Proposal for VERITAS - 2018/2019 (Cycle 12)

Proposal ID:	1201 [1]
Principal Investigator:	Matthew Lundy
Institution:	McGill University
Email:	matthew.lundy@mail.mcgill.ca

Short Abstract: Inspired by recent observations of the shocked stellar winds in Eta Carinae, we propose observations of a similar high mass stellar binary MWC 314. MWC 314 falls in the error ellipse of a nearby Fermi-LAT object and there is some evidence of periodic variability in gamma-ray emission matching the multi-wavelength period of the eccentric binary. This would be the first observation of emission from stellar winds at VERITAS and the second colliding wind binary observed in the VHE.

Science Working Group:	Galactic[2]
Is this part of a Fermi-GI proposal?:	No [3]
Target of opportunity observation?:	No [4]
Multiwavelength requirement:	No additional observations initially required
Thesis:	Yes

Analyzers:
Matthew Lundy will perform the VEGAS[5] analysis. William Arthurs will provide an Event Display secondary.
Data will be analyzed as it becomes available.

No	Target Name	R.A.	Dec	El	Tmax(Tmin)	ObsMode	Too	NTels	Moon	Sky	PrevObs
1	MWC 314	+19 21 33.977	+14 52 56.90	65	25(12)	Wobble(0.6)	N	3	N	B	-

[1] This proposal is formatted to meet the VERITAS TAC proposal requirements. Knowing that much of the readership on this committee would be unfamiliar with many concepts in gamma-ray astronomy, I have provided a series of footnotes to explain many of the concepts as well as a brief section to describe the form of the telescope. These would not be included in a real TAC proposal.

[2] Science Working Groups at VERITAS sort the broad fields of study within VHE astronomy, and help organize internally the research being done. The three primary groups are the Blazar Working Group, the Dark Matter and Astroparticle Working Group, and the Galactic Working Group.

[3] The Fermi Guest Investigator Program is a program where funding is given for the direct analysis of Fermi data in conjunction (usually) with a multi-wavelength project.

[4] A Target of Opportunity object is a target for which no specific time is allocated but instead if some condition is triggered there will be a "same night" observation of the object. Usually these are transient objects like blazar flares or GRBs.

[5] VEGAS and Event Display are independent analysis chains for VERITAS data and all data must be processed through both to ensure the validity of the conclusions.

Observing Proposal 2018/2019

Proposal Title : Search for Orbitally Modulated TeV Emission from MWC 314
Science Group : Galactic Working Group
Authors : Matthew Lundy

1. Introduction

There are two main interwoven problems that remain unresolved the field of gamma-ray astronomy. There is the problem of a associating a large number of unidentified point sources with their multi-wavelength counterparts and the problem of explaining excess emission from dense baryonic and non-baryonic regions. These two problems come to a head in the study of the gamma-ray emission from the galactic center, where there exists a constant debate on whether the gamma-ray emission can be accounted for by an unidentified system of pulsars or whether the excess is due to dark matter[6][1]. One solution to this issue is the inclusion of tertiary population of systems capable of producing gamma-rays with a high density in the galactic center. Spurred by recent results in the literature from H.E.S.S., and Fermi-LAT we propose that shocked stellar winds may account for a more significant portion of these associated sources than previous studies have assumed. In order to investigate this we propose a **25 hour** follow-up of MWC 314, one of the most luminous binaries in the Milky way, in order to confirm a potential periodicity uncovered in the Fermi data with the hopes of associating a nearby FL8Y source with the binary. If detected this would be the second colliding wind binary (CWB) measured in the gamma-rays and the first CWB measured by VERITAS.

The mechanism behind the CWB emission is similar to that of a pulsar wind nebula. Depending on the system it is either due to IC processes at the shock boundary or it due to protons in these shocks interacting with surrounding nuclei to form neutral pions that decay into the observed GeV photons. Two scenarios can generate these powerful shocks, the bow-shock model where high mass stars with high velocity winds and proper motions create a shock with the ISM. Alternatively, the CWB model where two high mass stars in the binary form a shock front between their two stellar winds. Eta Carinae, one of the closest CWBs, was detected by Fermi-LAT in 2012[2] and just recently by H.E.S.S.[7][3] marking the first observation of VHE[8] gamma-rays from stellar winds.

