



γ -Ray Emission from Classical Nova V392 Per: Measurements from Fermi and HAWC

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Abstract

This paper reports on the γ -ray properties of the 2018 Galactic nova V392 Per, spanning photon energies ~ 0.1 GeV–100 TeV by combining observations from the Fermi Gamma-ray Space Telescope and the HAWC Observatory. As one of the most rapidly evolving γ -ray signals yet observed for a nova, GeV γ -rays with a power-law spectrum with an index $\Gamma = 2.0 \pm 0.1$ were detected over 8 days following V392 Per's optical maximum. HAWC observations constrain the TeV γ -ray signal during this time and also before and after. We observe no statistically significant evidence of TeV



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γ -ray emission from V392 Per, but present flux limits. Tests disfavor the extension of the Fermi Large Area Telescope spectrum to energies above 5 TeV by 2 standard deviations (95%) or more. We fit V392 Per's GeV γ -rays with hadronic acceleration models, incorporating optical observations, and compare the calculations with HAWC limits.

Unified Astronomy Thesaurus concepts: [Novae \(1127\)](#); [Cataclysmic variable stars \(203\)](#); [White dwarf stars \(1799\)](#); [Gamma-rays \(637\)](#); [Binary stars \(154\)](#)

1. Introduction

A classical nova is an explosion in a binary star, occurring on a white dwarf that has accreted mass from a companion star until enough material has accumulated for a thermonuclear runaway. The subsequent eruption ejects the bulk of the accreted material at a few thousand kilometers per second (Gallagher & Starrfield 1978; Bode & Evans 2008; Chomiuk et al. 2021a). Classical novae have long been observed at optical wavelengths, but in 2010 the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope observed GeV γ -ray emission from the nova eruption of V407 Cyg (Abdo et al. 2010). Although novae had not been expected to produce GeV γ -ray photons (e.g., Chomiuk et al. 2019), Fermi-LAT has since detected γ -rays in the energy range of 0.1 to 10 GeV from over a dozen Galactic novae (Ackermann et al. 2014; Cheung et al. 2016; Franckowiak et al. 2018; Chomiuk et al. 2021a; Gordon et al. 2021).

These GeV γ -rays are thought to be the by-product of relativistic particles accelerated by shocks in the nova ejecta (Chomiuk et al. 2021a). In a few systems with evolved companions, the shocks may mark the interaction of the nova ejecta with preexisting circumbinary material (Abdo et al. 2010; Delgado & Hernanz 2019), but in novae with main-sequence star companions, the shocks are thought to be internal to the nova ejecta themselves (Chomiuk et al. 2014; Martin et al. 2018). The γ -rays are surprisingly luminous, weighing in at $\sim 0.1\%-1\%$ of the bolometric luminosity (Metzger et al. 2015). The implication is that the shocks must be very energetic (rivaling the luminosity of the white dwarf) and/or very efficient at producing γ -rays. In addition, Metzger et al. (2016) predict these events could generate photon energies up to 10 TeV, depending on the details of the shocks—although TeV emission has yet to be detected from novae.

This work uses Fermi-LAT to establish the GeV γ -ray properties of the 2018 nova V392 Per, and then uses archival data from the High-altitude Water Cherenkov (HAWC) Observatory to see whether this classical nova also produces TeV γ -rays. V392 Per before its 2018 classical nova outburst was known as a 17th (apparent) magnitude dwarf nova discovered in 1970 that had occasional outbursts of up to 3 mag (Darnley & Starrfield 2018). The system has a short 3.2 day period (Schaefer 2021). Although uncommon for dwarf novae, in 2018 V392 Per underwent a classical nova eruption, its brightness rising by 11 mag ($\approx \times 25,000$).

Two Fermi-LAT-detected novae have previously been examined for photon emission in the TeV band using air Cherenkov telescopes. VERITAS observed V407 Cyg (Aliu et al. 2012) and MAGIC observed the nova V339 Del (Ahnen et al. 2015), both reporting upper limits on TeV flux. Because HAWC is in operation over 95% of the time, HAWC can search for emission before, during, and after the GeV emission peak for any nova in its field of view.

In Section 2, we discuss the sample of novae we considered and our selection process. In Section 3 we present the GeV properties of the V392 Per nova. In Section 4, we discuss

HAWC analysis techniques and present significance maps of the nova eruption of V392 Per. In Section 5, we consider whether the GeV spectrum continues into the TeV region. Section 6 presents our energy-dependent flux limits. Section 7 considers systematic uncertainties of the HAWC results. Section 8 describes modeling of V392 Per, and Section 9 presents our conclusions from the study.

2. Selection of TeV Nova Candidates for Study with HAWC

To study novae most likely to be visible in the TeV band, we focused on sources that had been detected in the GeV γ -ray band with Fermi-LAT. We considered novae detected with $\gtrsim 3\sigma$ significance in their time-integrated LAT light curves, as presented in Table S1 of Chomiuk et al. (2021a).³⁶

The HAWC Observatory is located on the flanks of the Sierra Negra volcano in the state of Puebla, Mexico, at an altitude of 4100 m. HAWC has 300 water tanks, each of which contains four photomultiplier tubes (PMTs), and it covers approximately 22,000 m² (Smith 2015; Albert et al. 2020a). HAWC is located at a latitude of 19°N, and current analyses can handle sources within 45° of the zenith. Requiring some transit time within this range and enough margin to form a map around the nova restricts HAWC's view of the sky to a decl. range of about +61° to -23°. This eliminates all but one of the 10 novae detected by Fermi-LAT between 2015 (when HAWC began operation) and 2019. V392 Per is located within HAWC's sky coverage and had a clear Fermi-LAT detection (Li et al. 2018).

V392 Per was discovered to be in eruption on 2018 April 29 via the optical observations of amateur astronomer Yuji Nakamura (CBAT 2018; Endoh et al. 2018), and was later confirmed to be a Galactic nova by Wagner et al. (2018). V392 Per is located in the Galactic plane, but opposite the Galactic center (R.A. = 70°8390 and decl. = 47°35719 and in Galactic coordinates $l = 157^{\circ}9918$ and $b = 0^{\circ}9022$). This region has no strong TeV-steady sources, which means that for HAWC, background estimation at this location does not require subtraction of other sources. The geometric distance to V392 Per has been estimated by Chomiuk et al. (2021b) to be $3.5^{+0.7}_{-0.5}$ kpc, using Gaia Early Data Release 3 (Prusti et al. 2016; Brown et al. 2021) and the prior suggested by Schaefer (2018). We use this distance in the remainder of the paper.

3. Fermi-LAT Observations of V392 Per

GeV γ -rays were observed from V392 Per on 2018 April 30 at 6σ significance with Fermi-LAT (Li et al. 2018), but no follow-up analysis of the nova's γ -ray behavior has yet been published. Here we analyze the Fermi-LAT light curve and spectral energy distribution (SED) of V392 Per.

We downloaded the LAT data (Pass 8, Release 3, Version 2) with the instrument response functions of P8R3_SOURCE_V2) from the data server at the Fermi Science Support Center

³⁶ See also <https://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html>.

(FSSC). The observations cover the period of 2018 April 30–May 31 (note that there are no usable LAT data available for V392 Per between 2018 April 4 and 30 due to a solar panel issue). For data reduction and analysis, we used `fermitools` (version 1.0.5) with `fermitools-data` (version 0.17).³⁷ For data selection, we used a region of interest 14° on each side, centered on the nova. Events with the class `evclass=128` (i.e., the SOURCE class) and the type `evtype=3` (i.e., reconstructed tracks FRONT and BACK) were selected. We excluded events with zenith angles larger than 90° to avoid contamination from the Earth's limb. The selected events also had to have been taken during good time intervals, which fulfills the `gtmktime` filter (`DATA_QUAL>0`) $\&\&$ (`LAT_CONFIG == 1`).

Next, we performed binned likelihood analysis on the selected LAT data. A γ -ray emission model for the whole region of interest was built using all of the 4FGL cataloged sources located within 20° of the nova (Abdollahi et al. 2020). Since V392 Per is the dominant γ -ray source within 5° of the field, we fixed all the spectral parameters of the nearby sources to the 4FGL cataloged values for simplicity. In addition, the Galactic diffuse emission and the extragalactic isotropic diffuse emission were included by using the Pass 8 background models `gll_iem_v07.fits` and `iso_P8R3_SOURCE_V2_v1.txt`, respectively, of which the normalizations were allowed to vary during the fitting process. The spectral model of V392 Per was assumed to be a simple power-law (PL) model:

$$\frac{dN}{dE} \propto E^{-\Gamma}. \quad (1)$$

A preliminary light curve was first extracted with a spectral index $\Gamma = 2$ (fixed) to investigate the γ -ray active interval. Using a $>2\sigma$ detection significance as a threshold (i.e., $TS = 2 \ln(L_{s+b}/L_b) > 4$, where L is the Poisson likelihood function), we define the γ -ray active phase as 8 days starting from 2018 April 30 (MJD 58,238) to May 8 (MJD 58,246). A stacked analysis in this period gives a detection significance of 11.6σ (i.e., $TS = 133$). The average γ -ray flux integrated over 100 MeV–100 GeV over the Fermi-LAT detection period is $(2.30 \pm 0.42) \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}$ or $(2.19 \pm 0.41) \times 10^{-7} \text{ photons s}^{-1} \text{ cm}^{-2}$. A PL fit to the SED yields a best-fit photon index of $\Gamma = 2.0 \pm 0.1$ (coincidentally the same as the initially assumed $\Gamma = 2$) and normalization $F_\nu = (2.23 \pm 0.58) \times 10^{-9} \text{ photons s}^{-1} \text{ cm}^{-2} \text{ MeV}^{-1}$ at 100 MeV. The GeV γ -ray spectral energy distribution (SED) of V392Per is plotted in Figure 1. The updated spectral model was then used to rebuild the Fermi-LAT light curve of V392 Per, which is plotted in Figure 2. Due to the limited data quality, we did not test other more complicated spectral models in the analysis (e.g., a PL with an exponential cutoff).

