**Gamma-Ray Astronomy**

**Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi**

**H.E.S.S. Collaboration**

Recurrent novae are repeating thermonuclear explosions in the outer layers of white dwarfs, due to the accretion of fresh material from a binary companion. The shock generated when ejected material slams into the companion star’s wind can accelerate particles. We report very-high-energy (VHE; >100 giga-electron volts) gamma rays from the recurrent nova RS Ophiuchi, up to 1 month after its 2021 outburst, observed using the High Energy Stereoscopic System (H.E.S.S.). The temporal profile of VHE emission is similar to that of lower-energy giga-electron volt emission, indicating a common origin, with a 2-day delay in peak flux. These observations constrain models of time-dependent particle energization, favoring a hadronic emission scenario over the leptonic alternative. Shocks in dense winds provide favorable environments for efficient acceleration of cosmic rays to very high energies.

**RS Ophiuchi (RS Oph)** is a recurrent nova system composed of a white dwarf and a companion red giant star. Novae are a source of high-energy particles and photons (1, 2), with nonthermal gamma-ray emission in the range of ~100 MeV to ~10 GeV (3). We adopt a distance of ~1.4 kpc from Earth to the RS Oph system (4); analysis of astrometric data suggests larger distances of 2.3 kpc (5) or 2.7 kpc (6), but we regard these estimates as less reliable because of the binary orbital motion in RS Oph. The binary components have a separation of 1.48 astronomical units, close enough for the white dwarf to continuously accrete material from its companion star (7). At irregular intervals, enough material accumulates on the surface of the white dwarf to trigger a thermonuclear explosion, driving a quasi-spherical shock into the red giant’s wind (fig. S2). Eight outbursts were observed between 1898 and 2006, recurring at intervals of 9 to 26 years (9).

On 8 August 2021, an outburst of RS Oph was identified in optical observations (10), reaching a peak naked-eye visual magnitude of 4.5, more than 1000 times as bright as the quiescent visual magnitude of 12.5. We observed RS Oph with the High Energy Stereoscopic System (H.E.S.S.), an array of five atmospheric Cherenkov telescopes (8). Observations commenced on 9 August 2021 and continued for five nights, until 13 August 2021. A higher optical background due to moonlight prevented good quality observations for the next 10 nights. During each of the first five nights, H.E.S.S. detected point-like gamma-ray emission from the direction of RS Oph, with a significance of >6σ on each night (table S1). The combined data for those five nights are shown in Fig. 1. Observations recommenced on 25 August 2021, ~17 days after the initial outburst. We find evidence for a much weaker signal, ~3σ above the background, in ~15 hours (after quality cuts) of data accumulated over the subsequent 14 days.

We performed a spectral analysis of the H.E.S.S. data for the five first observation nights separately. We also separated the data from the array of four 106-m² mirror area telescopes (designated CT1 to CT4) and a fifth low-threshold telescope (CT5) with a mirror area of 612 m² (8). We find that the very-high-energy (VHE) flux is variable, with a spectral index >3 throughout (table S2).

Figure 2 shows the time evolution of the gamma-ray flux from RS Oph for photon energies between 250 GeV and 2.5 TeV. The VHE gamma-ray flux rises smoothly from $T_0$, the time of peak optical emission in the V band (10), until a VHE peak on the third night of observations. The VHE gamma-ray flux then decays by an order of magnitude over a 2-week period. We obtained 60-MeV to 500-GeV data taken by the Fermi-LAT (Large Area Telescope) instrument for the same time period as the H.E.S.S. observations, which are also shown in Fig. 2. The Fermi-LAT flux varies in the range of $\sim 1 \times 10^{-8}$ to $2 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, with a peak on $T_0 + 1$ day. The VHE gamma-ray emission peak is delayed by a further 2 days.

We used a power-law model $F_\gamma \propto t^{-\alpha}$, with exponent $\alpha$ and time $t$, to fit the decay of the flux after the peak. For the choice of $T_0 = 1$ day, the best-fitting values are $\alpha_{\text{H.E.S.S.}} = 1.43 \pm 0.18$ for H.E.S.S. and $\alpha_{\text{Fermi-LAT}} = 1.31 \pm 0.07$ for Fermi-LAT. We find consistent results for the flux and temporal decay if the Fermi-LAT data are analyzed in bins of 24-hour duration (8); the higher signal-to-noise ratio of these larger bins enables a more detailed spectral analysis.

