Search for TeV Radiation from Pulsar Tails

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(Dated: September 9, 2012)

The field of very high energy astrophysics is looking at the universe as seen in the TeV energy range. The goal is to figure out where these very high-energy (VHE) particles are coming from and what is accelerating them to that energy range. In order to study this we are using an array of four atmospheric Cherenkov telescopes called VERITAS.

One potential VHE source class relates to pulsars. Pulsars are neutron stars, created by supernovae, where the magnetic axis is out of alignment with its axis of rotation. If the pulsar stays in the supernova remnant it creates a pulsar wind nebula, which can accelerate particles to the VHE range. This is a well-studied phenomenon.

Pulsar tails are less studied. They are created when pulsars are ejected from their supernova remnants at supersonic speeds. A bow-shock is created behind them which can accelerate particles to at least the X-ray range. We would like to know if they can accelerate these particles all the way to the VHE range.

My analysis of the two pulsar tails PSR J0357 +3205 and PSR J1740 +1000 showed no detection. The upper limits on the integral fluxes were <1% of the integral flux of the Crab above the same energies.

I. VERY HIGH ENERGY ASTROPHYSICS

VHE Astrophysics is looking to solve the problem of the origin of cosmic rays and other particles with energies on the order of a teraelectronvolt or TeV, which is 10^{12} electronvolts. For a sense of scale, the Large Hadron Collider (LHC) operates with a beam energy in the same energy range.

Given that we see cosmic rays, we know they must be coming from somewhere, but where exactly? By considering the LHC we see that it is no mean feat to accelerate particles to the VHE range. Wherever this takes place in space there must be a truly spectacular process occuring.

These questions of how and where were what started the field of VHE astrophysics and they are the questions which we are still trying to answer. Yes, we have some answers, but for these questions we are not limited to one answer, and so we continue to seek more processes and more locations.

II. NEUTRON STARS AND PULSARS

In the event of a type II supernova, a massive star has converted all of the hydrogen and helium it can into iron and can no longer support itself. It therefore collapses in on itself. This process forces great numbers of electrons and protons into each other, producing neutrons and releasing >90% of the energy of the supernova in neutrino form. These neutrons then form what we call a neutron star.

If the magnetic axis of the resulting neutron star is out of alignment with its axis of rotation, as seen in Fig. 1, we call the neutron star a pulsar.

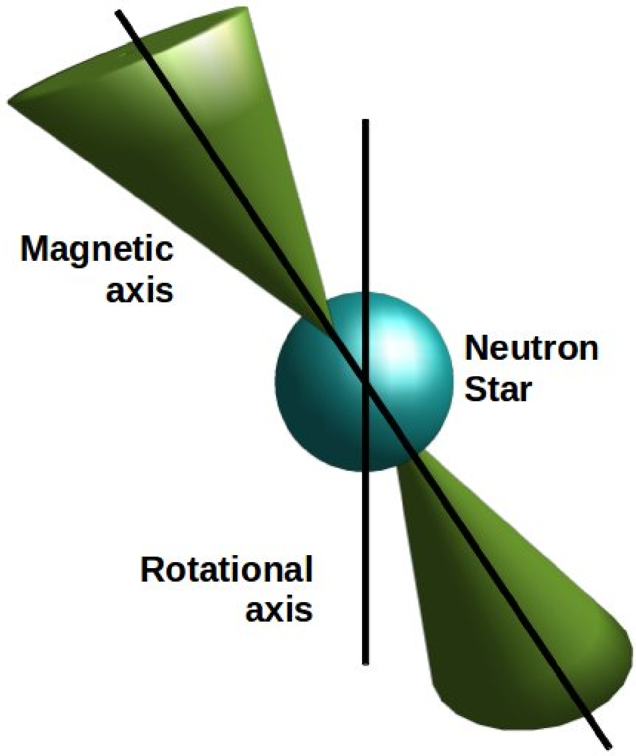

FIG. 1: A pulsar is a neutron star whose magnetic axis is not aligned with its axis of rotation.