4. HAWC Data Reduction and Analysis

4.1. Data Reduction

HAWC is sensitive to γ -rays with energy above 300 GeV. Based on the timing and locations of the PMTs struck by the shower, we reconstructed the location on the sky of the particle that initiated the shower. For this analysis we used the R.A. and

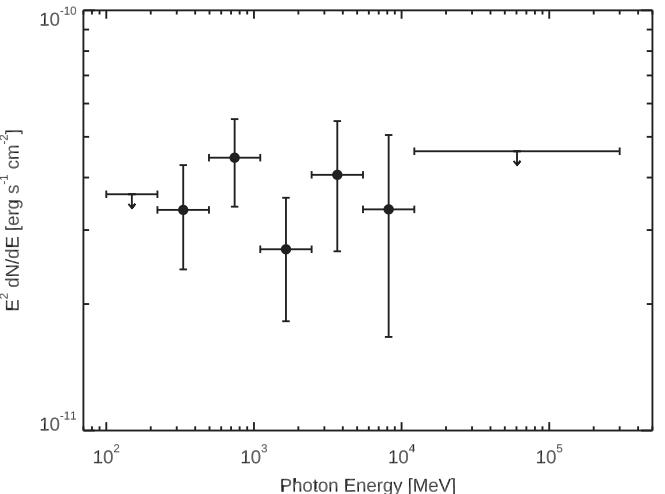


Figure 1. The Fermi-LAT SED for V392 Per. Upper limits in the lowest- and highest-energy bins signify 95% confidence limits (CLs).

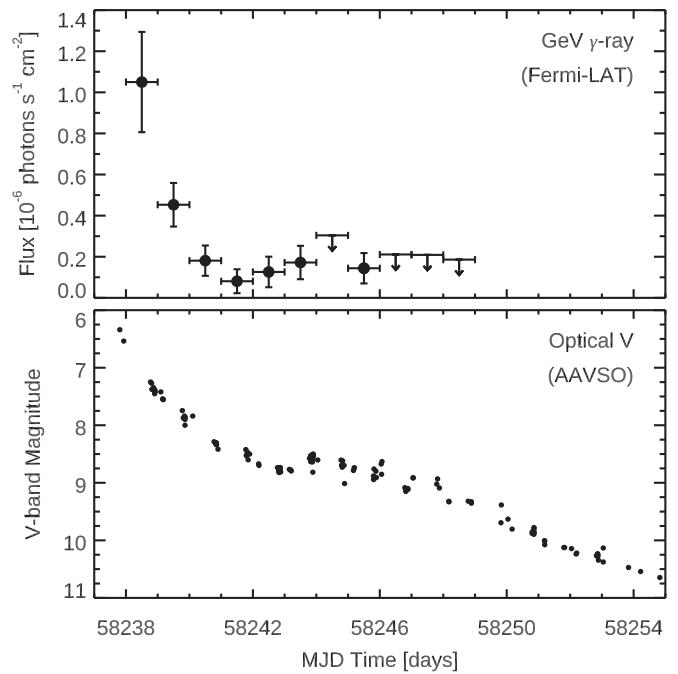


Figure 2. Top: the Fermi-LAT light curve for V392 Per. Photon flux is calculated over the energy range 0.1–300 GeV. The upper limits plotted are 95% CLs. Bottom: the optical V -band light curve of V392 Per over the same window of time as measured by the American Association of Variable Star Observers (AAVSO).

decl. for the J2000 epoch (Albert et al. 2020b). A key parameter for this analysis is `fHit`, the fraction of PMTs that are struck during the shower event. This quantity can be used to parameterize the angular resolution and the γ -hadron selection criteria, and is sensitive to the energy of the initiating particle as described in Albert et al. (2020b) and Abeysekara et al. (2017a, 2017b).

In the remainder of this section, we show the statistical significance of the HAWC observations, and report the best-fit flux and CLs assuming unbroken PLs. In Section 5 we set limits on the maximum (TeV) energy to which the Fermi-LAT SED could extend and be compatible with HAWC data; this method is applied to the nova for the first time, to our knowledge. In Section 6 we provide HAWC limits in different

³⁷ <https://fermi.gsfc.nasa.gov/ssc/data/analysis/software> and https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html.

bins of true energy, without imposing the assumption of an unbroken PL as the SED shape; this method is new, to the best of our knowledge. In Section 7 we assess systematic uncertainties on the HAWC limits.

4.2. Results Assuming Simple PLs: Significance Maps, Best Fits, and Limits

The time frame chosen for the main HAWC investigation of V392 Per covers 40 days, beginning 7 days before the optical discovery of the nova.

For each day of the observation, we made a significance map of the region of interest for each of the nine bins of fHit as described in Albert et al. (2020b). Throughout this paper, we measure significance in units of standard deviations (σ). The same shocks that produce GeV γ -rays are also generally expected to be the source of any TeV radiation, so we analyzed HAWC data assuming the same $\Gamma = 2.0$ PL index as observed for the Fermi-LAT data.

We defined three periods within this time range. The “On” period covers 7 days starting from 2018 April 30 (MJD 58,238 to 58,245), the same as the Fermi-LAT 8 day active period excluding the last day, when we had power issues at the HAWC site. The “Before” period is 7 days starting from 2018 April 23 (MJD 58,231 to 58,238), before the “On” period. This includes 1 day of optical activity during which Fermi-LAT was not observing due to a solar panel problem. The “After” period is 7 days after the end of the “On” period, starting on 2018 May 8 (MJD 58,246 to 58,253). In addition, we defined a 7 day “On – 1 yr” period on the same days as the “On” period, but a year before V392 Per’s eruption, in order to represent a period when no signal is expected.

For each period, we performed forward-folded fits of a $\Gamma = 2.0$ PL spectral model to the nine HAWC pixel-level data maps for each fHit bin, centered at the V392 Per location as in Albert et al. (2020b). Throughout the rest of the paper we report best-fit values for the SED point at $E = 1$ TeV ($S = E^2 dN/dE$), its uncertainty (dS), or the corresponding 95% upper CL (S_{95}); all are in units of $\text{erg s}^{-1} \text{cm}^{-2}$. Results are for the “On” period whenever no specific period is given. We used the method described in Albert et al. (2018) for setting 95% CLs. The SED points and SED 95% CL values in this paper were calculated using the HAL³⁸ (HAWC Accelerated Likelihood) plugin (Younk et al. 2016; Abeysekara et al. 2021) to the 3ML multimission analysis framework (Vianello et al. 2016).

We also calculated the statistical significance of the normalization of the $\Gamma = 2.0$ PL SED compared to zero TeV emission. A significance map is this calculation as a function of sky position. Figure 3 shows the significance map during the “On” period contemporaneous with the Fermi-LAT GeV detection. There is a mild excess of 1.6σ significance near the nova location.

Figure 4 shows the significance at the nova position for each day during the study period, with the “On” period indicated by the black lines. Some transits are missing when electrical storms or power outages interfered with HAWC data taking.

Table 1 shows the limits from a HAWC SED fit and the resulting significance for a $\Gamma = 2.0$ PL spectral model for all the

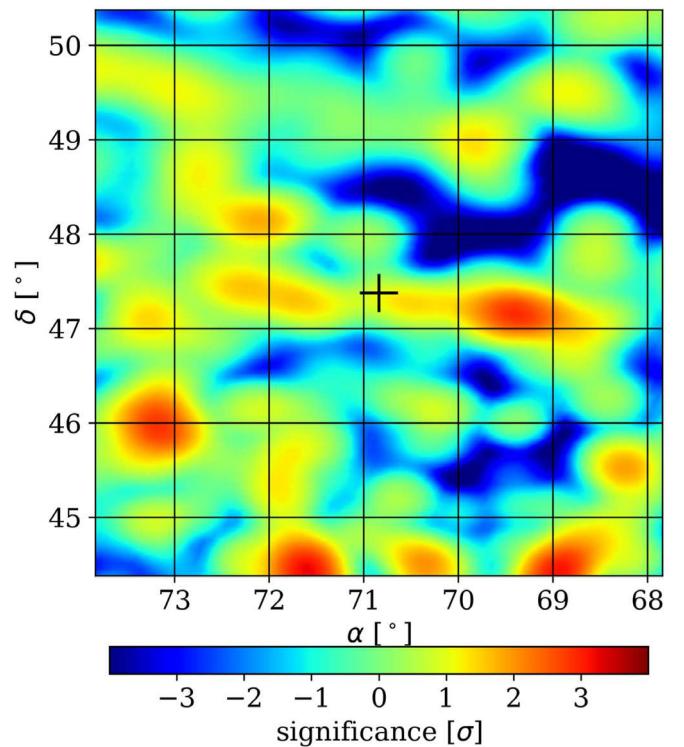


Figure 3. HAWC significance map of V392 Per during the week of Fermi-LAT detection (i.e., the “On” period). The position of the nova is indicated by a cross. HAWC pointing at this decl. is accurate to better than $0^{\circ}1$.