The combined H.E.S.S. and Fermi-LAT data allow us to measure wide-band gamma-ray spectra over more than four orders of magnitude in energy and to follow their temporal evolution (Fig. 3). The RS Oph spectra are consistent with a log-parabola model. Comparison of spectra taken on different nights shows a general trend for the flux normalization to decrease and the parabola to widen over time (8) (table S2).

The similarity between the spectra of the Fermi-LAT and H.E.S.S. data and their similar decay profiles after their respective peaks indicate a common origin for the gamma rays from 1 day to 1 month after the explosion (supplementary text). We assume that the gamma rays are emitted by particles accelerated at the external shock, as it propagates into the wind of the red giant (fig. S2). Optical spectroscopic measurements of the 2021 nova indicate shock velocities ($\langle v_{\text{sh}} \rangle$) ranging from 4000 to 5000 km s$^{-1}$ (11), compatible with measurements from the previous 2006 outburst of RS Oph (12, 13). High-resolution images of the 2006 event (14) indicated that the polar regions of the shock expanded at $\approx 5000$ km s$^{-1}$ over the first 5 months. We therefore assume that, during the first week after the 2021 outburst, the shock velocity did not fall below several thousand kilometers per second.

The images of the 2006 nova showed a quasi-spherical outflow, pinched at an equatorial ring (14, 15). This is consistent with a shock expanding into the wind of the red giant, orthogonal to the orbital plane of the binary but inhibited close to the plane by the denser gas (7, 16). We expect particles to undergo diffusive shock acceleration at the external fast-moving shocks, above and below the orbital plane of the binary. We consider two scenarios to explain the observed spectral and temporal properties of the gamma-ray emission from RS Oph: (i) gamma-ray production from accelerated protons colliding with dense gas in the downstream volume (hadronic $p^\gamma$ decay model) and (ii) gamma-ray production from energetic electrons scattering low-energy photons from the nova (leptonic inverse Compton model).

For both models, the observations place strong constraints on the physical conditions, particularly the acceleration efficiencies required to match the measured fluxes and maximum photon energies (supplementary text).

VHE gamma-ray emission requires acceleration of particles to energies above the teraelectron volt level. The maximum energy a particle attains at a shock is determined either by the time taken before radiative cooling dominates over acceleration or by when particles become too energetic and thus escape upstream of the shock (17). This confinement limit applies when the accelerating particles are unable to excite magnetic field fluctuations to a sufficient level ahead of the shock. Because particles spend more time diffusing upstream than downstream, the details of the downstream
magnetic fields can be neglected (18). For upstream magnetic field amplification to be effective, a sufficient flux of particles, typically protons, must escape upstream of the shock. This requires both efficient transfer of the shock kinetic energy to relativistic protons (i.e., those traveling at speeds close to the speed of light) and that a fraction of these protons penetrate far upstream. Escaping particles have energies concentrated close to the maximum particle energy; less-energetic particles are confined to the shock. The escaping flux per unit area at a given shock radius can be parameterized as

\[ j_{\text{esc}} = e \xi_{\text{esc}} F_e / E_{\text{max}} \quad (1) \]

where \( e \) is the elementary charge, \( F_e = \frac{1}{2} \rho_{\text{up}} U_{\text{sh}}^3 \) is the energy flux density for a high-Mach-number nonrelativistic shock. \( \rho_{\text{up}} \) is the immediate upstream gas density at that radius, \( E_{\text{max}} \) is the maximum particle energy that dominates the escaping flux, and the efficiency parameter \( \xi_{\text{esc}} \) depends on the assumed particle spectrum (supplementary text). For a wind-like density profile, and neglecting radiative losses, the confinement limit on the maximum energy for a particle with atomic number \( Z \), and thus charge \( Z|e| \), is

\[ E_{\text{max}} = 1.5|Z| \left[ \frac{\xi_{\text{esc}}}{0.01} \right] \left( \frac{M}{10^{51} \text{ kg m}^{-3}} \right)^{1/2} \left( \frac{U_{\text{wind}}}{5000 \text{ km s}^{-1}} \right)^{2} \text{ TeV} \quad (2) \]

