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A Search for High-Energy Emission from the Remnant of Supernova 1181

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Over the previous millennium, only five Galactic supernovae were observed and recorded by contemporary astronomers, and their current-day counterparts subsequently identified. The remnants of four of these have all been very deeply studied, and ultimately detected, by TeV instruments after exposures of typically hundreds of hours. The measured TeV fluxes range from 1 Crab (by definition) down to 0.3% Crab. The location of the fifth supernova remnant tied to a historical record of its supernova (SN 1181) has never been studied at TeV energies. The reason for this is simple – the associated remnant was only identified as such in 2021. The remnant, Pa 30, is an unusual object whose properties are best explained as resulting from a Type Iax supernova explosion. These are a rare sub-type of Type Ia supernovae in which the merging white dwarfs are not fully destroyed by the supernova explosion, leading to a double-degenerate merger product colorfully described as a "zombie star". We will present the results of a search for TeV gamma-ray emission from Pa 30 with VERITAS.

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1. Introduction

Supernova remnants have long been considered potential sites for cosmic ray acceleration and associated very high energy (VHE) gamma-ray emission (e.g. [1]). The remnants of historical Galactic supernovae are particularly good targets: contemporaneous observations of the supernovae mean that the age of the remnants is very accurately known, and give clues to the nature of their progenitors. In addition, they are extremely well-studied at all wavelengths. The locations of historical supernovae have therefore been observed with exposures of hundreds or thousands of hours with ground-based gamma-ray observatories and, in most cases, subsequently detected. These include SN 1006 (1006 AD) [2], Tycho's SNR (1572 AD) [3], Kepler's SNR (1604 AD) [4] and the Crab (1054 AD) [5]. In the case of the Crab the bright VHE gamma-ray emission is due to the pulsar wind nebula powered by the Crab pulsar, while for the other objects the emission is much fainter, and is the result of leptonic or hadronic particle acceleration in the supernova remnant shocks. VHE emission has also been discovered from Cassiopeia A [6] the remnant of a supernova which likely occurred in the mid-1600's, although no definitive historical observations of this event exist.

Absent from this list is the remnant of SN 1181, a historical supernova which was clearly described in contemporaneous Chinese and Japanese records. The supernova was visible as a "Guest Star" in the sky for 185 days, from 1181 August 6 to 1182 February 6, with no indication of motion on the celestial sphere. Modern-day searches initially identified 3C 58 as a possible counterpart [7]. 3C 58 is a bright pulsar wind nebula powered by a pulsar (PSR J0205+6449) with extremely high spin-down power (5% of the Crab). Gamma-ray observations focused on this object, eventually leading to a detection by MAGIC of a VHE gamma-ray source with a flux of just 0.65% of the Crab Nebula [8]. However, more recent studies suggest that the age of 3C 58 lies in a range from 2400 − 7000 years [9], significantly older than the expected age of $\sim$ 850 years for SN 1181.

Further re-evaluation now prefers an alternative counterpart to SN 1181 known as Pa 30. This object was first discovered by an amateur astronomer in 2013, in a search for planetary nebula candidates in WISE data [10]. Figure 1 shows a recent optical image of the nebula in the red [S II] band illustrating its extraordinary filamentary structure, with radial lines of emission converging on a hot central star [11]. The location of Pa 30 is shown on the left of figure 2, along with revised constraints on the position of SN 1181 from historical records [12]. 3C 58 is excluded as the counterpart by these constraints.

At first glance, these results provide a compelling new target for high-energy follow-up observations. However, the remnant displays some unusual features which reduce the likelihood of it being a strong gamma-ray emitter. First among these is the fact that the central star cannot have resulted from a Type II (core collapse) or Type Ia (thermonuclear explosion of a CO white dwarf) supernova. Rather, it is believed to be the product of the merger of two white dwarfs (ONe and/or CO) [13]. These mergers are associated with an unusual class of supernovae known as Type Iax, which are characterized by low ejecta velocity and low luminosity [14]. Nevertheless, as only the fifth Galactic supernova remnant for which we know the age and supernova class, Pa 30 is worthy of study across the entire spectrum. This motivates the VERITAS observations described in these proceedings.

