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Unlocking the Mystery of TeV J2032+4130 through VERITAS Data

Devon J. Barros
Bridgewater State University

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Devon J. Barros

Research Advisors: Dr. David Kieda, Binita Hona

Writing Advisor: Dr. Thomas Kling

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Devon Jamison Barros

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Dr. Thomas P. Kling, Thesis Advisor

Dr. Jamie Kern, Committee Member

Dr. Martina Arndt, Committee Member

Abstract

TeV J2032+4130 is a high energy celestial object that emits Very High Energy (VHE) gamma rays and is located in the star forming region of the Cygnus constellation. It was first detected by the High Energy Gamma Ray Astronomy (HEGRA) experiment. Later observations from the Very Energetic Radiation Imaging Telescope Array System (VERITAS 2014) were used to determine that the gamma-ray emission from the source could be coming from a Pulsar Wind Nebula (PWN) powered by a binary pulsar named PSR J2032+4127. For the PWN scenario, VERITAS predicted a cutoff in the gamma-ray spectrum above 10 TeV. Using ~ 33 hours of VERITAS data, this source was analyzed with the help of VERITAS' internal software named Event Display. The data were put through a series of steps in Event Display using Python and Root coding to obtain the results. The Spectral Index was found to be 2.1 $\pm$ 0.25, which is fairly similar to that of other observatories, which confirms the conclusion that TeV J2032+4130 is a PWN. Further studies with additional data and particle modelling at the region will help us understand and clarify the nature of this source.

Contents

1 Introduction

1.1 Gamma Rays

Light (or Electromagnetic radiation) can be emitted, transmitted, and received in various wavelengths, frequencies, and energies. When it comes to wavelengths and frequencies of light, the rule is that wavelength (λ) is inversely proportional to frequency (v) and Energy (E) , as shown in the equations below:

$$c = \lambda v$$

$$E = hv = \frac{hc}{\lambda}$$

where c is the speed of light ($3 \times 10^8\ m\ /\ s$) and h is Planck's Constant.

The names of each kind of light and their characteristic (specific) wavelengths are on The Electromagnetic Spectrum (as labeled in Fig. 1). Light with lower energy include Radio, Microwave, and Infrared light. Visible light is in the middle and is the only light that we can see with our eyes. Light with a higher energy than visible light includes ultraviolet light, X ray's, and gamma Rays, with gamma rays having the shortest wavelength and the highest energy.

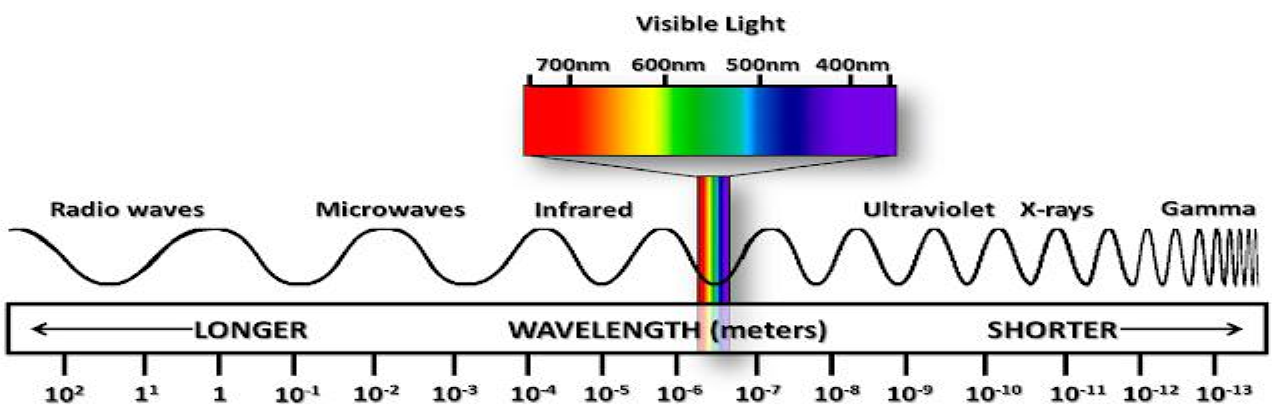

Figure 1: This is a representation of the Electromagnetic Spectrum. Longer wavelength forms of light are on the left and shorter wavelength forms of light are on the right. Retrieved from https://www.thinglink.com/scene/791837583360393216

Gamma Rays can form from the radioactive decay of atomic nuclei and can emit from high energy astrophysical sources such as Pulsars, Supernovae, and Quasars. Their energy level can range from a few kiloelectronvolts (keV) to ~ 8 megaelectronvolts (MeV). Very High Energy (VHE) gamma rays that range from 100-1000 teraelectronvolts (TeV), and are emitted from such sources of high energy and travel uninterrupted through the interstellar medium [15].