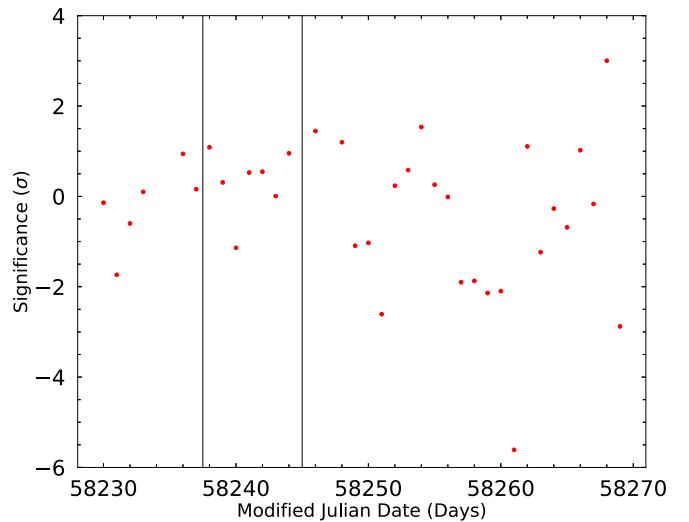


Figure 4. Daily significance of V392 Per from 2018 April 22 to May 31 in HAWC data, assuming a $\Gamma = 2.0$ PL spectrum. The vertical lines bound the “On” period of observation, coincident with the Fermi-LAT GeV detection.

time periods, as well as the best Fermi-LAT SED fit. While there is a weak 1.6σ suggestion of TeV emission during the “On” period, and an even weaker hint during the “After” period, the best-fit HAWC flux and 95% upper limit on the flux are far less than would be expected for a continuation into the HAWC TeV regime of the $\Gamma = 2.0$ PL seen by Fermi-LAT in the GeV regime.

Next we considered the effect of changing the PL index. Figure 5 shows the SEDs corresponding to the S_{95} limit for various PL indices. Also shown is the best fit to the Fermi-LAT flux assuming an unbroken PL extending to very high energies.

³⁸ https://threeml.readthedocs.io/en/latest/notebooks/hal_example.html (threeml hal_example).

Table 1

Best-fit SED Point at 1 TeV, Its Uncertainty, and the 95% Upper Limit on the SED Point and Data Significance

	S	dS	S_{95}	Z_0
“On”	1.2	1.1	3.9	1.6
“Before”	−1.9	1.1	1.4	−1.7
“After”	0.5	1.2	2.7	0.5
“On − 1 yr”	−0.1	0.7	1.4	−0.2
Fermi-LAT	35	10	...	11.6

Note. S is the best-fit SED point at 1 TeV in units of 10^{-12} erg s $^{-1}$ cm $^{-2}$, dS is its uncertainty, and S_{95} is the 95% upper limit on the SED point. Also shown is Z_0 , the statistical significance of the observation in standard deviations. Negative best-fit fluxes occur half the time when no real source exists. We also show for comparison the results of the Fermi-LAT SED fit in the GeV range described in Section 3.

Softer PLs (larger indices) produce less restrictive limits at low energy. The upper envelope of the lines in Figure 5 can be thought of as an SED limit as a function of energy, independent of the actual value of the PL index—at least within the family of PL spectrum shapes (Surajbali 2021). All the limits are statistical only; we discuss systematic uncertainties in Section 7.

5. Hypothesis Tests for Maximum TeV-detected Energy

We now quantify the level at which a Fermi-LAT SED extension to TeV energies is disfavored by the HAWC data. In the null hypothesis H_0 , we constrain the PL normalization to that found by Fermi-LAT. For the alternative hypothesis H_1 we take the normalization from a best fit to the HAWC data. In a series of hypothesis tests, we use a $\Gamma = 2.0$ PL spectrum model with a step function cutoff at some maximum energy. While this spectrum ends too abruptly to describe an actual nova spectrum, it allows us to consider the evidence against having observed TeV photons from V392 Per above a given energy.

We calculate the significance (in standard deviations) of the disagreement of observed HAWC data flux with the Fermi-LAT SED extended to the cutoff energy by

$$Z_F = (S_F - S) / dS_F, \quad (2)$$

where S_F is the Fermi-LAT flux from the last row of Table 1, S is the best-fit HAWC flux to the cutoff spectrum, and dS_F is the uncertainty of a measurement of a simulated source with the strength of the Fermi-LAT flux, again for the cutoff hypothesis spectrum. The results are shown in Table 2. We also show Z_0 , the number of standard deviations by which the best-fit flux is favored over no TeV emission at all, and show the best-fit flux value for each assumed cutoff.

The best-fit SED is always more than a factor of 5 below the Fermi-LAT extension SED. The HAWC data reject (by Z_F nearly 3 standard deviations, or more) extension of the 2.0 PL to 10 TeV or higher. Emission below 5 TeV at the extension flux level is not as strongly excluded. This is because HAWC is more sensitive at higher energies, as we will discuss further in the next section. All the truncated spectra fit to HAWC data have a significance (Z_0) less than 2 standard deviations compared to zero flux.

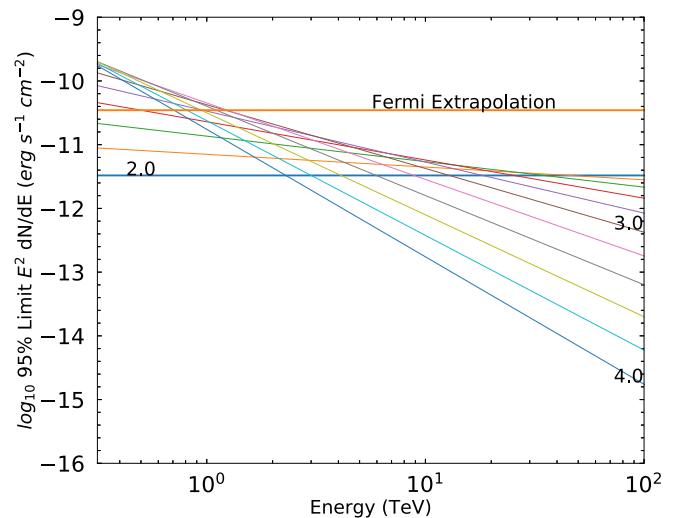


Figure 5. HAWC upper limits on the SED corresponding to S_{95} during the “On” period, when varying the PL index within $\Gamma = 2\text{--}4$ in steps of 0.2 (limits for 2.0, 3.0, and 4.0 are noted specifically). The upper horizontal line, in orange, denotes the Fermi-LAT best-fit SED extrapolated to high energy.

Table 2
Hypothesis Test of a $\Gamma = 2.0$ PL with Various Hard Cutoffs at High Energy

Cutoff E (TeV)	S	Z_0 (σ)	dS_F	Z_F (σ)
5	4.1	0.3	10.4	1.7
10	6.5	1.0	5.2	2.8
15	6.0	1.4	4.2	3.7

Note. The flux translated into an SED point (S) is the best fit of a $\Gamma = 2.0$ PL with the specified cutoff energy to the HAWC data, in units of 10^{-12} erg s $^{-1}$ cm $^{-2}$; in the same units, dS_F is the uncertainty of a fit to an injected source with the Fermi-LAT flux S_F (35 in these units, taken from Table 1). Z_0 is the significance of the HAWC flux (compared to zero flux). Z_F represents the significance by which the HAWC best-fit SED differs from an extension of the Fermi-LAT GeV SED to the cutoff energy.

6. TeV Flux Limits as a Function of Photon Energy

6.1. HAWC Flux Limits in Energy Bins

We now present limits in bins of energy, assuming a $\Gamma = 2.0$ PL index within each energy bin. In Figure 6 we show the Fermi-LAT SED for V392 Per and the S_{95} HAWC upper limits. This analysis uses maps binned in fHit, and its energy resolution effects are reasonably matched by half-decade energy bins (e.g., 1–3.16 TeV, 3.16–10 TeV, etc.). HAWC energy estimators could provide better resolution at higher energy, but the additional event selection criteria would reduce sensitivity to a transient source such as a nova.

The method used to find limits in true energy bins, using data consisting of maps binned in fHit, is as follows. First, we perform a forward-folded fit of the energy spectrum assumed, a point-source model, and the detector response including the point-spread function to the set of data maps for only the normalization \hat{k} of a PL of the form E^{-2} , where E is in TeV. Then for each true energy bin j we perform a second fit for the normalization k_j of the $\Gamma = 2.0$ PL, but with the contribution of energy bin j removed from the original unrestricted PL, in a way that retains the best-fit contributions of all other energy bins as determined by \hat{k} from the original fit. Specifically, we fit

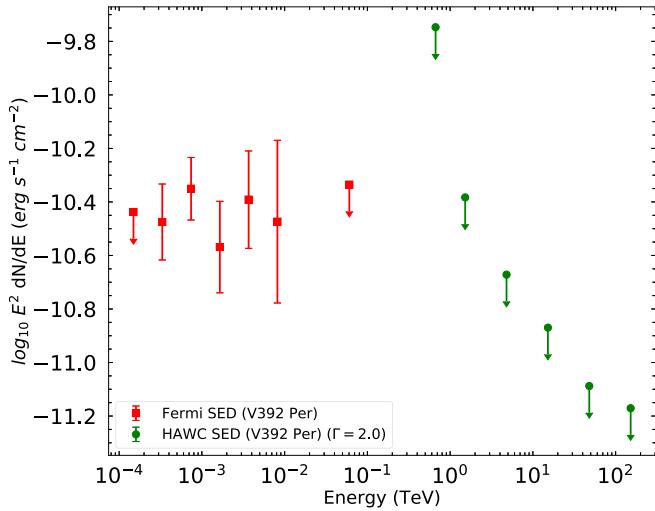


Figure 6. The γ -ray SED of V392 Per, based on the Fermi-LAT detections and HAWC 95% upper limits. $\Gamma = 2.0$ refers to a local PL assumed within a HAWC energy bin in the limit calculation.

to the data the form

$$dN/dE = \hat{k} [E^{-2} - \text{bin}(E, j) E^{-2}] + k_j \text{bin}(E, j) E^{-2} \quad (3)$$

where $\text{bin}(E, j) = 1$ when E falls between the lower and upper edges of energy bin j . Finally, the normalization of the limit is determined by increasing the value of k_j until the fit log-likelihood increases by an amount (2.71/2) appropriate for a 95% CL. This method allows us to report a limit separately in each individual energy bin, without assuming an overall PL SED, as the normalization of each energy bin is determined separately. Because now each energy bin contains less data than the whole of the data, these limits are less restrictive than those in Section 4, where a single unbroken PL is assumed for the underlying SED.

