven’t reached the sensitivity required to either validate or eliminate DM theoretical models. The next generation of Cherenkov telescopes, the Cherenkov Telescope Array, is a global project that will be able to detect energies from 30 GeV to 100 TeV and help further solve this problem.
Fig. 4. This figure is taken from the HESS project [1], it compares the Galactic DM halo profiles for both NFW and Einasto parametrizations, equations 4 and 5 respectively. The x-axis, r, refers to the distance from the galactic center. For both profiles the peak of DM density is at the center.

Fig. 5. This figure was also taken from the HESS project [1], “it displays the upper limits on the velocity-weighted annihilation cross-section $\langle \sigma v \rangle$ as a function of the DM particle mass $m$, for Einasto and NFW profiles.”[1] More on this upper limit will be able to be calculated with the production of the Cherenkov Telescope Array (CTA). “The green points represent DarkSUSY models.”[1]
5 Edge Sensor Calibration

Fig. 6. Top: This is a secondary panel drawing for the CTA telescopes. Each panel will have approximately 8 sensor systems to align it with all of the panels around it. Bottom: Drawing belonging to the primary panel of the CTA Telescope. It will also have around 8 sensor systems per panel. Both alignment systems will be fully automated.

The mirror alignment system in order to be functional and optimized needs to be a fully automated system. This system consists of a laser being pointed to an opal diffuser which sits between the laser and the camera. The laser and the diffuser are mounted on a stationary platform while the webcam is mounted to a platform that can be moved. Using a Newport Motion Controller we can move the platform in three directions. The Newport Motion Controller can be controlled remotely through an RS232 cable or an USB cable. By being able to remotely communicate with the motion controller we are able to automate the movement of the webcam and the mirror alignment. Using an RS232 cable with a Linux operating system and a Windows operating system proved fruitless. Using a USB cable to establish communication with the motion controller worked only on a Windows operating system but because of how a USB device is treated in a Linux system communication could not be established. A successful
communication was established using a RS232-to-USB converter. In order for this successful communication to be established a direct connection must occur. A RS232-to-USB converter that requires an RS232 cable as an in-between cable for connections will fail to send information, however a RS232-to-USB converter cable that can be directly plugged into the device will send information correctly.

Once remote communication is established I worked on getting an automated control of the system. Using and adapting a code used by our colleagues at UCLA we were able to run a code that would create a “scan” of the diffuser using the motion controller. This scan worked in a grid pattern and at every point on the grid the code was modified to open up a capture code that would take a series of pictures with the webcam and save them to a folder. For analysis purposes the capture program took 100 pictures and took about 2.64 seconds.

Fig. 7. Drawing of a grid structure that would be covered by the webcam with the help of the motion controller. Each circle represents a point where a stop will happen in the program and a capture code will be launched.

The code takes in multiple parameters on the command line, it was modified to take in the parameters of step size and folder. The step size parameter tells the code how big the steps between each point on the grid should be. The folder parameter tells the code where the pictures be taken by the webcam would be saved.

<table>
<thead>
<tr>
<th>scan_grid: scan specified grid (imitate measurements)</th>
<th>uses MotionControl library</th>
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<tbody>
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<td>options:</td>
<td></td>
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<tr>
<td>-p STRING : specify serial port of the device</td>
<td></td>
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<tr>
<td>--axis INT INT : specify device numbers for x and y axes</td>
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<tr>
<td>-a DOUBLE DOUBLE : specify area of the scan</td>
<td></td>
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<tr>
<td>-g UINT UINT : specify size of the scanning grid</td>
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</tr>
<tr>
<td>--corner DOUBLE DOUBLE : start scan from the specified corner</td>
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The scan_grid code was modified to save pictures in a folder structure necessary to facilitate analysis done by openCV and root code. This folder structure first creates a folder within the folder specified on the command line with the date and time when the scanning first started. It then creates a folder with the position of each point on the grid and inside that position it saves the pictures captured by the webcam. The code was further modified to analyze the pictures from within the code.

6 Conclusion

Analysis methods for eliminating background noise should be perfected as a faulty method could lead to a fake source. Analysis for the DM density using NFW and Einasto profiles should be created using VERITAS data that has been taken in the past four years. Once the profiles have been created an analysis for the DM annihilation cross section should also be created. CTA will allow us to further better our measurements. Fully automating the mirror alignment system will be the next step.

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References