When VHE gamma rays reach Earth, they strike particles in Earth's upper atmosphere and go through pair production. In this process, a neutral boson (in this case the gamma ray) strikes a particle and creates a subatomic particle and its pertaining antiparticle (in this case, an electron and a positron). These particles can then each create another subatomic particle and a neutral boson through a process called Bremsstrahlung, or Braking Radiation. In this process, an electron is slowed down by another particle's atomic nucleus, which then forces the electron to release lower energy gamma rays. These newly formed gamma rays then go through pair production, and so on. This cycle of pair production and Bremsstrahlung of photons and particles that fall towards Earth's surface is called a Particle/Air shower, as shown in Figure 2. This process also produces Cherenkov light which forms when particles are accelerated faster than the speed of light.

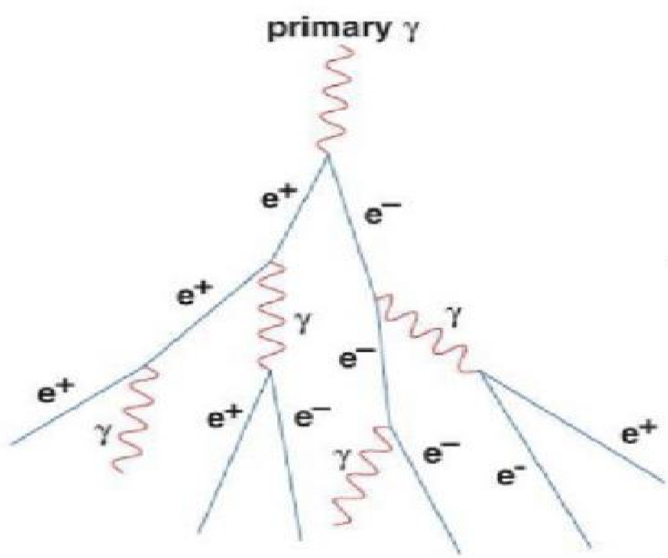

Figure 2: This is a diagram of a particle shower, with the primary gamma ray striking Earth's upper atmosphere and starting the cycle. Retrieved from https://www.researchgate.net/figure/Left-Electromagnetic-air-shower-generated-by-a-primary-g-ray-and-purely-composed-of_fig3_275329291

1.2 Extended Gamma Ray Source TeV J2032+4130

Cygnus is a massive star-forming region and is home to a handful of extreme celestial objects, like Pulsars, Quasars, and various gamma-ray sources. One of these is a mysterious extended gamma ray source by the name of TeV J2032+4130 that was first discovered by the High Energy Gamma Ray Astronomy (HEGRA) Observatory [Aharonian, F., Akhperjanian, A., et al.]. It is the first extended (i.e., signals from multiple congregated points rather than a single point) source to be observed in VHE gamma rays. It is also the first gamma ray source with no obvious counterpart at other wavelengths; in other words, to date, no one has observed a solid or compact source (such as a pulsar or star) responsible for creating these gamma ray signals. TeV J2032+4130 (RA 20h 31m 57s, Dec 41° 29' 57") is within the constellation of Cygnus [10]. It is visible in the Northern hemisphere from June until December and is visible in the Southern Hemisphere from June through September [11].

Multiple ground-based observatories have studied this source to attempt to classify it; HEGRA, the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescope [Albert, J., et al.], the Very Energetic Radiation Imaging Telescope Array System [VERITAS Collaboration et al.], and the High-Altitude Water Cherenkov (HAWC) Experiment [HAWC Collaboration et al.]. After nearly thirteen years of observing this extended source, astronomers concluded this source was most likely a Pulsar Wind Nebula.

1.3 Pulsar Wind Nebulae

A Pulsar Wind Nebula (PWN) is a complex high energy astronomical source that forms when a pulsar's wind interacts with particles around the pulsar.

When a high mass (8 solar masses or higher) star runs out of fuel and collapses, its outer atmosphere rebounds off the condensed core, resulting in a Supernova. If the mass is above 8 solar masses yet below 20 solar masses, the remaining core becomes a Neutron Star that has a rapid rotation rate and highly intense magnetic field that is encased within the confines of the surrounding ejecta (the material that exploded off of the star), also known as a Supernova Remnant (SNR). It is also possible that the central neutron star has two jets of material that emanate from the magnetic poles with the rapid rotation the neutron star looks like a pulse when observed from Earth: hence the name.

