PROCEEDINGS OF SCIENCE

Using Gamma-Rays to Reveal the Evolution of Novae

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In August of 2021, Fermi-LAT, H.E.S.S., and MAGIC detected GeV and TeV gamma-ray emission from an outburst of recurrent nova RS Ophiuchi. This detection represents the first very high energy gamma-rays observed from a nova, opening a new window onto particle acceleration and nova evolution. Both H.E.S.S. and MAGIC described the observed gamma-rays as arising from a single external shock. To better interpret this detection, we perform detailed, multi-zone modeling of RS Ophiuchi's 2021 outburst, including a self-consistent prescription for particle acceleration and magnetic field amplification. We demonstrate that, contrary to previous work, a single shock cannot simultaneously explain RS Ophiuchi's GeV and TeV emission. Instead, we put forward a model involving multiple shocks that reproduces the observed gamma-ray spectrum and temporal evolution. This result demonstrates the importance of modeling that properly accounts for the microphysics of particle acceleration when interpreting gamma-ray observations of novae and other astrophysical shocks.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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1. Introduction

A major discovery by the *Fermi* Large Area Telescope (LAT) was that novae−multi-wavelength transients produced by non-terminal thermonuclear explosions on the surface of white dwarfs accreting hydrogen-rich material from a donor star−are sources of luminous ~GeV (10^9 eV) γ-ray emission (e.g., [1]). In the standard picture, this emission is produced by nonthermal particles (ions or electrons) accelerated by the nova's shock(s).

RS Ophiuchi (RS Oph) is a binary consisting of a red giant (RG) orbiting a white dwarf which has undergone a nova eruption every $\sim 10-20$ years for over the last century [23]. Its most recent eruption, beginning on 2021 Aug 8, was not only detected at high-significance by *Fermi* LAT ([11]), but also at ~TeV (10^{12} eV) energies by the Atmospheric Cherenkov Telescopes H.E.S.S. [3] and MAGIC [2]. This discovery represents the first ever very-high energy (VHE) γ-ray detection of a nova outburst.

Interestingly, the TeV light curve peak in RS Ophiuchi is delayed by several days relative to the peak of the GeV light curve, with the *Fermi* LAT light curve peaking on 2021 Aug 9–10 [11] and the HESS light curve peaking on 2021 Aug 12 ([3]; see their Figure 2). The HESS collaboration interprets the entire GeV-TeV emission in terms of hadronic particle acceleration and emission at a single shock, attributing the observed temporal delay between the peaks at different energies to the finite timescale required to accelerate ions to $\gtrsim$ TeV energies. However, in this proceeding, we show that the γ-rays observed during RS Ophiuchi's 2021 outburst cannot be produced by a single, spherically symmetric shock. Instead, we put forward a scenario involving multiple shocks. These shocks may be generated as the result of distinct velocity components of the nova ejecta interacting with the aspherical external environment. This scenario reproduces key features of the observed γ-rays without ad-hoc modifications to the accelerated particle spectrum.

2. Method

To calculate RS Ophiuchi's expected γ-ray emission we use a multi-zone model of particle acceleration and photon production. A detailed description of this model can be found below.

Shock Hydrodynamics. To estimate shock evolution, we use a self-similar formalism similar to that described in [12]. Namely, we assume that both the material ejected by the nova and the material swept up during expansion are confined to a thin shell behind the shock [see, e.g., 19, for an example of this *thin-shell approximation*]. The evolution of the shock is thus set by the density profile of the ambient medium, chosen to reproduce the γ-ray observations and to be consistent with the presence of a RG wind. More specifically, we model RS Ophiuchi during two stages of evolution: the *ejecta-dominated stage*, in which the mass of swept-up material is less than the ejecta mass and the shock expands freely, and the *Sedov stage*, in which the swept-up mass exceeds the ejecta mass and the nova expands adiabatically.

Our formalism applies to a single, spherical shock. However, as we shall discuss in later section, the γ-ray emission and optical spectra of RS Ophiuchi both suggest the presence of multiple shock components. These shocks may arise due to distinct mass ejection events from the white dwarf, and/or a single ejecta shell interacting with non-spherically symmetric external medium. In the

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latter case, we will in effect be applying the above formalism separately to distinct angular sectors (e.g., the polar versus equatorial region) over which we assume the density is approximately uniform.