where \( M \) and \( U_{\text{wind}} \) are the mass-loss rate and the wind velocity, respectively, of the red giant. \( \xi_{\text{esc}} \) is predicted to be \( \sim1\% \) for high-Mach-number shocks (17). For RS Oph, \( M / U_{\text{wind}} = 6 \times 10^{50} \text{ kg m}^{-1} \) (15), which, together with the inferred shock velocities, indicates a maximum energy \( E_{\text{max}} \sim 10 \text{ TeV} \). This is compatible with the measured maximum photon energies \( E_{\gamma,\text{max}} \sim 1 \text{ TeV} \) (Fig. 3).

In the hadronic scenario, the gamma-ray light curves are consistent with an expanding shock in a decreasing density profile. With the adopted distance of 1.4 kpc (4), the measured gamma-ray fluxes require that \( \geq10\% \) of the post-shocked medium’s internal energy goes into accelerating protons or other nuclei. The delay between the peaks in the Fermi-LAT and H.E.S.S. light curves would then reflect the finite acceleration time of the \( >1 \text{ TeV} \) protons or, more specifically, the time taken to populate the high-energy tail of the distribution (19). A simple calculation of the acceleration time (supplementary text), on the basis of a comparison of the confinement and Hillas limits, implies that this should happen on the order of days. This is consistent with the spectral evolution seen in Fig. 3: a reduction in the Fermi-LAT flux, accompanied by a hardening in the H.E.S.S. flux and increased \( E_{\gamma,\text{max}} \) over the first few days after the outburst. Attenuation of gamma-rays, due to the nova’s optical and infrared photon fields, is minor below \( 1 \text{ TeV} \) a few hours after the explosion; therefore, attenuation alone cannot account for the observed hardening (supplementary text and fig. S10).

For the alternative leptonic scenario, in which tera-electron volt gamma-rays are produced by VHE electrons, the acceleration needs to overcome the strong radiative losses due to inverse Compton cooling in the strong photon fields of the nova, as well as synchrotron cooling in the magnetic field in the shock region. To achieve this, electrons must accelerate at close to the Bohm rate—i.e., the scattering rate equal to the rate of gyration in the magnetic field (18). Such efficient scattering requires strong self-generated magnetic fluctuations upstream of the shock, which implies the presence of an energetic relativistic hadronic component. In this scenario, the differences between the spectral slopes in the Fermi-LAT and H.E.S.S. energy ranges are a consequence of the energy-dependent cooling rates in time-dependent photon fields. Electrons that radiate in the VHE band cool on a time scale less than the age of the nova remnant at the times the observations were taken, whereas lower-energy uncooled electrons accumulate downstream over time. The Fermi-LAT light curve in this scenario then reflects the evolution of the energy density of soft-photon targets, whereas the H.E.S.S. light curve traces the full radiative output of high-energy electrons up to the VHE peak (supplementary text). After the peak, owing to the rapidly decreasing photon energy density, the cooling time increases faster than the remnant’s age, and the VHE emitting electrons are also slow cooling.

In this time-dependent numerical single-zone model, parameters can be found to approximately describe the light curves and spectra in both leptonic and hadronic scenarios, providing quantitative estimates for the acceleration efficiencies at early times \( t (t \leq T_0 + 5 \text{ days}) \). We are unable to account for the temporal delay at later times, probably because we do not consider the complex internal structure of the nova remnant, its nonspherical geometry, or the escape of particles from the emission zone. Both the leptonic and hadronic models at early times are consistent with continuous injection of particles following a power law spectrum in energy \( E^{-2.2} \) with a high-energy cutoff. To approximately match the observed flux, the hadronic model requires \( >10\% \) of the shocked gas’s internal energy to be transferred to nonthermal protons, whereas the leptonic model requires \( >1\% \) efficiency for nonthermal electrons.