CWBs mark a new source class in VHE which hold a far reaching potential. High mass stars appear in many of the same regions as stellar remnants and many of the regions where gamma-ray excess is claimed. A deeper understanding of CWB emission could lead to a modification the excess emission models for molecular clouds, the galactic center, dwarf galaxies, and starburst galaxies. It is clear that expanding the population should be a priority for VERITAS.

2. Relation to Previous Observations (VHE and other wavelengths)

Four recent observations have motivated the selection of MWC 314 as a potential VHE source. These are the analysis of Eta Carinae from Fermi and H.E.S.S. as well as the study of MWC 314 in Gaia and MOST.

The primary of the Eta Carinae binary is a luminous blue variable (LBV) and is among the most massive stars in the galaxy with a mass $M_A > 90M_\odot$[4]. The companion is thought to be an O or Wolf-Rayet star. When the winds of these two massive stars collide, models estimate they are capable of reaching speeds of 3000 km s^{-1}[4]. Since the system is highly eccentric (e$\approx$ 0.9[4]) the size and power of this region is orbitally varied. This orbital variation occurs on the time scale of years which is much slower

[6]Dark matter(DM) is predicted to emit gamma-rays in many weakly interacting massive particle(WIMP) models. This process works by particles with masses on the order of a GeV self-annihilating in dense dark matter regions. This is the same process by which thermal relic emit in the baryonic regime.

[7]H.E.S.S. is an IACT located in the southern hemisphere operating in a similar energy regime to VERITAS. Fermi is a space based telescope operating at a lower energy

[8]HE emission typically refers to 100 MeV - 10 GeV range and is detected using space based telescopes, VHE typically refers to the energy range between 10GeV - 10,000GeV and is typically detected on the ground using Imaging Atmospheric Cherenkov Telescopes (IACTs)

than typical pulsar variations and more regular than the quasi periodic behaviour of blazars. This gives CWBs a unique signature that separates them from other gamma-ray sources. This variable non-thermal emission was first observed for the Eta Carinae system in the hard X-rays by INTEGRAL[5]. AGILE and Fermi-LAT detected a variable gamma-ray source at the position of Eta Carinae soon after[2][6].

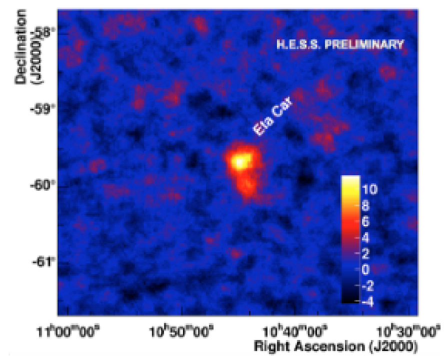

Figure 1: H.E.S.S. significance map for 25 hours of monoscopic observations with the central telescope

HESS observed Eta Carinae in 2012 and only obtained upper-limits[3]. This study was performed using the older 4 telescope array which has a much higher energy threshold than the newer system[9]. The newer arrangement led to an additional 25 hours of on data on Eta Carinae. It was taken before and just after periastron passage (taken between the phases of 0.78 and 1.1). As shown in Figure 1, they detected Eta Carinae with a pre-trial significance of 13.6σ[10].

The system that most closely resembles Eta Carinae in the Northern Hemisphere is MWC 314. In terms of binary parameters the new MOST analysis of MWC 314 revises the previous ephemeris and finds a ≈60 day orbital period with an eccentricity of ≈0.2