Particle Acceleration. We model particle acceleration using a semi-analytic model of nonlinear diffusive shock acceleration that self-consistently accounts for magnetic field amplification and the dynamical back-reaction of accelerated particles on the shock [see 7, 13, 14, and references therein]. We assume that protons with momenta above $p_{\rm inj} \equiv \xi_{\rm inj} p_{\rm th}$ are injected into the acceleration process, where $p_{\rm th}$ is the thermal momentum and we choose $\xi_{\rm inj}$ to produce CR pressure fractions $\sim 10\%$. We also calculate the proton maximum energy self-consistently by requiring that the diffusion length (assuming Bohm diffusion) of the most energetic particles accelerated be equal to 5% of the shock radius.

This model produces an instantaneous distribution of protons accelerated at each timestep of nova evolution. Instantaneous electron distributions are calculated from these proton distributions following the analytical approximation in [27]. We then shift and weight each instantaneous distribution to account for adiabatic and, in the case of electrons, synchrotron losses [see 13, for more details]. We then sum these weighted distributions to yield the cumulative, multi-zone spectrum of non-thermal particles accelerated by our model novae.

We also account for proton-proton losses by calculating the collision rate for each instantaneous distribution (i.e., each expanding shell of protons) at each timestep, assuming the collisional cross-section parameterized in [15] and a target proton density equal to the adiabatically expanded post-shock density of that shell. We further assume that a proton loses half its energy in a single collision (i.e., we assume an inelasticity $\kappa = 0.5$, consistent with [17]), and modify each instantaneous proton distribution accordingly.

Photon Production. To estimate photon spectra from our cumulative proton and electron distributions, we use the radiative processes code *naima* [26]. *Naima* computes the emission due to synchrotron, Bremsstrahlung, inverse Compton (IC) and neutral pion decay processes assuming arbitrary proton and electron distributions, as well as our chosen density profile(s). While the IC luminosity depends also on the radiation field chosen, we find that leptonic emission is subdominant regardless of our assumptions (see Section 3).

The main sources of opacity for GeV - TeV photons are pair production—on soft radiation fields in the RG wind and on nuclei in the nova ejecta. γ-ray photons can also be attenuated due to $\gamma - \gamma$ pair production with ambient IR/optical/UV photons, again either from the RG or from the nova outburst itself. We calculate the optical depth at the location of the nova shock γ-rays due to absorption on the IR/optical radiation field, and, while we do expect modest attenuation of TeV γ-rays (by a factor of ~ 2) at $t \simeq 1$ day, this attenuation is not sufficient to account for the order of magnitude rise in the TeV luminosity observed between days 1 and 4. Furthermore, since the $\gamma - \gamma$ opacity is negligible at the radius corresponding to the TeV luminosity peak, we neglect absorption in our emission estimates.

Magnetic Field Amplification. The streaming of energetic particles ahead of the shock is expected to excite various instabilities [e.g., 4, 6, 24], which amplify magnetic fields and enhance CR diffusion [9]. This amplification has been inferred observationally in supernova remnants [e.g., 21, 22], and is expected to proceed in a similar manner in nova shocks. We model magnetic field amplification

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as in [14] by assuming saturation of both the resonant streaming instability [e.g., 5, 16, 24], and the non-resonant hybrid instability [6]. This prescription reproduces the magnetic fields inferred from X-ray observations of young supernova remnants [8, 25].

For fast shocks ($\gtrsim$ 100 km s^{-1} for typical nova parameters), the non-resonant instability dominates amplification [see 14, for a detailed discussion]. Since this instability does not depend strongly on the strength of the initial magnetic field, the ambient magnetic field surrounding the nova—a relatively unknown quantity—does not affect our results.

