VHE Observation of CTA 1 with VERITAS

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CTA 1 (G119.5+10.2) is a composite supernova remnant (SNR) with a shell-type structure in the radio band and a center filled morphology at X-ray energies. Fermi has detected a radio-quiet pulsar PSR J0007+7303 within the radio shell of CTA 1 in a blind search within its first months of operation. Located within an X-ray synchrotron pulsar wind nebula (PWN), the Fermi source is spatially coincident with the EGRET source 3EG J0010+7309. We present the detection of the system in very-high-energy (VHE) gamma rays by VERITAS, with a preliminary comparison to other TeV-detected PWNe.

1. Introduction

The composite supernova remnant (SNR) CTA 1 (G119.5+10.2) consists of a shell-type structure visible in the radio band with a center filled morphology at X-ray energies. The radio shell, of diameter \( \sim 1.8^\circ \) [1], is fainter towards the north-west (NW) of the remnant, possibly due to rapid expansion of the shock into a region of lower density, as supported by HI observations [2]. The distance to CTA 1 is \( d = 1.4 \pm 0.3 \) kpc, derived from the associated HI shell [3]. Its age is estimated to be \( \sim 1.3 \times 10^4 \) yr [4].

Archival X-ray observations of CTA 1 in the 5-10 keV band show non-thermal diffuse emission of low surface brightness in the center of the remnant, likely corresponding to a pulsar wind nebula (PWN) driven by a young pulsar [5]. A faint point source, RX J0007.0+7303, is located at the brightest part of the synchrotron emission, and was suggested as a pulsar candidate by Seward et al. [6]. A Chandra image of this object provided further evidence of an energetic, rotation-powered pulsar, resolving a central point source, a compact nebula, and a bent jet [7].

1.1. Previous Gamma-Ray Observations

The earliest association of gamma-ray emission with CTA 1 comes from the detection of the source 3EG J0010+7309 by the EGRET instrument, with a relatively small 95% error circle of 28' [8]. Brazier et al. [9] proposed that the gamma-ray emission could originate from a young Geminga-like pulsar, based upon the coincidence with CTA 1, hard spectral index (\( \Gamma = 1.58 \pm 0.18 \) between 70 MeV and 2 GeV), and lack of flux variability. Confirmation of this association came recently when the Fermi Gamma-Ray Space Telescope discovered the radio-quiet, 316.86 ms gamma-ray pulsar PSR J0007+7303 in a blind search, using 0.14 years of data [10]. Subsequent observations by XMM-Newton resulted in the detection of pulsed X-ray emission out of phase with the gamma-ray pulsation [11]. The spin-down power of the pulsar (\( \dot{E} = 4.5 \times 10^{35} \text{ erg s}^{-1} \)) and characteristic age (\( \tau = 1.39 \times 10^4 \) yrs) confirmed estimates based on previous observations observations [10].

1.2. Broadband Modeling

Prompted by the discovery of PSR J0007+7303 by Fermi, Zhang et al. [13] modeled the pulsed and unpulsed spectral components of the pulsar magnetosphere and PWN. The pulsed high-energy spectrum was calculated with an outer-gap model and fit to the EGRET spectrum of Brazier et al. [9]. The unpulsed spectrum of the PWN was calculated with a time-dependent, broken power law injection model with non-thermal emission from synchrotron radiation and inverse Compton scattering of cosmic microwave background (CMB) and ambient infrared (IR) photons. These calculations predict that the PWN should be detectable in the very-high-energy (VHE) gamma-ray band by VERITAS.