III. PULSAR WIND NEBULAE

One type of source which can accelerate particles to the TeV energy range are pulsar wind nebulae (PWNe).

When the pulsar forms in the supernova it has two choices. It can either stay there or it can leave. In the

FIG. 2: An x-ray image of one of PSR J0357 +3205, one of our two pulsar tail sources, the other one being PSR J1740 +1000.

case of a PWN the pulsar stayed. It remains surrounded by its supernova remnant, which is simply what is left over (in addition to the neutron star) after the supernova.

It is in the shock-front where the particles are accelerated. Electrons go back and forth across the boundary between the wind and the intergalactic medium into which it is expanding, gaining energy with each pass. After many years (several hundred or more) of this, the particles can have reached the TeV energy range.

But it is not the accelerated electrons that we see, but gamma rays. These gamma rays are produced via inverse Compton scattering and synchrotron radiation. In inverse Compton scattering, an ultrarelativistic electron imparts energy to a low energy photon. Synchrotron radiation on the other hand, is given off when the same ultrarelativistic electrons spiral through a magnetic field.

IV. PULSAR TAILS

As discussed earlier, the pulsar created by a supernova can either stay or it can go. Pulsar wind nebulae result from the staying option. The other case forms what we call a pulsar tail. The pulsar is ejected from the supernova remnant at supersonic speeds, and as it speeds along, a tail of material forms behind it. Think of the water behind a speedboat, or the cloud behind a supersonic jet, or even the bow-shock of our own galaxy, the Milky Way.

Pulsar tails accelerate particles in a similar fashion to PWNe. As electrons go across the edges of the tails, they are accelerated. They go back and forth, potentially for hundreds of years, gaining energy with each pass. Then, once again, gamma rays are produced via inverse Compton scattering and synchrotron radiation.

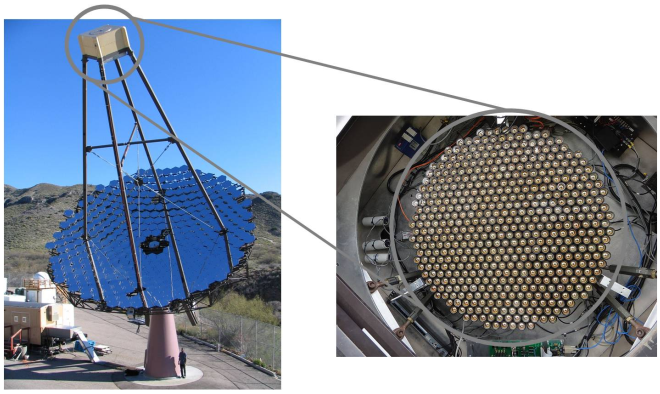

FIG. 3: Each of the four VERITAS telescopes consists of a 12m reflector comprised of 350 mirror facets, which focus light onto a camera with 499 pixels.

We know that this acceleration process does indeed occur, since pulsar tails have been studied in the X-ray range, and X-rays are created non-thermally. However, whereas we know that PWNe can reach the TeV energy range, we would like to discover pulsar tails can also do this.

V. VERITAS

In order to see in the TeV energy range, we use a detector called VERITAS, located in Arizona. VERITAS stands for Very Energetic Radiation Imaging Telescope Array System. It consists of four 12m optical reflectors arranged in a parallelogram. Each of the telescopes use 350 mirrors to reflect light into cameras of 499 pixels each.

These telescopes utilize an atmospheric Cherenkov technique. This works as follows. Very high energy particles, hopefully gamma rays, enter the atmosphere and create showers of electrons and photons. When one of the shower particles goes faster than the speed of light in the atmosphere, they create cones of blue light known as Cherenkov light.