The limit from the lowest-energy HAWC bin is compatible with the continuation of the Fermi-LAT SED, but higher-energy bins are incompatible at the 95% CL. The limit from fitting a single $\Gamma = 2.0$ PL across the full HAWC energy range is considerably more restrictive, placing a 95% upper limit at $E^{2dN/dE} = 4.0 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Figure 5).

We simulate by Monte Carlo the expectations for the energy-dependent limits for each energy bin under the hypothesis of no physical flux (only Poisson fluctuations of the background). The distribution of expected limits is shown in Figure 7. The inner (green) and outer (yellow) bands cover 68% and 95% of the simulated limits, respectively, and the central dashed (red) line shows the median of the expected limits in each energy bin. The observed limits (from Figure 6) are shown here in a black solid line to allow comparison with the expected distribution of limits assuming no flux. The observed limits for bins above 3 TeV are typically 1–2 standard deviations above expectation, consistent with either a modest statistical fluctuation or weak TeV emission.

6.2. Comparison with Other TeV Nova Limits

There have been two previous TeV observations of novae detected by Fermi-LAT. Both observations were made by imaging air Cherenkov telescopes (IACTs). IACTs have better

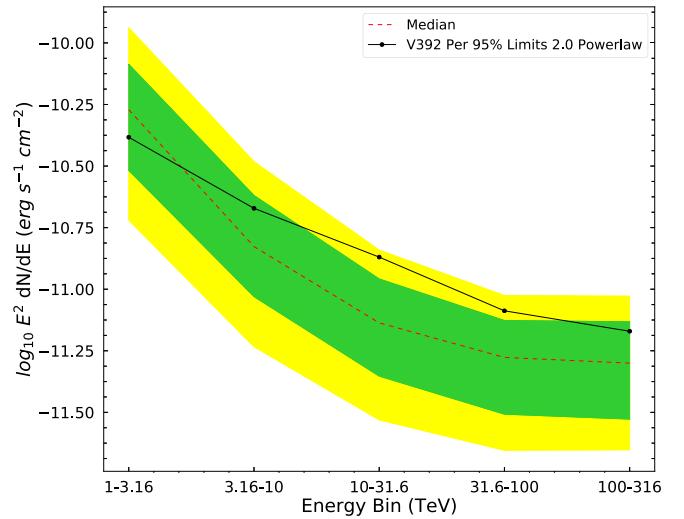


Figure 7. Expected and observed limits vs. energy for V392 Per. The observed limit is in black and the median expected limit is a dashed line in red. The central green band covers 68% of the expected limits (1σ) while the outer yellow bands cover 95% (2σ).

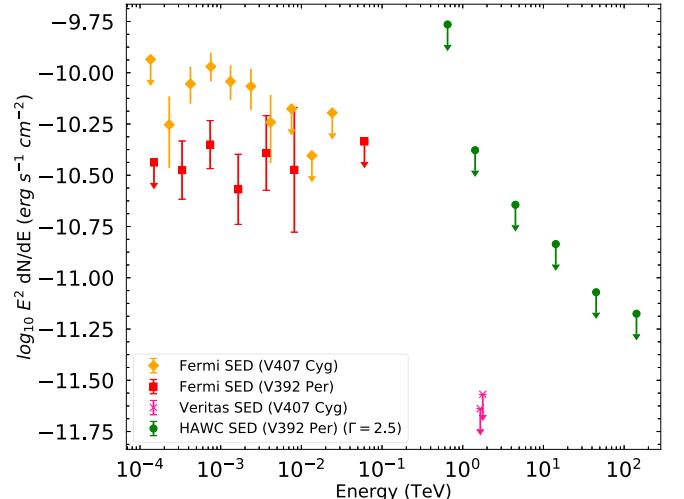


Figure 8. The γ -ray SED of nova V407 Cyg, with Fermi-LAT detections in yellow and VERITAS limits in magenta. Also plotted is the SED for V392 Per, with HAWC limits using the same $\Gamma = 2.5$ PL index as VERITAS.

point-source sensitivity than HAWC, but IACTs can only observe sources that fall into their limited field of view (a few degrees). This typically requires specific pointing, a source visible at night, and good weather. As a result, it is harder for IACTs to observe contemporaneously with a Fermi-LAT observation. In contrast, HAWC observes two-thirds of the sky daily.

The first search for TeV nova emission was conducted by the VERITAS collaboration on V407 Cyg (Aliu et al. 2012). VERITAS began observations 9 days after the beginning of the Fermi-LAT detection, and extended them over a week of continued Fermi-LAT detection. VERITAS was unable to detect significant flux above 0.1 TeV, and set 95% limits as shown in Figure 8. Figure 8 also shows the Fermi-LAT SED reported in Abdo et al. (2010). Because of the curvature of the Fermi-LAT SED, VERITAS analyzed their data with a $\Gamma = 2.5$ PL. The VERITAS limit is quoted at energies of 1.6–1.8 TeV, where the limit and assumed PL are least correlated

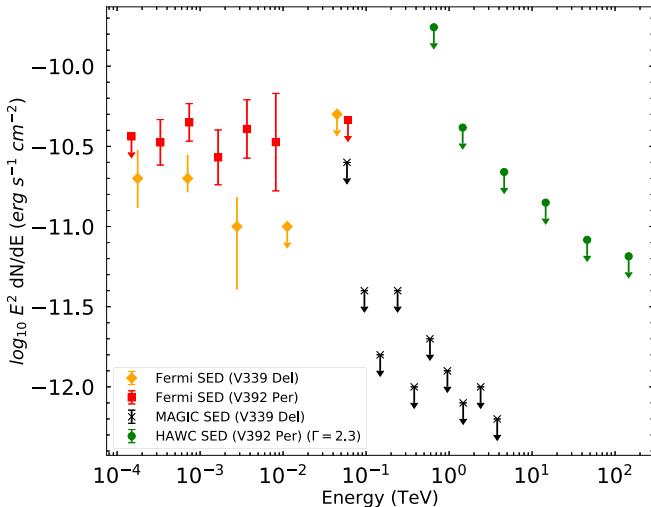


Figure 9. The γ -ray SED of nova V339 Del, with Fermi-LAT detections in yellow and MAGIC limits in black. Superimposed is the SED of V392 Per (red and green), with HAWC limits for V392 Per using the same $\Gamma = 2.3$ PL index as MAGIC.

(depending slightly on which of two analysis methods was used). To roughly compare this with the HAWC sensitivity, the HAWC differential limits on V392 Per are shown, but reanalyzed with the same $\Gamma = 2.5$ PL. These limits are calculated as described above, but instead of $\Gamma = 2.0$, using $\Gamma = 2.5$.

MAGIC searched for TeV emission from V339 Del (Ahn et al. 2015), which is slightly fainter than V392 Per in the GeV band (Ackermann et al. 2014). They found no TeV-detected flux and produced the limits shown in Figure 9. The MAGIC analysis used a $\Gamma = 2.3$ PL index, motivated by a fit to the observed Fermi-LAT SED. Again for rough comparison, we show HAWC’s V392 Per limits analyzed with this $\Gamma = 2.3$ PL. At the overlapping energies, the MAGIC results are about 30 times more constraining than our HAWC limits. It is also worth mentioning that MAGIC was able to observe one night at the beginning of the nova’s GeV γ -ray detection, albeit under poor conditions; that observation produced a flux limit about a factor of 10 worse than those on their best nights of observation 9–12 days later, by which time the GeV γ -ray signal had faded, though not as much as V392 Per had faded by its second week.

Thus, previous IACT nova observations have produced stronger constraints on TeV emission than HAWC, and started from lower energy than HAWC limits. However, they only apply to the period 9 days after the beginning of the optical nova; HAWC’s observations began 2 days after the optical nova, and temporally overlap with the entire period of GeV detection with Fermi-LAT. The HAWC “After” period (days 9–15 of the optical nova) matches the time delay of the VERITAS and MAGIC observations. Table 1 suggests the “After” period places slightly more restrictive limits than the “On” period.

7. Systematic Uncertainties in HAWC Analysis

Here we list the main systematic uncertainties affecting the HAWC results. These uncertainties reflect discrepancies between data and events from the HAWC detector simulation as discussed in Abeysekara et al. (2019) and Albert et al. (2020b). The size of the effects in this analysis will differ from those described in these references, because the analyses

Table 3
Systematic Uncertainties in S_{95} , the 95% CL SED at 1 TeV from a $\Gamma = 2.0$ PL Spectral Model, and Their Combination in Quadrature

Effect	% -Change	% +Change
late light	-2	8
charge	-5	2
threshold	-2	2
response	-5	...
combined	-7	9

undertaken are different. We quantify their effects by the changes in S_{95} at 1 TeV from the $\Gamma = 2.0$ PL spectral model in the “On” period. The size of each effect is given in Table 3; when relevant, we show the possible impact in both a possible increase (+change) or decrease (−change) in S_{95} . We estimate the size of an effect by running our analysis using a plausible alternative detector response and comparing the result with our best-estimate detector response.

Late light. This effect comes from the fact that the laser light used in the calibration system has a narrower time distribution than the arrival of light from air shower events. This is one of the largest sources of uncertainty.

Charge uncertainty. This encapsulates differences in relative photon efficiency among PMTs, and the uncertainty of PMT response to a given amount of Cherenkov radiation.

Threshold uncertainty. The PMT threshold is the lowest charge our PMT electronics can register; despite studies, it is imperfectly known. It is the smallest among the main uncertainties.

Detector response parameterization. The baseline detector response used is the same as that in Albert et al. (2020b). This detector response was simulated for decl. values spaced by 1° , so the best-match decl. is quite close to that of V392 Per. Overall, this is judged to be the best available response file. However, this response was calculated using weighting (within fHit bins, and for parameterization of the point-spread function) for a $\Gamma = 2.63$ PL, while we typically fit a $\Gamma = 2.0$ PL. We consider an alternative detector response calculated with a $\Gamma = 2.0$ PL weighting, but evaluated every 5° of decl. (coarser than ideal as some of our software selects the best decl. match to a source, rather than interpolating). Our estimate of the effect of the uncertainty in detector response is the difference between S_{95} for these two response files, neither of which is ideal.