As a pulsar rotates and is first formed, a charged magnetosphere is forms and particles (electron/positron) accelerate at the polar cap and the outer edge of the magnetosphere. If the magnetic axis of a pulsar is inclined relative to a pulsar's rotation axis, the electrons and positrons form a toroidal (donut shaped) wind. As this wind escapes the magnetosphere, it is then trapped within the ejecta in the SNR, which ultimately forms an expanding magnetic bubble known as a Pulsar Wind Nebula, as shown in Figure 3. A wind Termination Shock (TS) also forms as the fast pulsar wind is slowed down by the growing pressure of the PWN.

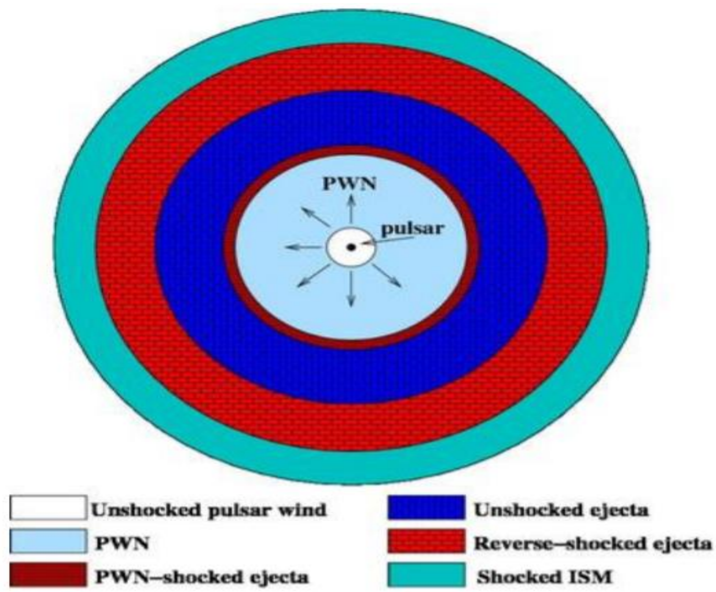

Figure 3: This is a cartoon representation of a Pulsar Wind Nebula, the surrounding ejecta, and Supernova Remnant. The Maroon boundary shows the border of the expanding magnetic bubble [Reynolds, S. P., Pavolv, G. G., et al.].

Pulsar Wind Nebula emission (or radiation) comes from either relativistic (fast-moving) particles within the nebula or particles on the outside that are swept up by the nebula. With particles coming into the PWN from the supernova ejecta around the nebula, the ejecta is heated which causes radiation from shocked gas and the acceleration of the now charged particles (continuum emission). The type of electromagnetic radiation emitted is dependent on how fast the PWN expands into the supernova ejecta. When expansion is slow, emission is observed as infrared or optical electromagnetic radiation; and when expansion is fast, emission is in the X-ray band. For relativistic particles within the actual PWN, their radiation is a combination of synchrotron and Inverse Compton (IC) radiation.

Synchrotron radiation is caused by the acceleration of charged particles, where the acceleration occurs perpendicular to the particle's initial velocity. IC radiation occurs when photons are scattered from charged particles and the energy of that particle is lowered. Low-energy particles in this process give off a prominent optical (visual) light with a flat (low) radio wave signal of the radiation. For younger Pulsar Wind Nebulae (PWNe) that have more intense magnetic fields, the synchrotron radiation produces gamma ray photons. In the case of TeV

J2032+4130, it would mean that it would be on the younger side cosmologically speaking if it were indeed a PWN.

TeV J2032+4130 also has more validity in being a PWN because within a few years after the source was characterized as a PWN, a Binary Pulsar by the name of PSR J2032+4127 that is a mere 0.07° away from the initial gamma ray detection made by HEGRA. This binary pulsar could be a candidate to be the central pulsar for the PWN. But even with this discovery, it is still not entirely clear that this object is a PWN with PSR J2032+4127 being the powering Pulsar, which is a major reason why the research on my part was conducted.