It is the pool of Cherenkov light which our telescopes see. When a telescope detects some of that light it appears as a streak in the camera. We can then use the directions in which the streaks are pointing to reconstruct where the original gamma ray came from.

However, it is not exclusively gamma rays which can produce Cherenkov light and trigger our detectors. But since we are only interested in the gammas, we need a system of rejecting the hadrons. The way we do this has to to with the shape of the streaks which the Cherenkov light leaves. For gammas, the traces are quite well-defined and compact, whereas for hadrons they are more spread out.

Since we use this atmospheric Cherenkov technique we have a much larger effective area than space-based

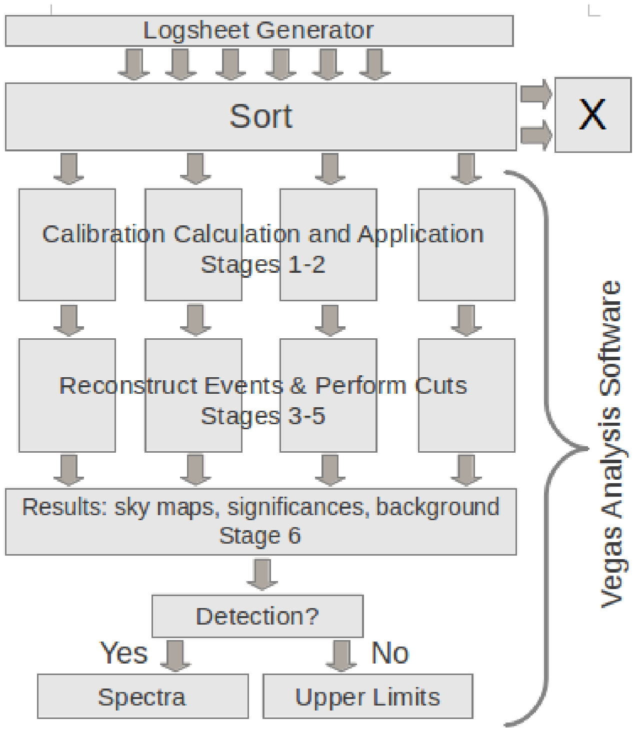

FIG. 4: An outline of the analysis procedure. A list of runs is obtained from the Logsheet Generator, which are then sorted for quality. The accepted runs move on, while the rejected runs are represented by the X. Once sorted, the runs go through the six stage analysis software called VEGAS. Then spectra are obtained if there is detection, and upper limits if there is no detection.

telescopes. This is because with a space-based telescope you detect the actual gamma ray and thus the gamma ray must hit the detector itself. On the other hand if a ground based telescope such as VERITAS is located anywhere within the Cherenkov pool of light, we can reconstruct where the gamma came from.

VI. ANALYSIS PROCEDURE

The analysis of these our two pulsar tail sources involved sorting runs, followed by the use our six stage analysis software called VEGAS, and finally, calculation of upper limits. An outline of the process in found in Fig. 4.

A. Run Selection

The first thing to do was to go to the Logsheet Generator, which stores and sorts the run numbers and information for all of the data taken by VERITAS. By looking at the sky quality information, as well as notes about hardware problems, the good runs were separated from the bad runs. This also allowed me to know when a cloud was passing over an otherwise good quality sky and so cut out those minutes. Runs are typically 20 minutes long, though for a variety of reasons they can have ended early. Short runs are acceptable, but cease to be useful if they are less than 5 minutes. The good runs then pass to the analysis phase.

B. Calibration

The performance of the telescoptes changes over time, and so the data runs need to be calibrated in order to take this into account. Therefore, during each night of observations, a “laser” or “flasher” run is recorded. For this, a known amount of light is flashed and the reaction of each camera pixel is recorded. This allows us to compensate for drifting gains, among other things.

Stage 1 of the VEGAS analysis software prepares the calibrations on both sides: the laser run and the data run. The calibrations are then applied in Stage 2 of the analysis.