The systematic uncertainties are summarized in Table 3. Because the effects are independent of each other, we separately combine in quadrature the positive and negative effects. The net result is that our limits carry approximately 8% systematic uncertainty in either direction.

8. Modeling of V392 Per

Before modeling the γ -ray emission from V392 Per we need to understand first the environment surrounding the nova. In Section 8.1.2, optical photometry is used to estimate the bolometric flux of V392 Per as a function of time after the outburst. In Section 8.1.3, we use optical measurements of the $H\alpha$ ($n = 3 \rightarrow n = 2$) line profile to estimate the velocity of the slow and fast flows in the ejecta (and the resulting shock). In Section 8.1.1, we use optical spectra taken 6 days after t_0 , to measure absorption from the interstellar medium along the line of sight, and measure the resulting extinction from the

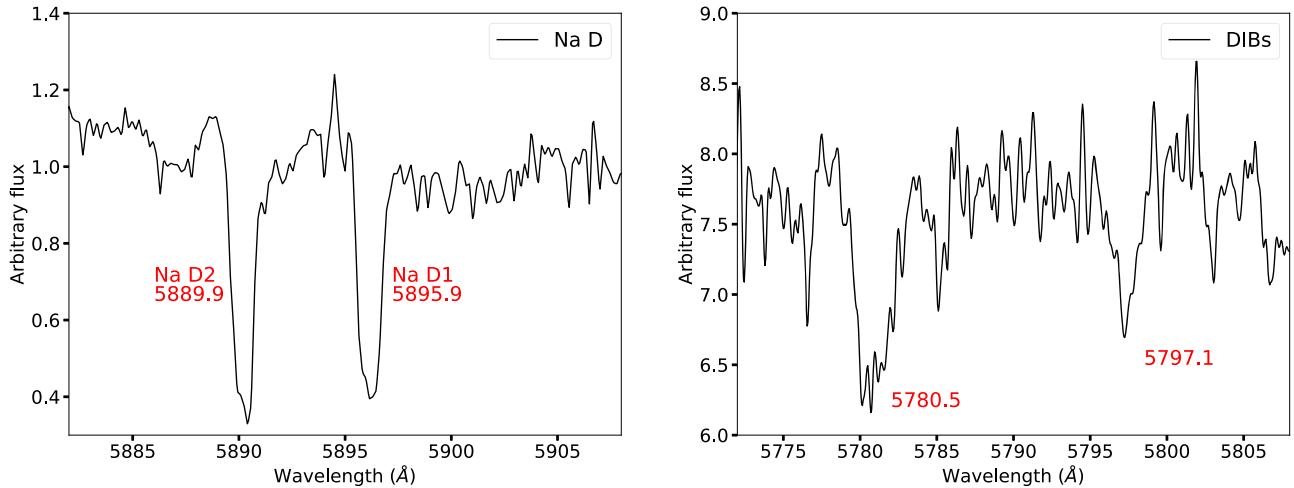


Figure 10. The spectral lines used to estimate the reddening taken 6 days after t_0 . Left: the Na I D interstellar absorption lines at 5895.9 Å (D1) and 5889.9 Å (D2). Right: the diffuse interstellar bands used to estimate the reddening.

associated dust column. The bolometric flux values are corrected for dust extinction, and when they are combined with the Gaia distance measurement, the bolometric luminosity is calculated.

We then describe the γ -ray emission from V392 Per. Collisions among nova ejecta shells, or between the ejecta and an external environment, form shocks that accelerate ions to relativistic energies. These relativistic particles collide with surrounding gas to produce pions, which then decay into γ -ray photons observable by Fermi-LAT and potentially, HAWC. In Section 8.2, we place the GeV properties of V392 Per in the context of other γ -ray detected novae. We next consider our ability to observe TeV photons, as they are limited by absorption due to e^\pm pair creation, which depends on the density of optical photons the TeV photons must pass through (Section 8.3). This radiation density depends on the nova luminosity, the radius of the shock, and the spectral shape of the optical emission. In Section 8.4, the nova's bolometric luminosity and shock velocity are used to estimate the magnetic field in the shock region, which in turn determines the maximum energy of the accelerated particles and hence of their γ -ray emission.

8.1. Optical Input Parameters

The modeling of V392 Per's γ -ray emission requires input parameters derived from optical data. Here we show how we derive these values.

8.1.1. Extinction from Interstellar Dust

To estimate the extinction due to interstellar dust along the line of sight to V392 Per, we rely on several interstellar absorption lines: the Na I D doublet and some diffuse interstellar bands (Figure 10). In this section and in Section 8.1.3, we make use of publicly available spectra from the Astronomical Ring for Access to Spectroscopy (ARAS³⁹; Teyssier 2019). The low- and medium-resolution spectra cover the first month of the optical outburst, starting from the time of optical maximum (day 0). To measure the interstellar lines, we use a high-resolution spectrum from day 6.

Based on the equivalent widths of the Na I D lines and the empirical relations of Poznanski et al. (2012), we derive a reddening value, $E(B - V) = 0.78 \pm 0.04$ mag, for V392 Per. Based on the equivalent width of the two absorption lines at 5780.5 and 5797.1 Å and the empirical relations from Friedman et al. (2011), we derive $E(B - V) = 1.04 \pm 0.05$ mag. This leads to an average reddening value of $E(B - V) = 0.90 \pm 0.18$ mag for V392 Per. For a standard interstellar extinction law ($A_V = 3.1 E(B - V)$; e.g., Mathis 1990), we find a V -band extinction value $A_V = 2.8 \pm 0.5$ mag. This value is consistent with the one derived by Chochol et al. (2021), and we use it in the remainder of the paper.

8.1.2. Bolometric Luminosity

Multiband optical photometry was performed by several observers from the AAVSO (Kafka 2020) from day 0 (2018 April 29; the time of discovery of eruption and also the time of optical maximum) and throughout the optical outburst of V392 Per (see Chochol et al. 2021 for a more detailed description of the light curve). We make use of photometry in the *BVRI* bands to estimate the nova's total (bolometric) luminosity in the few weeks following the nova eruption. Near the optical peak, the optical pseudophotosphere of the nova reaches its maximum radius and the SED is characterized by an effective temperature of 6000–10,000 K, peaking in the *BVRI* bands (e.g., Gallagher & Starrfield 1976; Hachisu & Kato 2004; Bode & Evans 2008).

In order to estimate the bolometric luminosity of the nova as a function of time, we use the `bolometric` task that is part of the SNoPy Python package (Burns et al. 2011). This task directly integrates the flux measured by the *BVRI* photometry (we use `method = 'direct'`), which adds a Rayleigh–Jeans extrapolation in the red (`extrap_red = 'RJ'`), and corrects this SED for extinction from intervening dust (we use $A_V = 2.8$ mag; see Section 8.1.1). We plot the *BVRI* photometry, along with the derived bolometric luminosity, in Figure 11.

8.1.3. Expansion Velocities from Spectral Line Profiles

Figure 12 shows the spectral evolution of H α during the first few days of the eruption of V392 Per. As noted by Wagner et al. (2018) and Chochol et al. (2021), the spectral lines initially show a P Cygni profile with an absorption trough at a

³⁹ http://www.astrosurf.com/aras/Aras_DataBase/Novae.htm

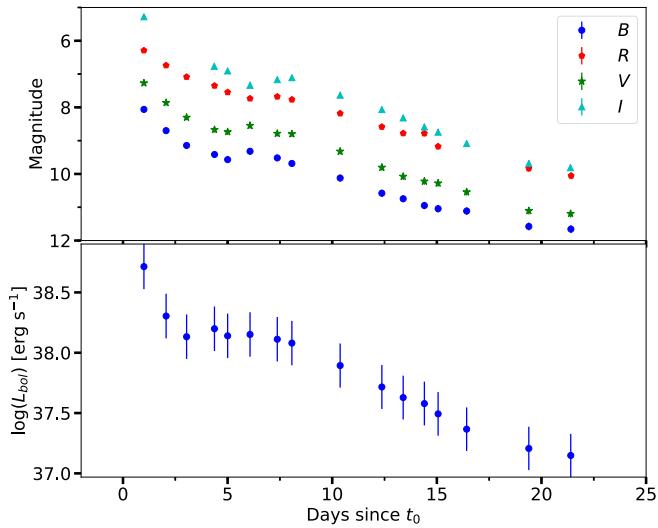


Figure 11. Top: optical light curve of V392 Per, measured in the B , V , R , and I bands by the AAVSO. Bottom: V392 Per’s bolometric luminosity as a function of time, estimated from integrating the optical SED.

blueshifted velocity of around -2700 km s^{-1} (blue line in Figure 12). On day +1, a broader emission component emerges, extending to blueshifted velocities of around -5500 km s^{-1} (green line in Figure 12; see also a zoomed-in view of this profile in the bottom panel of Figure 12). This indicates the presence of two physically distinct outflows: a slow one and a fast one, as described in Aydi et al. (2020b). At this time, there is another absorption component, superimposed on the broad emission, with a velocity of around 3800 km s^{-1} (black line in Figure 12). This component, which appears around the optical peak and has an intermediate velocity between those of the slow and fast components, is the so-called “principal component” as historically classified by McLaughlin (1943) and McLaughlin (1947). Friedjung (1987) and Aydi et al. (2020b) suggest that this intermediate-velocity component is the outcome of the collision between the initial slow flow and the following faster flow, and therefore the velocity of the intermediate component depicts the speed v_{cs} of the cold central shell sandwiched between the forward and reverse shocks (Metzger et al. 2014).