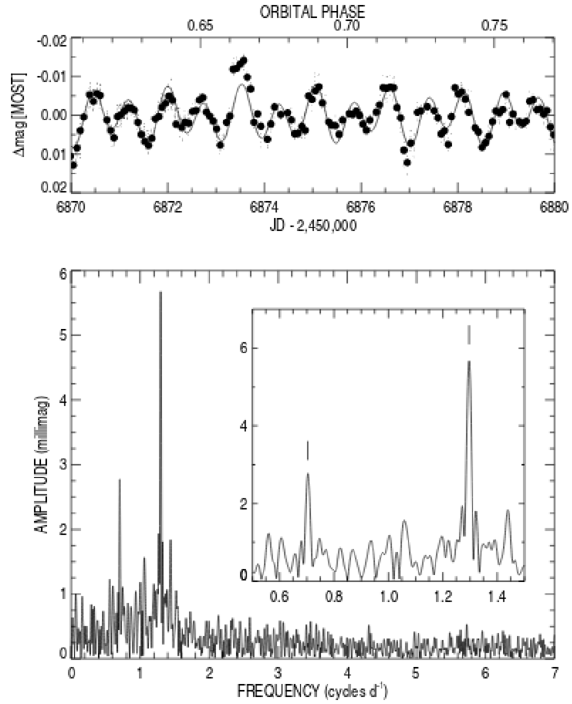

Figure 2: A portion of the MOST phaseogram of MWC 314 in the top panel. The orbital averages for a given phase are shown as black dots. The gray tracing is the two frequency fit from the Fourier transform (shown in bottom panel with the two frequencies highlighted) [8]

and semi major axis of ≈1 AU[8]. We can compare this to the orbital parameters of Eta Carina, with an eccentricity of ≈0.9 and period ≈2000days with semi major axis of ≈15 AU [9]. Although the variability of Eta Carinae may be higher there should exist a more continuous signal from MWC 314. The CWB model is also supported by the MOST photometry which has shown evidence of post periastron wind interaction. This can be seen in Figure 2.

Gaia[10] has recently revised the distance measurement of MWC 314. Using the bayesian analysis routine to calculate the distance they found an increase from 3kpc to 4.4kpc roughly doubling the luminosity of the MWC 314 primary ($L > 6.5L_{\odot}$, $T \approx 30,000K$). This moves it above the classical S-Doradus instability strip and very close to the same region of the HR diagram as Eta Carinae.

This inspired us to perform a search for a periodic signal in the archival Fermi-LAT data set. Currently there exists approximately 10 years of Fermi-LAT data, with the last point source catalogue being FL8Y. MWC 314 falls within the error ellipse of the

[9]Higher energy threshold corresponds to a lower sensitivity for low energy sources like stellar winds.

[10]It is common to represent non-standard significances in gamma-ray astronomy. They do not correspond to the ratio of the signal counts over the standard deviation of the background counts. Instead they represent the LiMa significance[7] which comes in the form $S_{LM} = \sqrt{2\left(N_{on}\ \ln\left(\frac{(1+\alpha)N_{on}}{\alpha(N_{on}+N_{off})}\right) + N_{off}\ \ln\left(\frac{(1+\alpha)N_{off}}{(N_{on}+N_{off})}\right)\right)}$, where α is the ratio of the expected counts in the on/off region, N_{on} is number of counts within your signal region, and N_{off} is the number of counts in your background region. Pre-trial refers to the "trial factors" which are penalties applied to your significance based on the number of cuts you applied to your data set before reaching that significance.

nearby FL8Y J1921.5+1501, a source that remains unassociated with any optical counterpart. There also appears to be a peak in the Fourier transform of the Fermi-LAT light curve centered around 60 days. A phaseogram showing the 10 year light-curve of the Fermi-LAT data can be seen in Figure 3. Fermi-LAT has been known to exhibit many temporal artifacts in the region of 1-100 days and so although the data seems to support the association, the additional VERITAS data is needed to make the confirm this periodic behaviour.

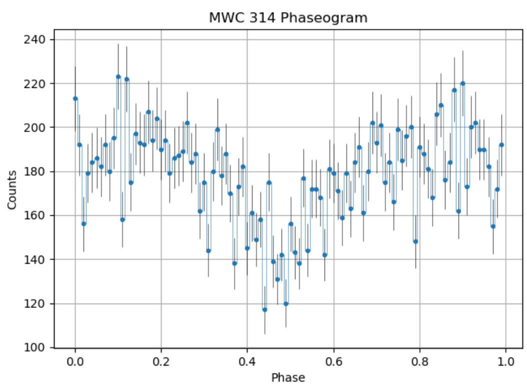

Figure 3: Phaseogram from 8 years of Fermi-LAT data. Made using gtpphase and P=60.753d

3. Quantitative Description of Expected Outcome

3.1 Description of IACTs

When a high energy photon enters the atmosphere the photon creates an electron positron pair through Cherenkov interactions in the upper atmosphere. The electron and position then lose energy via photon emission (bremsstrahlung radiation). These high energy photons then proceed to interact with more atmosphere and generate more electron positron pairs. This particle production chain is known as an electromagnetic cascade. We can detect gamma-rays indirectly by observing this electromagnetic cascade from the ground. One of the most precise instrument used is the Imaging Atmospheric Cherenkov Telescopes. IACTs use an array of optical telescopes focusing light to an array of PMTs(photo multiplier tube). PMTs have a far higher response rate compared to traditional CCDs with response times of a few nanoseconds. This allows them to capture the faint flashes of these showers against the NSB(night sky background).