C. Event Reconstruction

Once the calibrations are done we are ready to reconstruct the events. This happens in stages 3 and 4 of VEGAS. In order to reconstruct where the gamma ray came from which caused a given event, the software looks at which camera pixels were activated. The activated tubes create a sort of smear across the camera. These smears can be used to point to where the original gamma came from. Each telescope which saw the event gives us a plane, so two intersecting planes gives us the line which the gamma would have taken if not for the atmosphere. With more telescopes we can more accurately and precisely determine the source of the gamma ray.

The reconstruction portion of the analysis outputs not only the source of the gamma, but also where it would have hit the ground if not for the atmosphere. Using this information combined with the intensity of light seen by the cameras, VEGAS is able to tell us the energies of the gamma rays.

The arrangement of the telescopes also affects their pointing ability. Up until thel fall of 2009 the four VERITAS telescopes were arranged in a trapezoid configuration. At that point, the first telescope was moved so that the telescopes were in a parallelogram arrangement. This was done to improve sensitivity and increase angular resolution.

Since in the old telescope array, telescopes 1 and 4 were very near each other, when analyzing data from that time, I had to reject events which were comprised of only those two telescopes in order to reduce background.

D. Cuts

While still in stage 4, cuts are made on the number of tubes with hits, distance, and energy. We require at least five tubes in any one camera to be activated in order for us to consider that telescope to have seen the event. The distance cut says that we are only concerned with the events which took place within 1.43 degrees of where the telescopes were pointing. This is so that we aren't troubled with events where we detected the edge of a pool of Cherenkov light from an event that happened a considerable distance away. Finally, the energy cut says that for medium/regular cuts we only consider events with a minimum of about 250 GeV. For hard cuts the minimum energy is 750 GeV.

In Stage 5 we apply more cuts. This time the cuts are on the shape of the traces in the cameras. We set maximum dimensions for the traces. These cuts help us to separate the hadron events from the gamma events. Gamma events produce cleaner, more compact streaks, whereas hadron traces are less well defined.

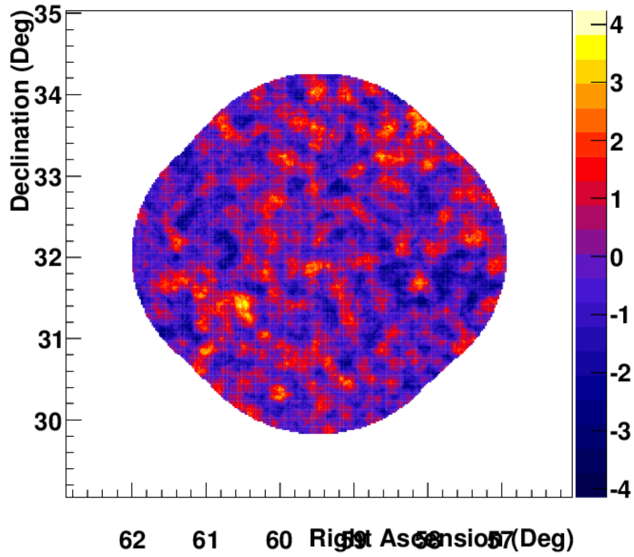

FIG. 5: The significance map for the pulsar tail PSR J0357 +3205 using medium cuts.

E. Obtaining Results

The final stage of the VEGAS analysis software, Stage 6, combines all of the runs and determines significances. In order for it to determine on and off events and so calculate background and significance we need to apply a cut on θ^2, where θ is the angle between the source and where the gamma actually came from. For both medium and hard cuts this is 0.01deg^2.

The background is determined as follows. When data are taken, the telescopes are not pointed directly at the source. Instead they are offset in one of the cardinal directions from the source. The background counts are then determined from those gammas which come from the region which is the mirror image of the source region. This way of doing background calculations is called Wobble mode.