8.2. GeV γ -Ray Behavior of V392 Per

Fermi-LAT detections of V392 Per were only made for 8 days following optical maximum, in one of the shortest-duration and most sharply peaked γ -ray light curve yet observed from a nova (see Figure 8 of Chomiuk et al. 2021a). We note that the turn-on of the γ -rays was not fully captured in V392 Per, as Fermi-LAT was suffering technical problems during its rise to optical maximum, so this duration is a lower limit. However, the true duration is unlikely to be substantially longer than observed, given that Fermi-LAT signals tend to first become detectable around optical maximum (e.g., Ackermann et al. 2014), V392 Per’s observed optical maximum was on 2018 April 29.8 (Chochol et al. 2021), and Fermi-LAT observations resumed on April 30.

The short duration of the Fermi signal in V392 Per is perhaps not surprising, as γ -ray light curves have been observed to correlate and covary with optical light curves in novae (Li et al. 2017; Aydi et al. 2020a), and V392 Per’s optical light curve evolves very quickly (Figure 2). In the top panel of Figure 13,

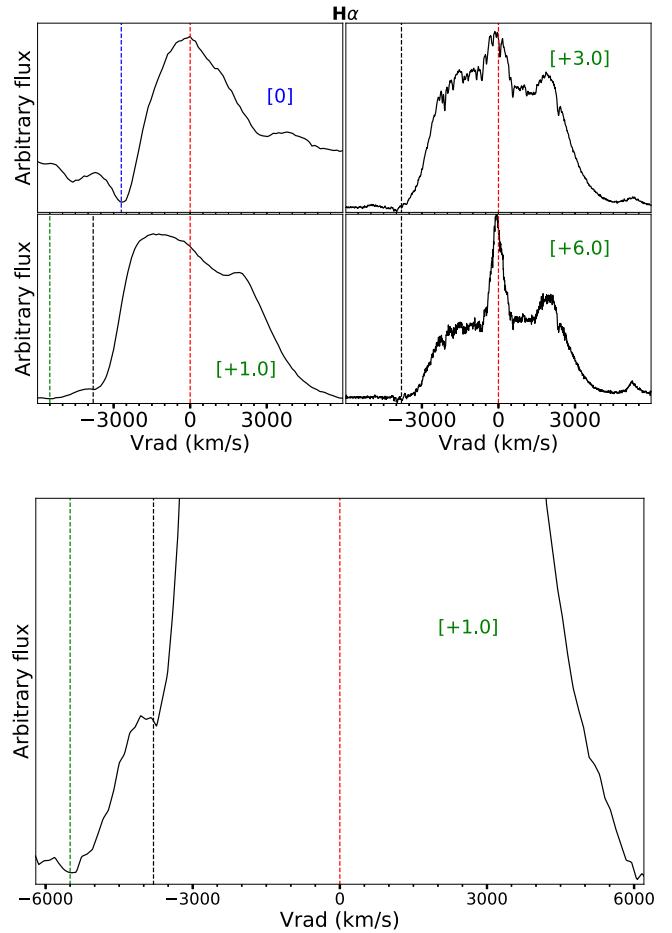


Figure 12. Top: the evolution of V392 Per’s H α line profile near the optical peak. The numbers in brackets represent days relative to the peak. The radial heliocentric velocities are derived relative to the line center, which is marked by a red dashed line. The blue, black, and green dashed lines represent $v_1 = 2700 \text{ km s}^{-1}$, $v_2 = 3800 \text{ km s}^{-1}$, and $v_3 = 5500 \text{ km s}^{-1}$ relative to the line center, respectively. Bottom: a zoomed-in view of the absorption components for the day +1 spectrum.

we compare the duration of Fermi-LAT γ -rays against the time for the optical light curve to decline by 2 mag from maximum (t_2) for the 15 γ -ray detected novae tabulated in Table S1 of Chomiuk et al. (2021a) (see Gordon et al. 2021 for associated t_2 values). We see that novae that are slower to decline from optical maximum generally remain γ -ray bright for longer. A Spearman rank correlation test gives $p = 0.0002$ (for a one-tailed test), indicating a significant correlation between the γ -ray duration and the optical decline time. With $t_2 = 5.9$ days, V392 Per has one of the fastest-evolving optical light curves and a similarly rapid γ -ray light curve to match.

During its Fermi-LAT detection, the GeV γ -ray luminosity of V392 Per was on average $5 \times 10^{35} \text{ erg s}^{-1}$. Such a luminosity is typical among γ -ray detected novae, which show variations in Fermi-LAT luminosity of >2 orders of magnitude (see Figure S1 of Chomiuk et al. 2021a along with Franckowiak et al. 2018). The average γ -ray luminosity but short duration of V392 Per motivated us to plot γ -ray duration against total energy emitted in the Fermi-LAT band in the bottom panel of Figure 13, comparing V392 Per (in red) with data on 14 other Fermi-detected novae (Chomiuk et al. 2021a). Based on Fermi-LAT light curves of five novae, Cheung et al. (2016) found a tentative anticorrelation between these

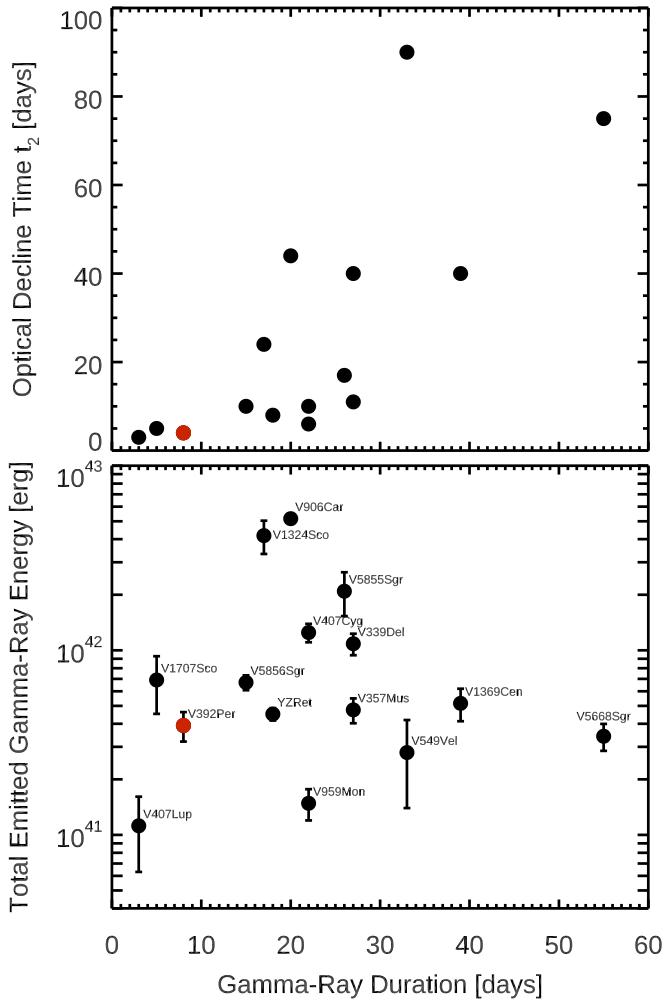


Figure 13. Top: for each of the 15 γ -ray detected novae, the duration over which Fermi-LAT achieved $>2\sigma$ detections is plotted against the time for the optical light curve to decline by 2 mag from maximum (t_2). Bottom: γ -Ray duration plotted against the total energy emitted during this time integrated over the LAT bandpass. In both panels, V392 Per is plotted as a red point.

properties, with the counterintuitive implication that novae that remain γ -ray bright for longer emit less total energy in the Fermi-LAT band. Figure 13 revisits this claimed anticorrelation with three times the number of Fermi-detected novae, and we find that it no longer holds; there are many novae with relatively short γ -ray duration and relatively low total γ -ray energy, V392 Per among them.

8.3. γ -Ray Attenuation in V392 Per

Before addressing the implications of the TeV non-detections by HAWC, we must ask whether such emission could even in principle be detected, due to absorption processes that occur close to the emission site at the shock. Of particular importance at TeV energies is attenuation due to pair creation, $\gamma - \gamma \rightarrow e^- + e^+$, on the background radiation provided by the optical light of the nova. In contrast, at the GeV energies that Fermi-LAT is sensitive to, pair creation would require X-ray target photons. Attenuation is therefore less important in the GeV range than in the TeV range, because the X-ray luminosity (and photon number density) of novae is low compared to the optical/UV luminosity during the early phases of nova eruptions when γ -ray emission is observed.

Other forms of γ -ray opacity, such as photonuclear absorption (the Bethe–Heitler process), are comparatively less important than the $\gamma\gamma$ opacity. In particular, the Bethe–Heitler opacity increases slowly with photon energy, being only ~ 3 times larger at 100 TeV than at 1 GeV (Chodorowski et al. 1992); hence, if the Bethe–Heitler optical depth through the nova ejecta is low enough to permit the escape of γ -rays detectable by Fermi-LAT, then it is unlikely to impede the escape of photons in the HAWC energy range across the same epoch, particularly considering that the optical depth of the expanding ejecta is expected to decrease rapidly with time.

Figure 14 shows the optical depth, $\tau_{\gamma\gamma}$, as a function of time since the nova eruption, for a photon leaving the vicinity of the shock at a radius $R_{\text{cs}} = v_{\text{cs}}t$, where $v_{\text{cs}} \approx 3800 \text{ km s}^{-1}$ is the intermediate-component velocity estimated from the optical spectrum, thought to trace the shock’s cold central shell (see Section 8.1) and hence the location of forward and reverse shocks. In calculating the value of $\tau_{\gamma\gamma}$, we have made use of the energy density of the optical/near-infrared radiation field,

$$u_{\gamma} = \frac{L_{\text{bol}}}{4\pi R_{\text{cs}}^2 c}, \quad (4)$$

estimated from V392 Per’s bolometric light curve $L_{\text{bol}}(t)$ (Figure 11). We separately consider the cases of the optical/infrared (IR) SED having the form of a blackbody at temperature $T_{\text{eff}} \approx 8000 \text{ K}$ (top panel of Figure 14) and that of free–free (bremsstrahlung) emission also at temperature $T_{\text{eff}} \approx 8000 \text{ K}$ (bottom panel of Figure 14). For the effective temperature we avoid using the optical colors to derive a blackbody temperature, given that these colors are heavily affected by the emission line’s evolution, and would give an overestimate of the relevant temperature. These two cases (blackbody and free–free) roughly bracket the physically expected range of optical spectral shapes, given the lack of available near-IR observations of V392 Per to provide additional guidance. For example, Kato & Hachisu (2005) argue that the nova emission can be dominated by blackbody emission at early times (during the so-called fireball phase) and later transition to being dominated by free–free emission from a wind or expanding ejecta shell.