1.4 VERITAS Gamma Ray Observatory

The data used in my research comes from The Very Energetic Radiation Imaging Telescope Array System (VERITAS), a ground-based gamma ray observatory located at the Fred Lawrence Whipple Observatory (FLWO) in Tucson, AZ. The observatory is an Imaging Atmospheric Cherenkov Telescope (IACT) that observes Cherenkov light from the particle showers caused by GeV-TeV gamma rays (as shown in Fig. 2) [Aharonian, F., Buckley, J., et al.]. VERITAS is used to observe emission from Pulsars, Blazars (an Active Galactic Nucleus with two jets of material spewing out of it), Supernovae, and other high energy sources. Data taken from this observatory is also used to better understand cosmic rays and gamma rays themselves, while also doing some Dark Matter and Dark Energy research [Master, W.].

VERITAS is made up of four individual 12-meter telescopes (as shown in Fig. 4), each with 350 mirrors and a camera with 499 photomultiplier tubes (PMT's) that multiply the current coming in from the incident gamma rays [Master W.]. These telescopes take in Cherenkov light or flashes (as mentioned above), which occur when the particles in the resulting Particle shower move faster than the speed of light. The light from the Cherenkov flash goes into the photomultipliers in the telescopes and dynodes are used to create and multiply electrons to gain a signal. This signal from each PMT is then transferred via a Coaxial cable to a Fast Analogue to Digital Controller. This controller digitizes the signals, which then go to an event building computer, which then finally end up at the Data Harvester Machine. Once the gamma ray data reaches the Data Harvester Machine, it is ready to use and transfer to whoever needs it.

Figure 4: This is an image of the VERITAS gamma ray observatory, which operates at the Fred Whipple Observatory (FLWO) base camp in Tucson, AZ. Seen in the image are the four individual 12-meter telescopes and the facilities that help run the telescopes. Retrieved from https://veritas.sao.arizona.edu/

VERITAS also has an internal software system named Event Display which can be used to interpret the data and analyze it (more details in Section 2.1). In the software, the main types of analysis used to interpret the data is either point source analysis or extended source analysis, where point source analysis is more favorable to the system.

VERITAS has observed TeV J2032+4130 and the binary pulsar PSR J2032+4127 multiple times in the past {[Popkow, A., and the VERITAS Collaboration], [The VERITAS Collaboration et al.]}. However, analysis on these sources (more specifically TeV J2032+4130) has not been done since 2014. Because VERITAS has not done analysis on this specific source for an extended period of time, it gives a good reason to reanalyze this source to make sure that the Event Display Software is still running smoothly with no errors.

1.5 Research Question

The observatories that have studied TeV J2032+4130 within the past 19 years have all concluded that this extended source is most likely a Pulsar Wind Nebula. The desire for the research described in this thesis was to use new data from the VERITAS observatory to confirm earlier conclusions about this extended source, while also checking for errors in VERITAS' internal software because it has not observed this source for an extended period of time.

Although other observatories have concluded that this extended source is a PWN the conclusion that this extended source is a PWN, the research I conducted was more of a way to introduce me to and train me in this kind of High Energy Astrophysical research. I learned the coding and processes described with no prior experience in this type of research. By having a result already established about this source, it made it easier to compare my results and introduce me to Gamma-ray research. Learning these processes carefully while having other results to use as a reference gave me the proper first experience in this field.

2 Methods

2.1 Event Display

The new VERITAS data of TeV J3032+4130 for this research were taken in May of 2021 (see Sec. 1.3 for the data taking process). Once this data (which is in the form of images and events) was gathered, it was saved on my research advisor Binita Hona's drive in Linux, so that from there it could be put through Event Display (VERITAS' internal software).

Before I got the chance to use the new data, I ran through the Event Display program using concrete data of a well-known high energy astronomical source named the Crab Nebula. This data of the Crab Nebula has been run through Event Display multiple times by other researchers within the last decade. This way, I could get used to Event Display and the Linux commands as a whole and check to see if there were any major errors in the system before running the new data of TeV J2032+4130 through it. Sure enough, there were no major errors, and my results were similar enough to past results; hence making it safe to say that there were no faults in the program. This was a good sign to start using the new data of TeV J2032+4130 in the software.

I transferred the new data from my research advisor's drive to a new drive I created within Linux. From there, I took the data through the Event Display software and followed certain steps to gain my results and plots. These steps have coding within them to manipulate the data in a certain way so that it is ready to be fully analyzed to gain the results. The set of code in step one calibrates and parametrizes the data images, while also reconstructing the events. These processes are meant to fine tune the new data, and in a way make it easier to analyze; almost like editing a photo to make it look more precise [Maier, G., Holder, J.].