The shape of the projected ellipse of the shower on the array holds information about the original photon that can be reconstructed via a comparison to shower simulations. From this one can obtain the position, energy, and mass of the original particle. This helps in the removal of noise generated from hadronic showers. Hadrons also can cause similar particle cascades that can trigger a response from IACTs but the shape of the ellipse becomes distorted and can be removed during the data capture. This significantly lowers the noise in the gamma-ray data.

VERTIAS currently employs four 12 m dishes and can detect particles in the energy range of 85S-300 TeV. In this range the standard candle is the Crab Nebula. VERITAS can detect a source that emits 1 percent of the flux of the Crab Nebula in approximately 25 hours. The sensitivity of VERITAS can be seen in Figure 4.

3.2 Time requirements

We suggest **25** hours of dark time for this object split between DR1 and DR11[11]. As can be seen in Figure 5, the minimum zenith angle for MWC 314 is 30 degrees. This is a relatively high zenith angle for VERITAS and as such the sensitivity of the instrument should decrease by roughly 25 percent. As the strength of the signal from this source is unknown in the VHE, we ask for the standard source detection demands for weather and moon altitude (weather greater than a B, and moon phase of 0.8 or below). We also require the sensitivity of the full array, but at minimum 3/4 of the telescopes will suffice.

The value of 25 hours was reached by comparing the integrated flux of the nearby Fermi-LAT source to that of the Crab to obtain the flux in Crab units of the source given a 1 GeV energy threshold. We then fit a power law to source's spectral energy distribution giving a spectral index of 2.86 ± 0.09 which we compared to the differential Crab flux with power law index ≈ 2.83 in order to extrapolate to the energy threshold of VERITAS at 85 GeV. This leads to a flux of roughly 0.02 Crab units. Comparing this to the standard sensitivity of VERITAS, MWC 314 should be detectable with a significance of 5σ after 12 hours. Applying the correction for higher zenith angles, this time extends to ≈ 16 hours.

Although it should be noted that the Fermi-LAT SED is based on the orbitally averaged flux of the system. If we take Eta Carinae as a point of comparison once more, we see that the flux from the system varies by over 80 percent throughout the orbit of the binary[2]. We expect that the flux from MWC 314 during periastron could be as high as double the average flux estimated from the Fermi-LAT observa-

[11] DR stands for data run, which is the system by which VERITAS allocates time. DR1 and DR11 correspond to the month of September and July respectively.

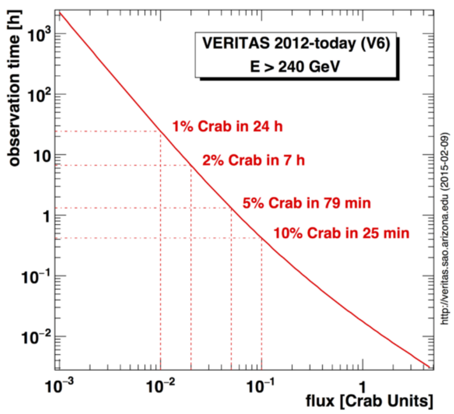

Figure 4: The sensitivity of the VERITAS telescope. The flux of a given source(in Crab units) is plotted against the length of time need to obtain a 5 σ detection.

tions. However, as the VHE SED of Eta Carinae still remains unpublished by H.E.S.S. , it is still unclear how this variability scales in the VHE.

We recommend a split of 12.5 hours in DR1 and DR11. We also recommend performing a bulk of the DR1 time at periastron for the system as this is when the strength of the non-thermal emission should be at a maximum due to the wind interaction region being larger. The split time allocation will allow us to analyze data from DR1 between the data runs and suggest whether the source should be followed up during periastron or apastron. Due to the period of the object being 2 months, and the RA band allocation being monthly, we would be able to suggest whether this object should be viewed earlier or later in DR11 time based on the result of the VEGAS analysis of DR1. If the source is significantly detected during DR1 then the follow-up can be done at apastron to demonstrate variability, whereas if time is still needed for a 5 σ detection than the source can be observed earlier during the run in order to extend the integration time around the emission maximum.