The optical depth for TeV photons is computed as

$$\tau_{\gamma\gamma}(x) = R_{\text{cs}} \int_{1/x} \sigma_{\gamma\gamma}(x, y) \frac{dN_{\text{ph}}}{dydV} dy, \quad (5)$$

where $x = h\nu/m_e c^2$ and $y = h\nu_{\text{opt}}/m_e c^2$ are the dimensionless energies of the high-energy and optical (target) photons, respectively, and $\sigma_{\gamma\gamma}$ is the angle-averaged pair production cross section (e.g., Zdziarski 1988). The target photon spectrum is normalized to the total radiation energy density given by Equation (4),

$$u_{\gamma} = \int \frac{dN_{\text{ph}}}{dydV} m_e c^2 y dy. \quad (6)$$

The shape of the target spectrum follows $dN_{\text{ph}}/(dydV) \propto y^2/[\exp(m_e c^2 y/kT_{\text{eff}}) - 1]$ for a blackbody (Figure 14, upper panel) or $dN_{\text{ph}}/(dydV) \propto y^{-1} \exp(-m_e c^2 y/kT_{\text{eff}})$ for an optically thin bremsstrahlung spectrum (Figure 14, lower panel). It is worth noting that at identical energy densities, the blackbody spectrum places a smaller fraction of target photons at energies

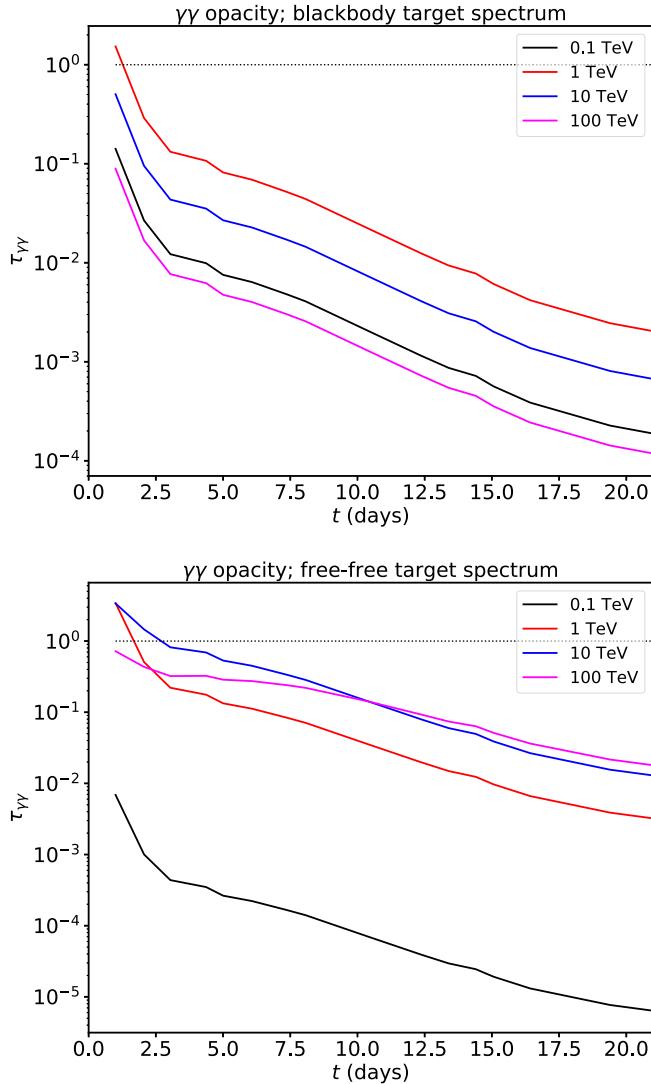


Figure 14. Optical depth in the vicinity of the γ -ray generating shock $\tau_{\gamma\gamma}$ as a function of time, with different γ -ray energies shown as lines of different colors as marked. The opacity is due to $\gamma\gamma$ pair creation on the target background radiation of the nova optical light. The results shown in the top panel assume the spectrum of the optical radiation is that of a blackbody at $T_{\text{eff}} \approx 8000$ K, while the bottom panel assumes a free-free emission spectrum of gas at the same temperature (accounting for self-absorption at low frequencies). These two choices roughly bracket the expected level of attenuation for the more realistic but complex optical spectral shape in novae. Epochs when $\tau_{\gamma\gamma} > 1$ may have their γ -ray emission strongly attenuated close to the source, where $\tau_{\gamma\gamma} = 1$ is given by the dotted line.

$h\nu_{\text{opt}} < kT_{\text{eff}}$ compared with other plausible physically motivated spectra. As a result, the opacity for photons at $h\nu > (m_e c^2)^2/kT_{\text{eff}} \sim 1$ TeV is comparatively lower in the blackbody case, as those photons preferentially pair-produce on the low-energy tail of the target spectrum. Note also that at $h\nu \gg (m_e c^2)^2/kT_{\text{eff}}$, the $\gamma\gamma$ opacity behaves approximately as $\tau_{\gamma\gamma} \propto T_{\text{eff}}^{-2}$ and $\propto T_{\text{eff}}^{-1}$ in the blackbody and free-free cases, respectively.

In the most conservative case of the free-free target spectrum, we see that $\tau_{\gamma\gamma}$ remains larger than unity for a few days after eruption at energies $\gtrsim 1$ TeV. Meanwhile, $\tau_{\gamma\gamma} \lesssim 1$ at all times in the more optimistic case of a blackbody spectrum. Furthermore, insofar that near the peak of the nova optical light curve the observed emission tends to be dominated by the

optically thick emission from the photosphere instead of optically thin free-free emission (e.g., from a wind above the photosphere; Kato & Hachisu 2005), we favor the interpretation that over most, if not all, of the time of Fermi-LAT detection, V392 Per is transparent to TeV photons. Still, the Fermi-LAT light curve of V392 Per is unusual among γ -ray detected novae for being sharply peaked at early times (Figure 2), and its brightest GeV flux occurs within the first ~ 2 days of eruption; it is possible that TeV photons were attenuated from V392 Per at these earliest times, when the nova was brightest at GeV energies. In the next section, we consider the shock conditions that would produce very high energy photons in V392 Per.

8.4. Constraints on the Highest-energy γ -Rays from Nova Shocks

In this section we use V392 Per bolometric luminosity and ejecta expansion velocity derived from optical data to estimate the maximum energy to which particles could be accelerated and hence the maximum γ -ray energy.

The γ -ray emission from novae is understood as nonthermal emission from relativistic particles accelerated at shocks (e.g., Martin & Dubus 2013; Ackermann et al. 2014), through the process of diffusive shock acceleration (e.g., Blandford & Ostriker 1978). A variety of evidence, from across the electromagnetic spectrum, suggests that the shocks in classical novae are internal to the nova ejecta (e.g., Chomiuk et al. 2014; Aydi et al. 2020a; Chomiuk et al. 2021a), as a fast outflow impacts a slower outflow released earlier in the nova. On the other hand, in symbiotic novae where the companion is a giant star with dense wind, the shocks may occur as the nova ejecta collides with the external wind (e.g., Abdo et al. 2010). V392 Per has an orbital period intermediate between those of cataclysmic variables and symbiotic novae with an atypical radio light curve (Munari et al. 2020; Chomiuk et al. 2021b) and hence the nature of the shock interaction—internal or external—is ambiguous. However, our discussion to follow regarding the particle acceleration properties is relatively unaffected by this distinction.

Physical models for the γ -ray emission divide into “hadronic” and “leptonic” scenarios depending on whether the emitting particles are primarily relativistic ions or electrons. Several independent lines of evidence support the hadronic scenario (Chomiuk et al. 2021a), including (a) the presence of a feature in the γ -ray spectrum near the pion rest mass at 135 MeV (e.g., Li et al. 2017), (b) the nondetection of nonthermal hard X-ray emission by NuSTAR (which should be more prominent in leptonic scenarios; Vurm & Metzger 2018; Nelson et al. 2019; Aydi et al. 2020b), and (c) efficiency limitations on leptonic scenarios due to synchrotron cooling of electrons behind the shock (Li et al. 2017). Motivated thusly, we focus on hadronic scenarios for the γ -rays.

In the hadronic scenario, relativistic ions collide with ambient ions such as protons, producing pions that decay into γ -rays:

$$\begin{aligned} pp \rightarrow \pi^0 &\rightarrow \gamma\gamma \\ \rightarrow \pi^\pm &\rightarrow \mu^\pm \nu_\mu (\bar{\nu}_\mu) \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu). \end{aligned} \quad (7)$$

Here, $\approx 1/3$ and $\approx 2/3$ of the inelastic p-p collisions go through the π^0 and π^\pm channels, respectively (Kelner & Aharonian 2008).

The π^0 channel is expected to dominate the γ -ray luminosity (e.g., Li et al. 2017), but secondary leptons produced via π^\pm decay can also produce γ -rays through bremsstrahlung and inverse Compton processes. A useful rule of thumb is that it requires a proton of energy $10E$ to generate a γ -ray of energy E . Therefore, to produce emission up to the HAWC sensitivity range (~ 1 –100 TeV) requires proton acceleration up to $E_{\max} \gtrsim 10$ –1000 TeV. Can nova shocks accelerate particles up to such high energies?

