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Evidence of hadronic origin of the gamma-ray emission from the nova RS Oph by the MAGIC telescopes

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RS Ophiuchi (RS Oph) is a symbiotic recurrent nova that shows eruptive events roughly every 15 years. On August 8th, 2021, RS Oph erupted with its latest outburst. This event was detected by a wide range of multi-wavelength (MWL) instruments from radio up to very-high-energy (VHE) gamma rays. The MAGIC telescopes followed up on optical and high-energy triggers and initiated an observation campaign from August 9th till September 1st. RS Oph is the first nova detected in the VHE gamma-ray energy range. We report on the detection of VHE gamma rays at a significant level of 13.2σ during the first 4 days of RS Oph with the MAGIC telescopes. We combine the VHE emission detected by MAGIC with optical and high energy observations and conclude RS Oph accelerated hadrons during its eruption. We will present the MWL modeling revealing this hadronic emission, and its further implications for Galactic cosmic-rays.

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A symbiotic nova arises when a red giant (RG) star acts as the companion to a white dwarf (WD) [1]. Material can be collect from the RG donor star via its dense wind onto the surface of the WD until it reaches the fusion flash-point for hydrogen and undergoes thermonuclear runaway. The expanding ejecta of symbiotic novae occur within the dense wind emanating from the RG companion. Typically, nova outbursts persist for weeks to months. Although they are anticipated to repeat numerous times, the interval between consecutive events can extend to hundreds of thousands of years [2]. However, a subset of objects known as recurrent novae provides us with the ability to observe such repeated outbursts within a human lifespan. Within our Galaxy, there are currently ten known objects of this nature, where bursts have been witnessed to reoccur within a century [2].

RS Oph is a recurrent symbiotic nova, which displays a semi-regular occurrence of major outbursts with an average interval of 14.7 years [2]. The most recent outburst, which took place in August 2021, was promptly followed-up in the optical, x-ray, and high-energy (100 MeV < E < 10 GeV) gamma-rays [3–5]. The optical emissions exhibited behaviour similar to the 2006 outburst [4]. Subsequently, the MAGIC observatory initiated observations of RS Oph as part of its nova follow-up program, commencing on August 9, 2021, at 22:27 UT, approximately one day after the initial optical and GeV detections [7]. In parallel, the H.E.S.S. Collaboration reported the detection of very-high-energy (VHE, > 100 GeV) gamma rays from RS Oph [6]. The MAGIC observations unveiled VHE emission coinciding with the *Fermi*-LAT and optical peaks, followed by a decline below the VHE detection threshold two weeks later. The initial four days of MAGIC observations (August 9-12) yielded a VHE signal with a significance of 13.2σ, covering the energy range from 60 GeV to 250 GeV. This MAGIC signal was well-described by a single power law fit (χ^2/Ndof = 5.9/5, where Ndof represents the number of degrees of freedom) [7].

Novae have the proper conditions to accelerate protons and electrons up to the energies needed to produce VHE gamma rays. This has been observed by the *Fermi*-LAT telescope for over a decade but unable to distinguishing the emission mechanism [8]. In a similar method to supernovae, the ejected material during a nova eruption expands into the interstellar medium and the dense environment from the RG wind and will produce a fast shock and additional internal shocks [9]. A correlation between optical and gamma-ray emissions provides additional evidence indicating that a significant portion of the power released during a nova eruption is transferred into the accelerating of particles fast shocks [10]. The dense environment, provided by the RG wind, and nova ejecta, acts as a target for the accelerated cosmic rays from these fast shocks and thereby producing a majority of the observed gamma-rays via hadronic process [7]. The obvious signature of hadronic processes is delayed VHE emission and a general hardening of the spectra with time, as protons are accelerated and cooled slowly, with a timescale of $t_{pp} = 21\ (n_p/(6 \times 10^8\ \text{cm}^{-3}))^{-1}$ [day], while electrons, with energy E, are accelerated quickly via inverse Compton processes and cool very quickly with $t_{IC} = 4.4 \times 10^{-3}$ (E/(300 GeV))$^{-1}$ (1 + 10 (E/300 GeV))$^{1.5}$ [day] [7].

Fitting the leptonic and hadronic models to the *Fermi*-LAT and MAGIC spectra, between 50 MeV to 250 GeV, show a clear preference for hadronic origin over leptonic origin. We use the Akaike Information Criteria (AIC) to find the model that best fits the data due to the fact the hadronic and leptonic models are non-nested [11]. We find an ΔAIC = 15.3 with preference toward the hadronic model. Additionally, the leptonic model requires an ad hoc strong break in the intrinsic electron spectrum, further disfavouring the leptonic models. Finally, temporal evolution of *Fermi*-LAT and MAGIC data show evidence towards the signature spectral hardening of VHE signal, but remains

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a tantalising hint [7].

The contribution of novae to the larger cosmic-ray sea can also be roughly estimated based on the rate of novae per year and the derived total energy of RS Oph. We find that novae only contribute a small fraction to the total cosmic-ray population, around 0.1%, but can easily dominate the local environment of 0.5 pc radius bubble for classical novae and a 9 pc radius bubble for recurrent novae similar to RS Oph. RS Oph represents the first detection of a nova outburst by VHE telescopes and evidence towards the hadronic origin of gamma-rays from novae. Further novae detections are needed to clarify whether classical novae also produce VHE gamma-ray and the origin of their emission.

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