2. CTA 1 imaged by VERITAS

2.1. VERITAS observations

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12-meter imaging atmospheric Cherenkov telescopes (IACTs) located at the base camp of the Fred Lawrence Whipple Observatory in southern Arizona. Each telescope consists of a Davies-Cotton design optical reflector which focuses the Cherenkov light from atmospheric showers onto a camera consisting of 499 photomultiplier tubes and light concentrators with a total FOV of 3°. VERITAS is able to detect a point source with the strength of 1% of the Crab Nebula flux at a statistical significance of 5 standard deviation (5σ) level in approximately 26 hours of observations. VERITAS is sensitive to gamma rays over a wide range of energies (100 GeV to tens of TeV) with an energy resolution of 15-20%.
VERITAS observed CTA 1 between September 2010 and January 2011 with a total live time of approximately 26 hours, after selection for good weather conditions and hardware status. Observations were taken in “wobble” mode \[14\], in which the telescope pointing is offset from the source position by some angular distance. An offset distance of 0.7° was used to accommodate the large size of the remnant and the extension of the PWN as seen in X-rays. Two sets of \textit{a priori} defined gamma-ray/hadronic shower separation cuts, optimized for weak sources of moderate and hard spectra, were applied to the data. Background was estimated using the ring background model (see, for example, \[15\]), with squared angular integration radii of 0.01 deg\(^2\) and 0.055 deg\(^2\) used for point-source and extended-source searches, respectively. The statistical significance of the excess is calculated using Equation (17) from Li & Ma \[16\].

### 2.2. Results

Figure 1 shows the map of excess events in the region around CTA 1 as measured by VERITAS. The hard-spectrum, extended-source analysis produced an excess with a pre-trial significance of 7.3σ, in a blind search region of radius 0.4° around the pulsar PSR J0007+7303, within the radio shell of the SNR CTA 1. Accounting for the sets of cuts and integration radii, and implementing a trails factor for the search region by tiling it with 0.04° square bins \[17\], we conservatively estimate a post-trials significance of detection of 6.0σ.

The TeV gamma-ray emission region exceeds the point-spread function (PSF; measured from analysis of the Crab Nebula) of VERITAS, as seen in Figure 1. Figure 2 shows the \textit{ROSAT} X-ray image of the region around CTA 1, overlaid with the VERITAS significance contours. The \textit{ROSAT} image reveals a center-filled morphology and faint compact source. The VERITAS excess is roughly centered on the location of PSR J0007+7303, which may be indicative of a young PWN, as opposed to older “relic” PWNe which have been offset from the pulsar by an interaction with the SNR reverse shock \[18\].

A preliminary spectral analysis gives an integral flux above 1 TeV of \(F_\gamma (> 1 \text{ TeV}) \sim 4\%\) of the flux from the Crab Nebula. (Final spectral analysis and flux estimates will be given in a forthcoming paper \[19\].) Using the distance of 1.4 kpc, we estimate the luminosity \(L_\gamma = 4\pi d^2 F_\gamma\) to compare with other PWNe and PWNe candidates detected at TeV energies. Fig. 3 and Fig. 4 present the results of these comparisons, following the work of Kargaltsev and Pavlov \[20\]. Fig. 3 shows the relative luminosities of PWNe in the TeV and X-ray bands, as functions of spin down power and characteristic age. It is seen that TeV PWNe are generally found around younger, more energetic pulsars, although the TeV luminosities...
do not depend on the pulsar age as strongly as X-ray PWN luminosities do. Fig. 3 shows the distance-independent ratio of TeV gamma-ray luminosity to X-ray luminosity versus the characteristic age. The TeV luminosity of a PWN reflects cumulative pulsar wind properties integrated over a significant fraction of the young pulsar’s lifetime while the X-ray luminosity characterizes the freshly injected pulsar wind, which might explain the hint of flattening at larger ages. Again, CTA 1 fits nicely in the middle of the TeV/X-ray PWN population, suggesting that the TeV emission is indeed due to the PWN.

3. Summary and Conclusion

VERITAS has detected extended TeV emission within the composite SNR CTA 1 at a 6σ post-trials significance level in approximately 26 hours of observation. The gamma-ray excess lines up with the gamma-ray pulsar PSR J0007+7303, and its X-ray PWN. Preliminary spectral analysis shows an integral flux above 1 TeV at 4% of the Crab nebula flux, and the properties of this new TeV source seem consistent with those for the known TeV/X-ray PWN population, lending support to its identification with the PWN of CTA 1.

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