Stage 6 outputs a variety of plots, including a significance sky map. Using this plot you can determine whether you detected something or not. If there was a detection, you can re-run stage 6, but this time asking it to calculate a spectrum. If there was no detection, you can ask stage 6 to calculate upper limits on the flux instead.

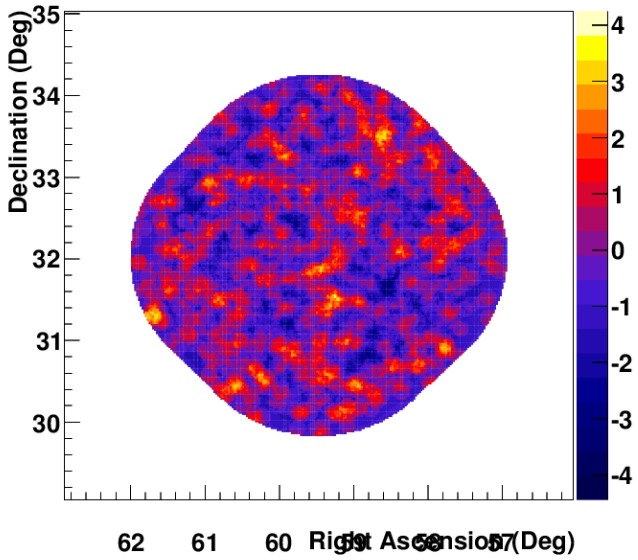

FIG. 6: The significance map for the pulsar tail PSR J0357 +3205 using hard cuts.

VII. PULSAR TAIL ANALYSIS

VERITAS has taken data pointed towards two pulsar tail candidates which we can see in the x-ray and would like to know if they show up in the TeV gamma range. These are PSR J0357 +3205 and PSR J1740 +1000. PSR J0357 +3205 has a length of 15 arcminutes and PSR J1740 +1000 of 5 arcminutes, both translating to roughly 2pc in length.

There were 36 runs taken for PSR J0357 +3205 during the fall and winter of 2011. Of these 29 were analyzed. For PSR J1740 +1000, there were 60 runs from summer 2007 and spring 2008, 42 of which were analyzed.

Running this data through the VEGAS analysis software resulted in the graphs in Fig 5- 8. As you can see, the significance range is roughly -3σ to 3σ, with only a few events above 3σ, and those not in the center of view.

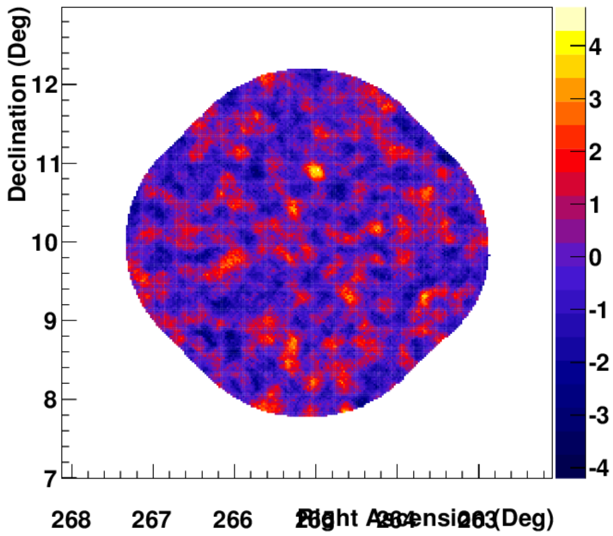

FIG. 7: The significance map for the pulsar tail PSR J1740 +1000 using medium cuts.