Such a high fraction of the total energy in nonthermal electrons is inconsistent with theories of injection at high-Mach-number shocks, for which the ion injection efficiency is expected to be much higher than that of electrons (20). Numerical simulations of high-Mach-number shocks find a ratio of \( <10^{-2} \) for electron to ion energy densities (21), consistent with multiwavelength models of supernova remnants (22). A \( >1\% \) efficiency of conversion to nonthermal electrons cannot be realized in a purely leptonic model. For this reason, we prefer the hadronic scenario discussed above, for which both the implied high-proton-acceleration efficiencies and inferred maximum energy are in line with theoretical predictions (17). Our findings support previous hadronic models of gamma-ray novae (23–25).

The VHE detection of RS Oph demonstrates that particle acceleration to energies around the tera–electron volt level can occur within the dense wind environments of recurrent novae. The total kinetic energy from each nova of
RS Oph is estimated to be \(-10^{53}\) erg [10^-7 solar masses (M☉) of ejecta at \(-4000\) km s^{-1} (13)], with a large fraction of this being converted to relativistic protons and heavier nuclei, which are the main constituents of Galactic cosmic rays. Each nova event generates enough cosmic rays to fill a cubic parsec volume with an energy density of \(-0.1\) eV cm^{-3}, similar to the local Galactic cosmic-ray energy density of \(-0.8\) to 1.0) eV cm^{-3} (26) sustained by supernovae. In the case of RS Oph, the cosmic-ray energy input recurs approximately every \(\Delta t = 15\) to 20 years, leading to an almost-continuous injection of nonthermal particles. For a diffusion coefficient \(D\) in the neighborhood of RS Oph, the cosmic-ray output from each nova is spread over a diffusion length \(L_{\text{diff}} = \sqrt{4D\Delta t}\). Using a Galactic average \(D = (3 - 5) \times 10^{28}\) cm^{2} s^{-1} (27), we find \(L_{\text{diff}} > 1\) pc, and the contribution from each nova is less than the average Galactic cosmic-ray population. If the diffusion coefficient in the neighborhood of the nova is much lower than the Galactic average, perhaps due to enhanced turbulence after previous novae, such a sustained source of cosmic rays will raise the local abundance. If efficient acceleration of particles to tera-electron volt energies in recurrent nova is commonplace, with spectral energy distribution harder than that of the Galactic cosmic-ray background \(\propto E^{-2.7}\), the local contribution from novae would dominate at tera-electron volt energies over volumes above the cubic parsec level. The size of the affected region will depend on the value of the diffusion coefficient, which can be constrained with measurements of the diffuse gamma-ray emission at energies \(-10\) to 100 GeV (28).

Our time-resolved gamma-ray emission measurements have implications for the origin of cosmic rays. Acceleration of cosmic rays to peta-electron volt energies in supernova remnants requires substantial amplification of magnetic fields. Fast shocks (\(-10,000\) km s^{-1}) propagating through the dense winds (\(M_\text{wind} \sim 10^{15}\) kg m^{-1}) associated with the progenitors of supernova remnants from massive (\(\gtrsim 8 M_\odot\)) stars provide the only known environments where the required conditions can (in theory) be met (17, 29). However, observational confirmation of this prediction has not been found. The detection of VHE gamma-rays from RS Oph provides an example of a Galactic accelerator reaching the theoretical limit for the maximum achievable particle energy via diffusive shock acceleration (17). If our results can be extrapolated to the most optimistic supernova conditions, they support the prevailing model of Galactic peta–electron volt cosmic rays originating in supernova remnants from massive stars (17, 29).

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Data and materials availability: The H.E.S.S. data are available at www.mpi-hd.mpg.de/hfm/HESS/pages/publications/auxiliary/2022_RS_Oph/. This includes the sky maps in Fig. 1, the light-curve data plotted in Fig. 2, the spectral energy distributions used to produce Fig. 3, and the data values plotted in figs. S8 and S9. The Fermi-LAT data were downloaded from https://fermi.gsfc.nasa.gov/cgi-bin/LAT/LATDataQuery.cgi; we used 60-MeV to 500-GeV photons within 15° of RS Oph from 7 August 2021 to 13 September 2021. Our emission modeling software code is available at https://github.com/dmikha/RS_Oph.

SUPPLEMENTARY MATERIALS
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Materials and Methods
Supplementary Text
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