3. The Single-Shock Scenario

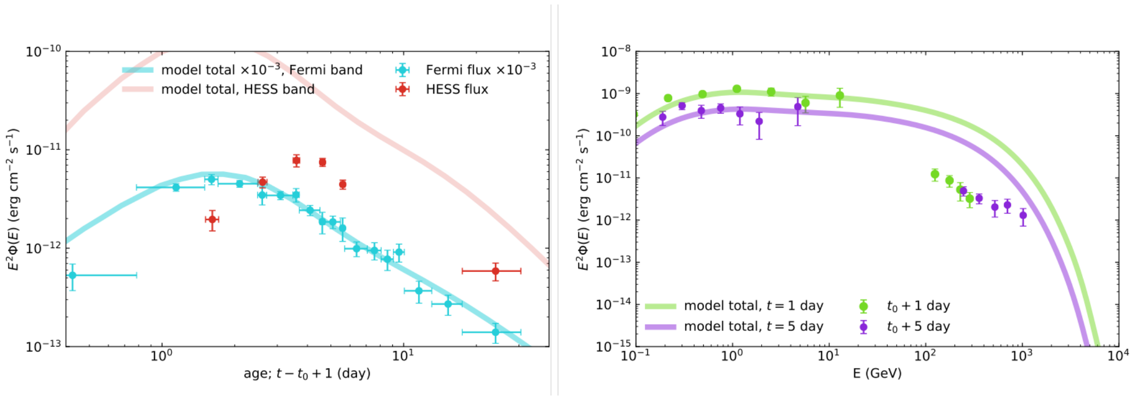

Figure 1: *Left:* Light curves from our single-shock model that best fits the Fermi data [3], displayed in the bands observed by Fermi (blue lines), and H.E.S.S. (red lines). For the overlaid observational data, t_0 corresponds to the peak of the optical light curve. *Right:* Modeled spectra after one and five days. The modeled light curves and spectra match the Fermi data quite well, but substantially overestimate the H.E.S.S. data. This overestimation demonstrates that the combined Fermi and H.E.S.S. data cannot be described as a single power law with an exponential cutoff, implying a more complex picture than a single, external shock.

In this section we apply our model to RS Ophiuchi assuming its emission arises from a single, external shock. Broadly speaking, a viable model must reproduce three key features observed by Fermi, H.E.S.S., and MAGIC [2, 3, 11]:

1. An initial rise in both the GeV and TeV luminosities.

2. An eventual decay in both the GeV and TeV luminosities that goes as $t^{-\alpha}$ where $\alpha \simeq 1.3-1.4$.

3. A delay in the TeV luminosity peak with respect to the GeV luminosity peak of roughly 2-3 days.

It is worth noting that, while H.E.S.S. observes a clear delay between GeV and TeV peaks, as well as a rise in the TeV emission at early times, MAGIC does not [2]. This discrepancy may be due to the fact that MAGIC began observing slightly later; we will therefore take the H.E.S.S. results at face value for the remainder of our analysis. Regardless, as we will show, the shape of the combined GeV-TeV spectrum alone requires the presence of multiple shock components.

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The first two items on the above list can be reproduced with hadronic emission arising from a single external shock expanding into a medium of uniform density that transitions to a red giant (RG) wind profile with density $\rho_0(r) \propto r^{-2}$ at large radii ($\gtrsim 3$ AU). Shock parameters are chosen to be broadly consistent with observations and to provide a good fit to the Fermi (GeV) data. Note that a region of uniform density is required to produce a light curve that rises to a peak. The light curves and spectra predicted by this model are plotted in Figure 1.

While the single-shock model can describe the overall shapes of both the GeV and TeV light curves, it is inconsistent with observations in two key ways. First, and most obviously, it overestimates the very high energy (VHE) γ-ray flux by more than an order of magnitude. This arises from the fact that the combined Fermi and H.E.S.S. data are inconsistent with the theoretically-motivated power-law γ-ray spectrum with an exponential cutoff. We note that MAGIC [2] and HESS [3] interpret the combined Fermi and VHE spectra as arising from a single shock. To fit these combined spectra, H.E.S.S. evokes a slow exponential cutoff ($\propto e^{-(E/E_{\max})^{\beta}}$), where $\beta < 1$. This modification results in a good fit to the data but is not theoretically motivated. Meanwhile MAGIC does fit their spectra with a theoretically motivated power-law with exponential cutoff. However, they achieve this fit by invoking arbitrary normalizations and maximum energies that do not evolve in a physical manner.

A second key tension regarding the single-shock model is that it cannot reproduce the delay between the GeV and TeV peaks. As our model demonstrates, a single shock yields a luminosity peak that occurs at approximately the same time for all energies. However, as put forward in [3], the VHE peak may be modulated by the maximum energy or, equivalently, by the finite acceleration time for TeV particles.