In step two, the code does energy reconstruction on the data and uses lookup tables to get variables that help separate the needed gamma-ray data from hadronic data (also known as gamma-hadron separation). These variables include mean-scaled width (msw), mean-scaled (msl), shower direction, spread of energy reconstruction, and height of the maximum Cherenkov emission. For the purposes of this research, the msw, msl, and energies from the energy reconstruction is all that is needed. The msw and msl are just the width and length parameters of the data images that are scaled by the mean of the intersection points of certain telescope's images [Maier, G., Holder, J.].

After the gamma-hadron separation is finished, the third step uses the newly furbished data to produce the maps/plots and calculate the analytical results. In other words, it takes the data and turns them into scientific data that can be used by researchers. The background measurement at the position of TeV J2032+4130 was determined using Ring-Background analysis, and the coding allows for the exclusion of bright stars or other gamma-ray sources not being studied in the field of view [Maier, G., Holder, J.].

2.2 Handling the Data

The majority of the data handling was spent in coding kernels using Linux, an operating system kernel. Initially, there were 124 runs (approximately 39.5 hours) of VERITAS data on TeV J2032+4130 that were put through Event Display to be analyzed.

Before putting these runs (events/images) through Event Display, I had to create directories for the data and their individual log files. Each log file contains the information about the pertaining run and if the run goes through a change (for example running one of the steps) then the change is noted and set into a new log file, along with the changed run. Once each necessary directory was created, I had to change the information on the bash file (which contains the labels for each set of code) to that of my target source. After these prerequisites, putting the data through Event Display was a slow process. Each time a step ran, it took hours for the code to run because of the amount of event files that the software had to go through. This meant that in some cases, it would take the entire workday to set up the code and have it run, and if something went wrong, it would take yet another day to fix the code and run through it. After the event files were put through a certain step, I did a combination of making and moving directories, checking the log files to make sure there were no errors, and prepping the data for the next step. More details on Linux and its commands can be found in Section 7.

2.3 Plots

There were three important plots that came out of Event Display after the data on TeV J2032+4130 was analyzed, which include the Sky Map, Significance Distribution, and Energy Spectrum.

The Sky Map is essentially a map (based on RA/DEC) of the part of the night sky where the target of interest is. It is centered on the RA and DEC of 20h 31m 57s and 41° 29’ 57”, which is where TeV J2032+4130 is located, and the x-axis goes from 20h 21m 57s to 20h 41m 57s, while the y-axis goes from approximately 39° 36’ 0” to 43° 36’ 0”. There is a color bar on the righthand side of the Sky Map that tells the significance (measured in units of σ) or brightness corresponding to certain colors. Any signal above 5 σ is considered a gamma ray signal. The black circles on the plot are various bright sources that the system has considered for analysis.

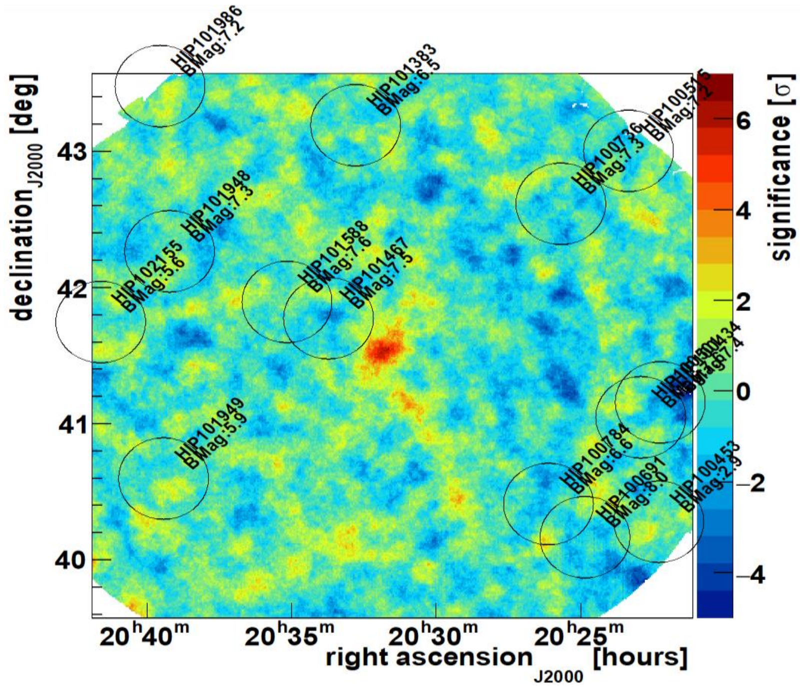

Figure 5: This is a sky map centered on the target source TeV J2032+4130. The blue to red color in the scale indicates increasing significance. The significance of a source at 5σ is a threshold for detection (any detection below this significance is not considered a gamma-ray detection). The black circles are the bright stars that were excluded from the analysis.