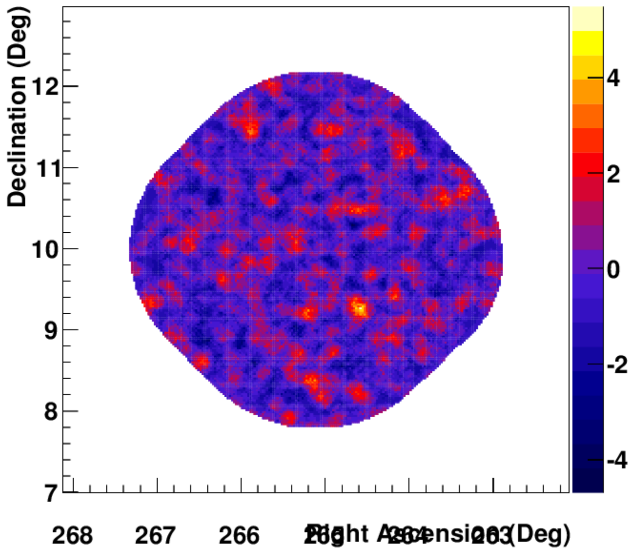

FIG. 8: The significance map for the pulsar tail PSR J1740 +1000 using hard cuts.

A. Upper Limits

Since there was no detection, it was time to calculate upper limits. Therefore I reran Stage 6, this time asking for upper limits on the flux at the 99% confidence level.

This outputs live time, energy thresholds, and integral upper limits. Since it is hard to get a sense of what the fluxes mean, we compare them to the Crab (a pulsar wind nebula), which is our VHE standard candle, due to its brightness and well-studied nature.

The integral flux above a threshold energy E_0 takes the form

$$\Phi(E > E_0) = \int_{E_0}^{\infty} \left(\frac{dN}{dE}\right) dE \tag{1}$$

where $\frac{dN}{dE}$ is the differential flux and takes the form

$$\frac{dN}{dE} = AE^{-\alpha} \tag{2}$$

where α is the spectral index and A is a constant.

The Crab spectral index is 2.39, and the integral flux above 1TeV is $2.26 \times 10^{-11}\text{cm}^{-2}\text{s}^{-1}$. These two pieces of information allow for the calculation of the constant A. Once we know that, we can calculate $\Phi(E > E_0)$ for any E_0 we desire. More specifically, we can calculate it for the various energy thresholds which the Stage 6 upper limit calculation gave us.

Now we can compare the integral flux upper limits to the integral flux of the Crab. What we get is the following percentages found in Table I.

VIII. SUMMARY & CONCLUSIONS

Pulsar tails are created when pulsars, formed in supernovae, are ejected from their supernova remnants at supersonic speeds. A bow-shock is created behind them which can accelerate particles to at least the x-ray range. We would like to know if they can accelerate these particles all the way to the TeV range.

	PSR J0357 +3205 med	PSR J0357 +3205 hard	PSR J1740 +1000 med	PSR J1740 +1000 hard
Live Time (hr)	7.4	7.4	12.4	12.4
Energy Threshold (TeV)	0.22	0.42	0.32	0.66
Upper Limit on Integral Flux ($10^{-9}m^{-2}s^{-1}$)	19	6.2	13	4.8
Percentage of Crab (%)	0.74	0.59	0.83	0.86

TABLE I: The results of the upper limit analysis. Live time is the number of hours of data which were analyzed. The energy threshold is the E_0 above which events were accepted and corresponds to the energy at which the peak in the detected gamma-ray events occurs. The integral flux is the number of gamma events above E_0 per area per time. The percentage of Crab is what percentage of the flux from the Crab Nebula above E_0 the upper limit on the source is.

My analysis of the two pulsar tails PSR J0357 +3205 and PSR J1740 +1000 showed no detection. The upper limits on the integral fluxes were <1% of the integral flux of the Crab above the same energies.

IX. ACKNOWLEDGEMENTS

I would like to thank Rene Ong for taking me on for the summer and for supporting me throughout my time at UCLA. I would also like to thank Pratik Mujumdar for teaching me how to use the analysis software and for answering all of my questions about it. Finally, I would like to thank UCLA for the opportunity to do this research and NSF for the funding which made it possible.

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