To illustrate why such a modulation cannot resolve the time delay issue, let us consider some simple scaling relations. Assuming $E_{\max}$ is set by requiring that the acceleration time be approximately equal to the diffusion time, and that this time be less than or equal to the age of the system, we find that $E_{\max} \propto B_2 v_{\rm sh}^2 t$ for Bohm diffusion [10]. Here, $v_{\rm sh}$ is the shock velocity and B_2 is the magnetic field behind the shock, $\propto \rho_0^{1/2} v_{\rm sh}^{3/2}$ if the non-resonant streaming instability dominates magnetic field amplification. Thus, we find $E_{\max} \propto \rho_0^{1/2} v_{\rm sh}^{7/2} t$. This framework for $E_{\max}$ is broadly equivalent to that in our model, in which the diffusion length of the highest-energy particles is a fixed fraction of the system size. The maximum energy should thus increase prior to the GeV luminosity peak, when the shock velocity and density are roughly constant. However, after the GeV luminosity peak, the shape of the light curve (Item 2 on the list above) demands that the shock enter the Sedov stage. During this stage, the maximum energy decreases with time, regardless of whether the ambient density is constant or follows a wind profile. Thus, a rise in the maximum particle energy cannot account for the delayed VHE luminosity peak.

Finally, we note that IC emission cannot resolve the issues mentioned here or, more to the point, contribute significantly to the γ-ray spectrum. Cosmic ray (CR) electrons suffer strong synchrotron losses in the amplified fields calculated in our model (~ 1 G), severely reducing their ability to produce substantial VHE emission. More importantly, the large radiation fields expected near the forward shock (~ 1 erg cm^{-3}, see the supplementary materials of [3]) give an IC loss time $\simeq 15$ seconds for TeV electrons, less than their acceleration time.

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4. A Multi-Shock Scenario

The previous section demonstrates that a single external shock cannot describe both the GeV and TeV emission from RS Ophiuchi's 2021 outburst, unless spectra and maximum energy scaling are chosen ad-hoc rather than calculated based on the DSA theory. In this section, we instead explore a scenario involving two shocks which initially expand into different, roughly homogeneous media, but eventually probe the same RG wind on large scales. Specifically, we aim to test whether multiple shocks, be they internal interactions between distinct ejecta components or a manifestation of a single ejecta running into an aspherical medium, could feasibly explain the observed γ-ray emission. Conversely, this exercise shows how the observed γ-ray emission places a constraint on the environment within and surrounding the nova system.

We shall focus our efforts only the simplest scenario–in terms of number of shock components–that reproduces the main features of the γ-ray observations. There may exist more complex scenarios that also yield a good fit to the GeV and TeV data. Our goal here is simply to provide further evidence for a complex outburst involving multiple shock components.