The fact that the center of the Sky Map is showing a decent amount of dark red signifies a high significance in that region, which makes it highly probable the extended source is a gamma ray source.

The Significance Distribution shows the number of entries for a certain significance, ranging from -6 to 10. The green dashed line shows a normal Gaussian distribution, while the other lines show various scenarios of significance for the area of the sky shown in the Sky Map (Figure 4). The red line shows the significance distribution (SD) with everything in that area of the sky including TeV J2032+4130, the blue shows the SD of that area of the sky excluding TeV J2032+4130, and the black line shows the SD excluding the target source and the surrounding bright sources.

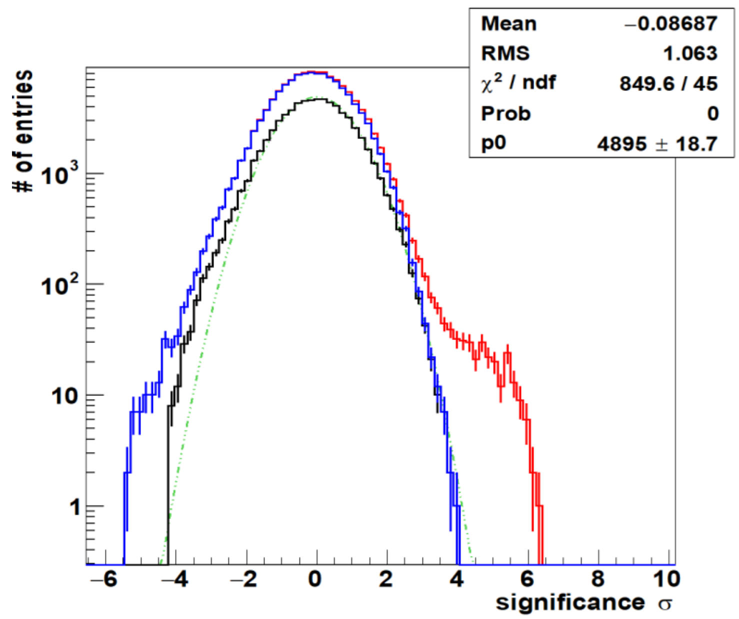

Figure 6: This is the Significance Distribution of the same region of the sky as the Sky Map. The dashed green line represents the normal Gaussian distribution, the red line is the distribution of the entire region with TeV J2032+4130, the blue line represents the region without TeV J2032+4130, and the black line is the region without the target source and the other excluded regions such as bright stars.

Because the red line veers off from the blue line at approximately 3 σ and has a significant gap from the blue line until reaching zero entries, it makes it even more safe to say that the detections are of gamma ray origin.

The Energy Spectrum shows the amount of flux at a certain energy (in units of Giga electron volts GeV) and is represented using a Power Law Spectrum. The resulting spectrum from my research is shown in Figure 7 with other Energy Spectra plotted with it, with an explanation of the Power Law (Section 3.1).

2.4 Problems

At some points during the process, there were issues with getting Event Display to run correctly. Some of these issues came about because of my inexperience with the software, in which case the solution to the problem was not complicated. In the simpler cases, there was a letter missing or a spacing issue in the coding. In other cases, it was saving certain files and data into the wrong drive on Linux, which took longer to fix but still was not a major issue.

Once my initial results were gathered after going through the steps in Event Display, there was an issue with the important values I obtained. The initial spectral index (α) value came out to be too soft (farther from the expected value) compared to the VERITAS results from 2014 and compared to other observatories. After not finding any errors when going back in the coding, my advisor recommended to not use the more recent runs of data (the most recent 21 runs out of 124 runs). This was because those 21 runs were of lower quality than the runs before them, even though they were usable for the initial analysis. Once these recent runs were removed (but not deleted) in the code, the spectral index came out to be much harder (closer to the expected value) compared to the other results.

3 Results

3.1 Power Law Spectrum

The Energy Spectrum can be represented through a Power Law Spectrum, and the important values to determine the type of source TeV J2032+4130 is, can be found through the power law equation as shown below:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_0 \left(\frac{E}{E_0}\right)^{-a} dE$$

where N_0 is the flux normalization, E is energy that varies in value, E_0 is the pivot energy and $-a$ is the spectral index. The power law itself is a functional relationship between two quantities, where the relative change in one quantity results in a proportional relative change in the other quantity. In other words, one quantity varies as a power of another. A Power Law Spectrum is simply a spectrum that is quantified in terms of a power law, which is what the resulting Energy Spectrum is described as.