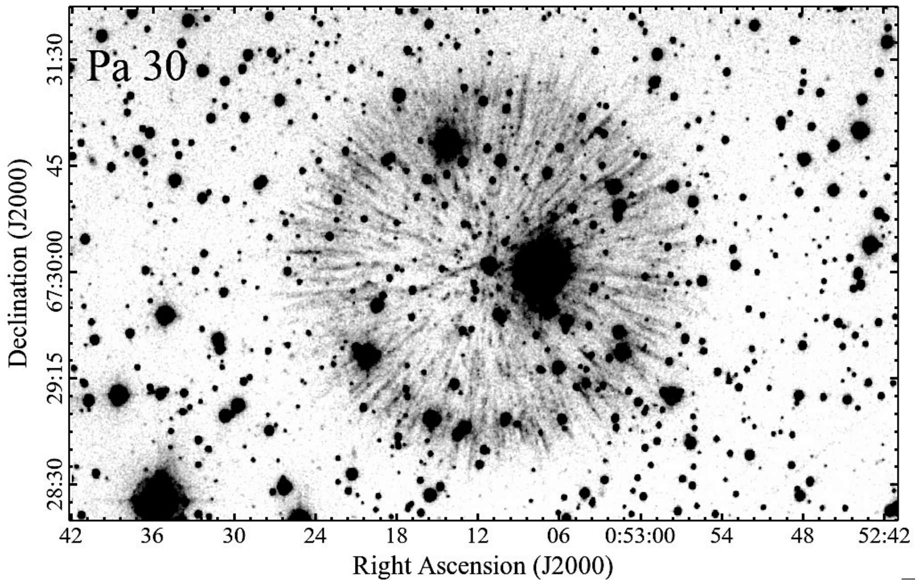

Figure 1: Red [S II] image of Pa 30. Figure from [11].

2. Observations and Analysis

VERITAS is an array of four, 12-m aperture imaging atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona. Now approaching its 20th year of operations, the array is still among the most sensitive facilities for gamma-ray astronomy in the VHE region. Observations of Pa 30 with VERITAS were conducted in *wobble* mode between 2024 September 30 and 2025 January 2, with the source offset by 0.5° from the camera center. 20 hours of good weather observations were collected, leading to a total exposure of 16.3 hours after the removal of data with hardware issues and correction for data acquisition deadtime (12.5%).

The data were analyzed and the results cross-checked using standard VERITAS analysis tools [15, 16] with gamma-ray selection cuts appropriate for a source with a power-law spectral index of -2.5 (but with good sensitivity over a wide range of possible spectral indices). The reflected region method was used to estimate the residual background in the source region after selection cuts [17].

3. Results and Discussion

The VERITAS significance skymap is shown on the right of figure 2. No evidence for emission was found, and the integral upper limit on the photon flux is 6.52×10^{-9} m^{-2} s^{-1} above 500 GeV at 99% confidence (approximately 1% of the Crab Nebula flux at this energy).

We also note that there is no coincident or associated source in the Fermi LAT 14-Year Point Source Catalog (4FGL-DR4 [18, 19]). The closest catalog source is the unassociated object 4FGL J0057.5+6814 at an angular separation of 0.84 ± 0.04° from Pa 30.

We have performed preliminary modeling of the system, adopting the one-dimensional, spherically symmetric framework from [20] to describe the expansion of a Type Ia supernova remnant into a uniform ambient medium. We use the RATPaC code [21] to model the acceleration of cosmic rays