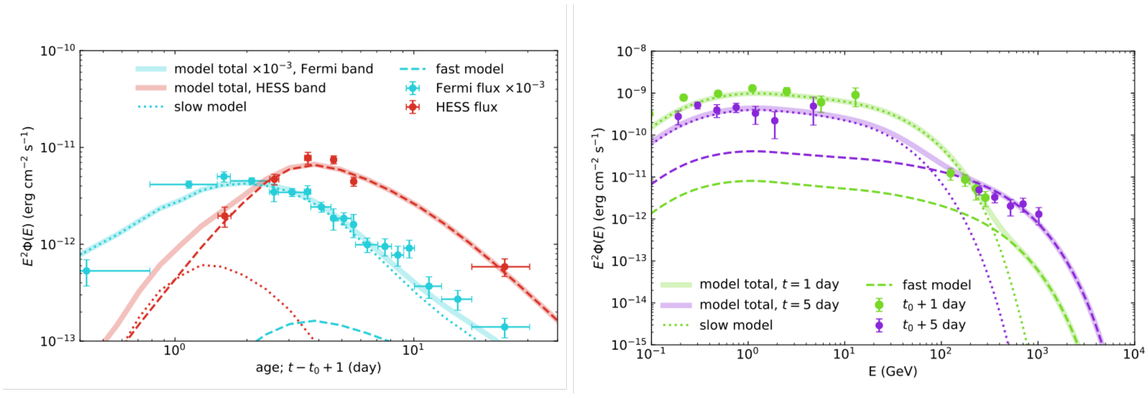

Figure 2: *Left:* Light curves from our two-shock model, displayed in the bands observed by Fermi (blue lines), and H.E.S.S. (red lines). The slow and fast components are shown with dotted and dashed lines, respectively, while the solid line gives their sum. *Right*: Modeled spectra after one and five days. As in Figure 1, all times are given in terms of shock age for the model and relative to t_0, the time of optical peak, for the observational data. This two-shock model reproduces both the γ-ray light curves and spectra observed by Fermi and H.E.S.S.

The simplest scenario that fits both the outburst's GeV and TeV light curves consists of two shocks: a slow, highly luminous component (i.e., a component that probes a relatively high density), and a fast, less luminous component (i.e., a component that probes a relatively low density). In this picture, the slow component produces the bulk of the GeV emission along with the very steep TeV spectrum at early times, while the fast component produces the hardened TeV emission at later times. This TeV hardening occurs because the fast component achieves both a higher maximum γ-ray energy and, since it sweeps up less mass at early times, a later luminosity peak. Note that the fast component of our multi-shock model has a Sedov-Taylor time of $t \simeq 3$ days, in better agreement with the deceleration timescale implied by X-ray observations [11, 20].

The shock velocities we adopt are chosen to produce the best agreement with the observed γ-ray data. While these velocities are broadly consistent with optical data, they differ somewhat

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from those inferred from X-ray data [11]. This discrepancy may be the result of additional shock components, but may also be attributed to uncertainties arising from the conversion of X-ray temperatures to shock velocities [see 18, for a detailed discussion].

The resulting light curves and spectra are shown in Figure 2. This two-shock model yields good agreement with both the GeV and TeV observations. In particular, because the fast component takes longer to reach its luminosity peak and has a higher $E_{\rm max}$ at that time, it reproduces the observed TeV delay.

5. Conclusion

We have modeled the γ-ray emission of RS Ophiuchi's recent outburst using a semi-analytic model of particle acceleration that self-consistently accounts for magnetic field amplification as well as the back-reaction of nonthermal particles. We demonstrate the properties of the observed γ-ray emission is not consistent with a single, external shock. This inconsistency arises from the facts that: a) the finite acceleration time of TeV particles is too short to explain the delay between the GeV and TeV peaks as observed by Fermi-LAT and H.E.S.S.; and (b) the combined GeV-TeV spectra are inconsistent with theoretically-motivated emission models for a single shock, in particular a power-law with an exponential cutoff.

On the other hand, we find that the observed γ-ray emission is naturally reproduced in a scenarios involving multiple shocks. In particular, both the spectra and GeV/TeV light curves are consistent with the combined emission from two shocks: one with a low initial velocity expanding into a dense ambient medium, and one with a fast initial velocity expanding into a comparatively rarefied medium. Different combinations of shocks with non-equal filling factors may also be able to reproduce the observations, as could scenarios with three or more shocks. The key takeaway, then, is that RS-Ophiuchi's recent outburst must be more complicated than the single-shock scenario presented in the literature.

Given that symbiotic novae are often treated as rapidly-evolving analogs for supernova remnants [e.g., 17], the complex behavior of RS Ophiuchi revealed in this work is also an important reminder that novae are fundamentally different systems with their own unique properties. That being said, some of this behavior may also be relevant for young supernovae, particularly those expanding into nonuniform media.

6. Acknowledgements

R.D., D.C., and S.G. were partially supported by NASA (grants NNX17AG30G, 80NSSC18K1218, and 80NSSC18K1726) and the NSF (grants AST-1714658, AST-1909778, PHY-1748958, and PHY-2010240). B.D.M. was supported in part by NASA (grant 80NSSC22K0807). E.A. acknowledges support by NASA through the NASA Hubble Fellowship grant HST-HF2-51501.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. L.C. and E.A. are grateful for support from NSF grant AST-1751874 and NASA grant 80NSSC20K1535. I.V. acknowledges support by the ETAg grant PRG1006 and by EU through the ERDF CoE grant TK133.

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