We consider a shock generated as a fast wind of velocity $v_f \approx v_3 \approx 5500 \text{ km s}^{-1}$ (see Figure 12) collides with a slower outflow of velocity $v_s \approx v_1 \approx 2700 \text{ km s}^{-1}$, generating an internal-shocked shell of velocity $v_{\text{cs}} \simeq \xi v_1$ (where the dimensionless parameter $\xi \lesssim 2$, typically; if $v_{\text{cs}} = v_2 = 3800 \text{ km s}^{-1}$, then $\xi = 1.4$). Recent studies have shown that the values of v_f , v_s , and even v_{cs} may be observed directly in the optical spectra of novae (Aydi et al. 2020b), and we have taken our fiducial values here to match those inferred from V392 Per’s optical spectra (Section 8.1.3).

Insofar as an order-unity fraction of the optical nova light is reprocessed thermal emission by the (radiative) reverse shock (e.g., Li et al. 2017; Aydi et al. 2020a), the nova luminosity is related to the mass-loss rate according to

$$\begin{aligned} L_{\text{bol}}(t) \sim L_{\text{sh}}(t) &\simeq \frac{1}{2} \dot{M}_f v_f^2 \\ &\approx 8 \times 10^{36} \text{ erg s}^{-1} \frac{\dot{M}_f}{10^{-6} M_{\odot} \text{ yr}^{-1}} \left(\frac{v_f}{5500 \text{ km s}^{-1}} \right)^2, \end{aligned} \quad (8)$$

where we assume $v_f \gg v_s$ and treat the fast outflow as a wind of mass-loss rate \dot{M}_f .

In diffusive shock acceleration, as cosmic rays gain greater and greater energy E , they can diffuse back to the shock from a great upstream distance, z , because of their larger gyroradii $r_g = E/eB_{\text{sh}}$, where

$$\begin{aligned} B_{\text{sh}} &\approx (6\pi\epsilon_B m_p n_f v_{\text{cs}}^2)^{1/2} \simeq \left(\frac{3}{2} \frac{\epsilon_B \dot{M}_f}{v_f t^2} \right)^{1/2} \\ &\approx 0.07 \text{ G } \epsilon_{B,-2}^{1/2} \left(\frac{\dot{M}_f}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{1/2} \left(\frac{v_f}{5500 \text{ km s}^{-1}} \right)^{-1/2} \\ &\quad \times \left(\frac{t}{1 \text{ wk}} \right)^{-1} \end{aligned} \quad (9)$$

is the magnetic field behind the reverse shock, for an assumed efficiency of magnetic field amplification $\epsilon_B = \epsilon_{B,-2} \times 10^{-2}$. This is commensurate with the required field amplification to accelerate ions with an efficiency $\sim 1\%$ (Caprioli & Spitkovsky 2014), as inferred through application of the calorimetric technique (Metzger et al. 2015) to correlated γ -ray/optical emission in novae (Li et al. 2017; Aydi et al. 2020a). In the above, we have taken $n_f = \dot{M}_f / (4\pi m_p R_{\text{cs}}^2 v_f)$ for the density of the fast outflow at radius $R_{\text{cs}} = v_{\text{cs}} t$.

The maximum energy to which particles are accelerated before escaping from the vicinity of the shock, E_{\max} , is found by equating the upstream diffusion time $t_{\text{diff}} \sim D/v_{\text{cs}}^2$ to the minimum of various particle loss timescales. These include the downstream advection time $t_{\text{adv}} \sim z_{\text{acc}}/v_{\text{cs}}$, where z_{acc} is the width of the acceleration zone, and (in hadronic scenarios)

the pion creation timescale $t_{\pi} = (n_f \sigma_{\pi} c)^{-1}$, where $\sigma_{\pi} \sim 2 \times 10^{-26} \text{ cm}^2$ is the inelastic cross section for p–p interactions (Kamae et al. 2006). We consider these limiting processes in turn.

Equating $t_{\text{diff}} = t_{\text{adv}}$, and taking $D \approx r_g c / 3$ as the diffusion coefficient (Caprioli & Spitkovsky 2014), one obtains (e.g., Metzger et al. 2016; Fang et al. 2020)

$$\begin{aligned} E_{\max} &\sim \frac{3eB_{\text{sh}} v_{\text{cs}} z_{\text{acc}}}{c} \\ E_{\max} &\approx 340 \text{ TeV} \left(\frac{z_{\text{acc}}}{R_{\text{cs}}} \right) \left(\frac{\xi}{2} \right)^2 \epsilon_{B,-2}^{1/2} \left(\frac{\dot{M}_f}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{1/2} \\ &\quad \times \left(\frac{v_f}{5500 \text{ km s}^{-1}} \right)^{-1/2} \left(\frac{v_s}{2700 \text{ km s}^{-1}} \right)^2 \end{aligned} \quad (10)$$

where $R_{\text{cs}} = v_{\text{cs}} t$ is the radius of the shock.

On the other hand, equating $t_{\text{diff}} = t_{\pi}$, we obtain

$$\begin{aligned} E_{\max} &\sim \frac{3e v_{\text{cs}}^2 B_{\text{sh}}}{c^2 n_f \sigma_{\pi}} \approx 12\pi \frac{m_p}{\sigma_{\pi}} \frac{e}{c^2} \frac{B_{\text{sh}} v_f v_{\text{cs}}^4 t^2}{\dot{M}_f} \\ E_{\max} &\approx 2 \times 10^7 \text{ TeV} \left(\frac{\xi}{2} \right)^4 \epsilon_{B,-2}^{1/2} \left(\frac{\dot{M}_f}{10^{-6} M_{\odot} \text{ yr}^{-1}} \right)^{-1/2} \\ &\quad \times \left(\frac{v_f}{5500 \text{ km s}^{-1}} \right)^{1/2} \left(\frac{v_s}{2700 \text{ km s}^{-1}} \right)^4 \left(\frac{t}{1 \text{ wk}} \right)^2. \end{aligned} \quad (11)$$

The maximum energy is given by the minimum of Equations (10) and (11), which for the system parameters of interest works out to be the former. In particular, taking our fiducial velocity values and $L_{\text{opt}} \sim 10^{37}$ – 10^{38} erg s $^{-1}$ on a timescale of days to weeks (Section 8.1), we see that $\dot{M}_f \lesssim 10^{-5}$ – $10^{-6} M_{\odot} \text{ yr}^{-1}$ (Equation (8)). Thus, from Equation (10) we infer $E_{\max} \lesssim 200$ –600 TeV ($z_{\text{acc}}/R_{\text{cs}}$), in which case we could expect γ -ray energies up to $E_{\gamma,\max} \sim 0.1 E_{\max} \sim 20$ –60 TeV ($z_{\text{acc}}/R_{\text{cs}}$).

If acceleration occurs across a radial scale of the order of the shock radius (i.e., $z_{\text{acc}} \sim R_{\text{cs}}$), our estimated $E_{\gamma,\max} \sim 20$ –60 TeV would appear inconsistent with our constraints on an extension of the measured Fermi-LAT spectrum to energies $\gtrsim 10$ TeV (Section 5). However, various physical effects may reduce the effective extent of the accelerating layer to a width $z_{\text{acc}} \ll R_{\text{cs}}$ (and hence reduce $E_{\gamma,\max}$), such as ion–neutral damping of the Bell (2004) instability (Reville et al. 2007; Metzger et al. 2016) or hydrodynamical thin-shell instabilities of radiative shocks (which corrugate the shock front and alter the effective portion of its surface with the correct orientation relative to the upstream magnetic field to accelerate ions; Steinberg & Metzger 2018). The maximum γ -ray energy generated by the shock could also be lower if the magnetic field amplification factor is less than the fiducial value $\epsilon_B = 0.01$.

9. Conclusions

The only γ -ray detected nova in the HAWC data set used in this study is the 2018 eruption of V392 Per. We present an analysis of the Fermi-LAT observations of its GeV γ -ray signal in Section 3. The Fermi-LAT luminosity and spectral shape of V392 Per are typical compared to other Fermi-detected novae, but the duration of the γ -rays is relatively short. Given this, in Section 8.2 we revisit the claimed anticorrelation between γ -ray duration and total emitted energy in the Fermi-LAT band

(Cheung et al. 2016), and find no such anticorrelation with an improved, larger sample of 15 novae. We do present evidence for a correlation between the duration of the Fermi-LAT signal and the optical decline time t_2 .

HAWC did not detect significant TeV flux in the direction of V392 Per. Therefore, we calculated 95% confidence upper flux limits for this event, and our hypothesis tests disfavor (at 2.8σ significance; see Table 2) an extension of the Fermi-LAT SED to photon energy as high as 10 TeV, and more strongly reject extension to even higher energies. We compared our observations with previous IACT nova studies, and while HAWC is less sensitive, its time agility provides limits during the first week of the GeV emission.

Optical spectroscopy of V392 Per’s eruption provides evidence of shocks internal to the nova ejecta, likely occurring between a fast flow expanding at 5500 km s^{-1} and a slow flow of 2700 km s^{-1} (Section 8.1)—although we cannot rule out the possibility of external shocks with preexisting circumstellar material. Simple models imply that V392 Per’s shocks can accelerate hadrons up to ~ 400 TeV, potentially yielding γ -rays of energies up to ~ 40 TeV (details depend on complexities like ion–neutral damping; see Section 8.4). In Section 8.3, we assess whether very high energy γ -rays will be observable, given that TeV photons are attenuated by pair production on the optical/IR background at early times. For plausible parameters, the nova is expected to be transparent to TeV photons over most of the Fermi-LAT detection time window. The nondetection of TeV photons with HAWC is likely attributable to a combination of attenuation at the earliest times (i.e., around the first day of eruption, when the GeV γ -rays are brightest) and the details of diffusive shock acceleration and magnetic field amplification within nova shocks.

The HAWC analysis software is undergoing an upgrade that promises both better sensitivity at low energy, and an increased field of view. We will apply the new analysis to V392 Per, RS Oph, and several other novae in a future publication.

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