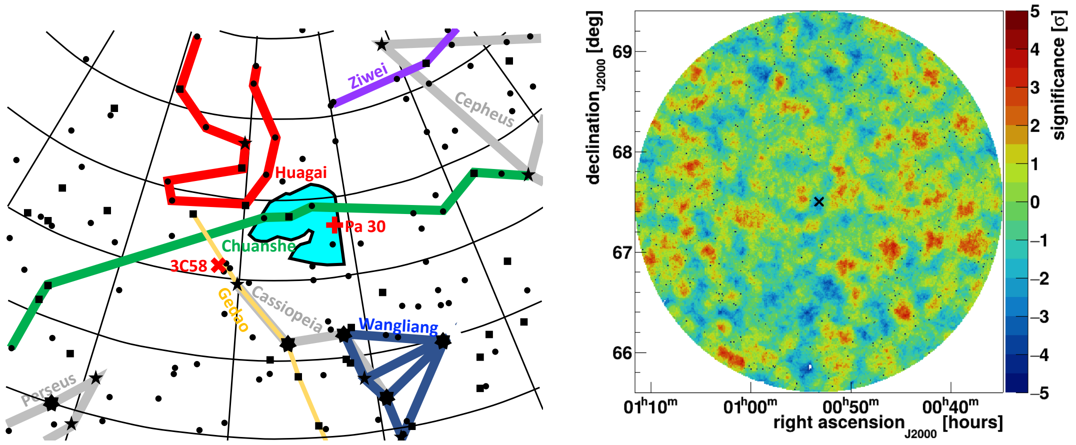

Figure 2: Left: The constraints on the position of SN 1181 from contemporaneous Japanese and Chinese records as shown by the cyan region with black edges (figure from [12]). Thick colored lines show ancient Chinese constellations. The locations of 3C58 and Pa 30 are indicated. **Right:** The VERITAS significance skymap in the region of Pa 30. The location of the 3-arcminute diameter nebula is indicated by the black cross.

in this scenario for three representative Type Iax supernova configurations, each varying in ejecta mass and explosion energy, as shown in table 1. The number density of the ambient interstellar medium is constrained to the low value of 0.1 cm^{-3} by the dynamical model of Ko et al. [22]. Figure 3 shows the predicted inverse Compton and pion-decay fluxes, suggesting that any emission in the gamma-ray band lies far below the sensitivity of VERITAS, or planned facilities such as CTAO. This can be explained as a result of the low Type Iax supernova explosion energy (hence low shock speed), coupled with the low-density ambient medium that gives few cosmic rays and little target material for hadronic interactions.

Model	$M_{\rm ejecta}$(M⊙)	$E_{\rm ejecta}$(erg)	$n_{\rm ISM}$(cm^{-3})
R1	0.1	1.5×10^{48}	0.1
R2	0.6	2.8×10^{48}	0.1
R3	1.0	3.375×10^{48}	0.1

Table 1: Summary of supernova explosion parameters for the three model configurations tested.

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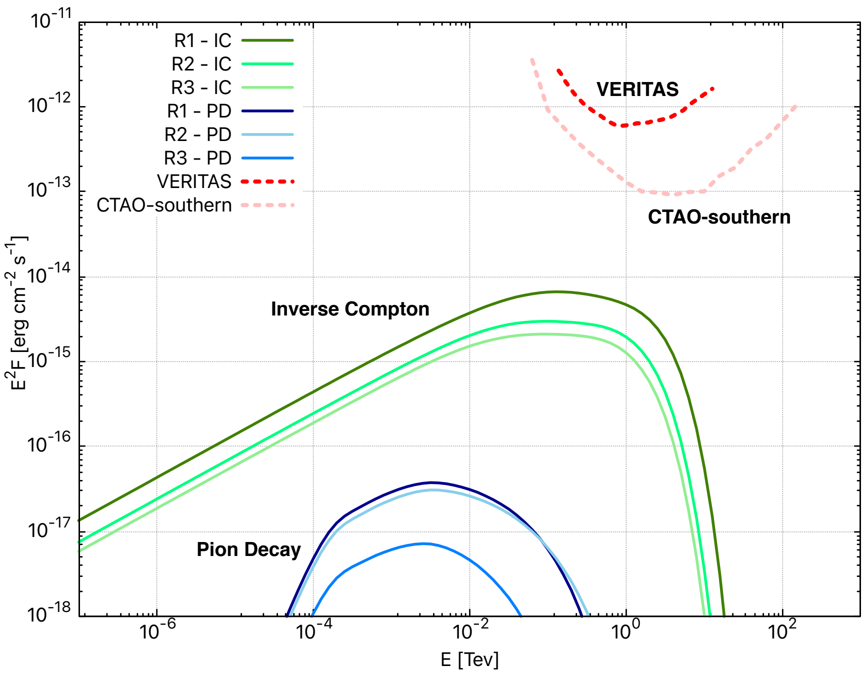

Figure 3: Predicted gamma-ray spectra from pion decay and inverse Compton emission for the three different model configurations. Also shown are the sensitivities of VERITAS and the southern CTAO array.

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