For this source a wobble of 0.6^o is suggested such that a ring background method(RBM) can be used to estimate the NSB. This is selected as it is the standard for low-signal sources where integration time is at a premium and on/off is too time consuming. [12]

For the analysis we plan to use SOFT point source cuts. [13] The relevant parameters for the RBM method are :

- $0.05 < \mathrm{MSW} < 1.1$
- 0.05<MSL<1.3
- $\mathrm{MHL} < 7$
- Ring size $= 0.03^o$

We will not modify any of these parameters. Exclusion regions will be used with the exception of any sources within the ON region of MWC 314.

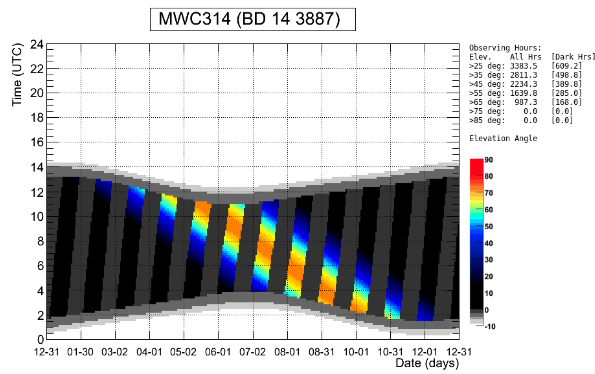

Figure 5: TEVCAT Observability plot for MWC 314 at VERITAS. The UTC time is plotted against the date. The black region shows the local dark time, with gray bands demarking the time when the full moon is occuring in the 2018/2019 year. The colored band indicates the altitude of MWC 314 during that night. It should be noted that although the target is viewable during the summer, VERITAS is not operational because of the monsoon season. TeVCat can be found at http://tevcat.uchicago.edu/

[12]Wobble anlysis is the technique placing your source off the center of your telescope's pointing. VERITAS has an FOH of 3^o so an offset of 0.6^o means placing the object about a quarter of the way off. You can then take a series of images such that the offset is distributed in the cardinal directions. We can then take multiple regions of NSB at equal distance from the center in a ring, such that the response, and therefore the background, should be equal to the region where the source is located. This is called the ring background method. The alternative is on/off background method. This is where you slew off the source in order to take background measurements. This works very well for dense fields and is required if you have multiple sources within your image, but it demands additional observation time and is not sensitive to changes in the NSB during the observation.

[13]These are based on the Hillas parameters of the projected ellipses. For example MSW is mean scaled width and has to do with the semi-minor axis of the ellipse that has been scaled based on the total size of the ellipse. The SOFT cuts for the V4 arrangement of VERITAS are standardized, and optimized for systems at lower energies. Some extended systems benefit from harder cuts where the low energy signal is removed, as the NSB is stronger in that domain. It is ill advised to apply many cuts to the same data set as it increases your trial factors and decreases the effective significance of your results.

4. Publication Plans

Gamma-ray binaries form a very small class of systems with only 5 such systems being known[11]. Most of these are an accreting systems with a central compact object, like a neutron star or black hole. The detection of another CWB in the VHE, (and a confirmation of the Fermi-LAT HE detection simultaneously) would be very significant addition to the field. We would assume a similar publication route to LS I +61 303 (one of the only x-ray/gamma-ray binaries currently seen by VERITAS), which produced an ApJ detection publication as well as a series of follow up proceedings based on the continuous monitoring of the system. VERITAS was also included in multiple multi-wavelength papers after the initial detection. Unlike LS I +61 303, MAGIC has not yet detected MWC 314 and as such this would be a novel detection. The original paper reporting the initial MAGIC detection of the microquasar in 2006 has garnered nearly 400 citations. There is reason to believe that a detection of MWC 314 would be equally novel. An MWC 314 detection would also be of much greater interest to the massive star community than LS I +61 303, as the shocked stellar winds allow for an additional parameter constraint to measure wind velocities and mass-loss rates in an LBV system. There also exists a wealth of other massive star binaries that occupy a similar parameter space to MWC 314 and Eta Carinae, leading to many additional sources for VERITAS in the future.

References

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