3.2 Values and Spectra Comparisons

My resulting Power Law equation of TeV J2032+4130 from the VERITAS data taken in May of 2021 is shown below:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = [(3.8 \pm 0.7) \times 10^{-13}] \left(\frac{E}{1\ TeV}\right)^{-2.10 \pm 0.25} dE$$

The important value to compare with other observatories is the spectral index, which I obtained to be -2.10±0.25. This value with error being considered, is extremely similar (if not the same) as other detections of TeV J2032+4130, which is shown in Table 1 below along with the other value comparisons:

Observatories	Flux Normalization	Pivot Energy	Spectral Index
VERITAS 2021	$(3.8 \pm 0.7) \times 10^{-13}$	1 TeV	-2.1 ± 0.25
VERITAS 2014	$(9.5 \pm 2.2) \times 10^{-13}$	1 TeV	-2.1 ± 0.21
MAGIC 2008	$(4.5) \times 10^{-13}$	1 TeV	-2.0
HEGRA 2005	$(6.9 \pm 1.8) \times 10^{-13}$	1 TeV	-1.9 ± 0.3

Table 1: This table shows the power law equation value comparisons between various observatories that have detected TeV 2032+4130. The MAGIC 2008 row has no error because the values could not be found, but it was considered.

Because my resulting Spectral Index is extremely similar to that of other detections, it makes it safer to conclude that TeV J2032+4130 is still most likely a Pulsar Wind Nebula. This conclusion can be further confirmed when looking at the Energy Spectra themselves as shown in Figure 6:

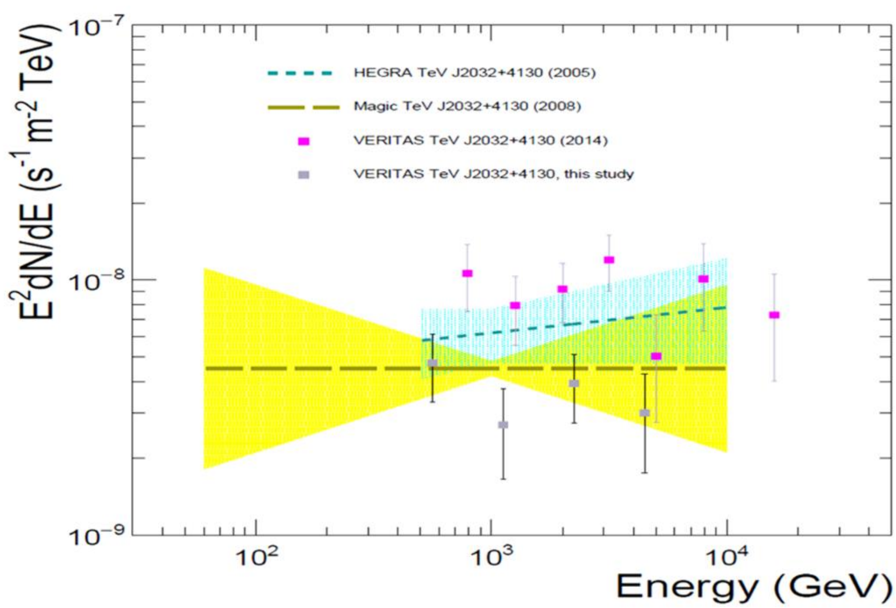

Figure 7: This plot shows multiple Energy Spectra (with error bars) from various observatories including one from VERITAS taken in 2014. Both the horizontal and vertical axis are log scaled. The solid colors around MAGIC's spectrum and HEGRA's spectrum is the error of each spectrum.

As shown in the figure above, my resulting energy spectrum (shown in gray) is fairly similar to those of other detections. This combined with the spectral index similarities makes it safe to confirm the conclusion that TeV J2032+4130 is a Pulsar Wind Nebula.

3.3 Flux Normalization Variance

Although my resulting spectral index was extremely similar to other detections of TeV J2032+4130 and is what was needed to confirm my conclusion, my resulting Flux Normalization seemed to be a bit softer or less than the other detections. This difference in value can be seen in Figure 6 with the majority of my data (in gray) being lower than the majority of the other data, and it is significant enough to ponder why this is the case. The one prominent thing that could have caused this is the fact that point source analysis was used instead of extended source analysis. Using point source analysis could have caused this because TeV J2032+4130 is an extended source, and it would be preferred that extended source analysis was used on an extended source. The catch in my research is that point source analysis is the more favorable kind of analysis in Event Display; even though extended source analysis can be used.

4 Future Work

If I were to continue this research in the future, I would attempt to figure out the Flux Normalization variance and take a deeper dive into TeV J2032+4130 as a source.

To look into the Flux Normalization variance, I would run the same data through Event Display but use extended source analysis instead of point source analysis even though it is less favorable in Event Display. In the past, VERITAS has used extended source analysis on this source with success; but it has been over five years since that analysis was done.

To take a deeper look into TeV J2032+4130 as a source, I would do what is known as Particle Modeling (with multiwavelength data) on the source and its nearby Pulsar PSR J2032+4127 to see some of its characteristics, knowing that is most likely a Pulsar Wind Nebula. This particle modeling will not only give a deeper look into the characteristics of this source but will also reveal possible connections between TeV J2032+4130 and PSR J2032+4127. In other words, it could show that PSR J2032+4127 is the Pulsar that is powering the PWN that is TeV J2032+4130.

5 Acknowledgements

I would like to first acknowledge my primary research advisor this project Binita Hona, who guided me every step of the way. I would also like to acknowledge Dr. David Kieda and the High Energy Astrophysics group as a whole for accepting me into the program and also helping me in my research. And lastly, I acknowledge my writing advisor Dr. Thomas Kling, who helped and guided me throughout the thesis writing process.

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7 Appendix

Command	Meaning
mkdir test	Creates a directory named test
cd test	Opens the test directory
cd test/gallery	Opens the gallery directory within the test directory
cd ..	Goes back up one directory
cd	Goes back up to the initial directory
ls	Lists files in a directory
vi file	Creates and/or opens a file named file
:w	Saves something within a file
:q	Exits from a file
:wq	Saves and exits a file
:q!	Exits from a file without saving
rm file	Removes file
rm -r test	Removes the directory named test
cp file newfile	Copies file into a new file named newfile
./ codefile.sh	Runs the python code within codefile.sh
screen -S screenname	Opens a screen (place where code continues to run even after exiting the screen) named screenname
screen -ls	Lists all screens in use
ctrl+A+D	Detaches from a screen without killing it
screen -r screenname	Shows list of detached (not in use) screens
screen -x screenname	Shows list of attached (in use) screens

Table 1.A: This table shows various commands that were used in Linux to conduct my research, along with what they do in the Linux terminal (or their meaning).

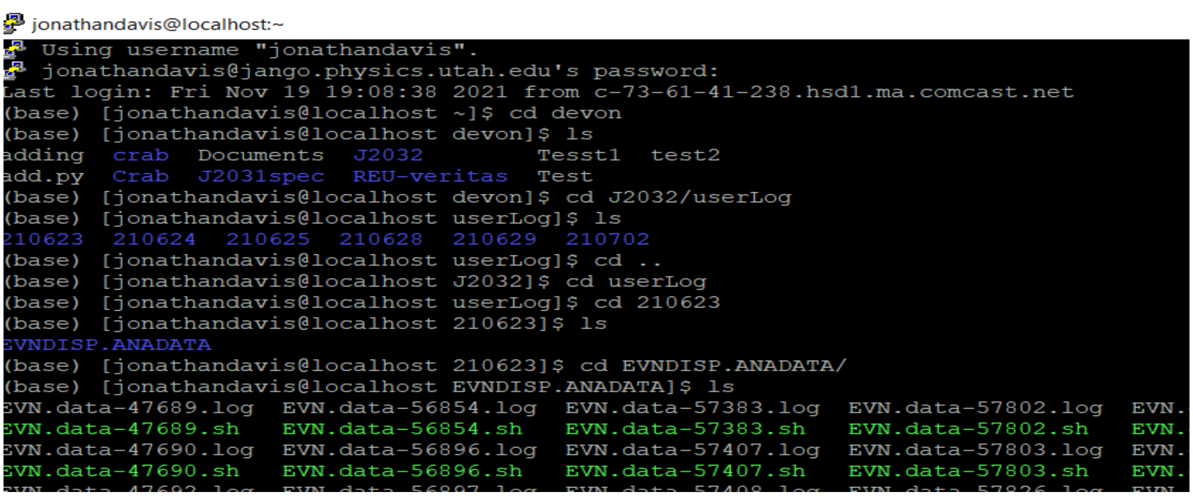

Figure 1.A: This is a screenshot of an example of Linux code; starting from when I logged into the system, moving through directories, and seeing what are in them.