Neutrino Flux Deduced from $\gamma$-rays Emitted by Novae

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ABSTRACT

The recently discovered high energy emission from the recurrent nova RS Ophiuchi by Fermi-LAT ($>100$ MeV), H.E.S.S, and MAGIC ($>100$ GeV), hints towards a possible hadronic origin of this radiation component. From this high energy photon flux we derive the expected number of neutrino events that could be detected by present and future neutrino telescopes in the different energy ranges. We find the number to be well below the detectors’ capabilities. Therefore, both hadronic and leptonic processes remain valid interpretations of this $\gamma$-ray emission. Preliminary estimates indicate that in order to detect a plausible number of neutrino events with IceCube-DeepCore and KM3NeT the novae distances should not be greater than $\sim 1$ and $\sim 2$ kpc, respectively. Current values of the rates of nova eruptions in the Milky Way will allow present and future neutrino facilities to detect neutrino events from novae on a time scale of the order of once or twice per decade.

Keywords: (stars:) binaries: symbiotic — (stars:) novae, cataclysmic variables — neutrinos — gamma rays: general

1. INTRODUCTION

A nova is a powerful eruption following a thermonuclear runaway (TNR) that occurs below the surface of a white dwarf (WD) (Starrfield et al. 1972; Shara 1981; Starrfield et al. 2008). The TNR is the inevitable result of a critical amount of (mostly) hydrogen being pulled away from its companion, less evolved star, and accumulating on the degenerate surface of the WD. As this mass piles up in a degenerate environment, the pressure below the surface increases, causing the temperature to rise until becoming sufficiently high to ignite the hydrogen, entailing fusion in a runaway process and the violent ejection of the envelope (e.g., Shara 1981), exhibited as an enormous visual brightening (Payne-Gaposchkin 1957) of order $\sim 10^4$--$10^5$ times the solar luminosity — the nova eruption (Hellier 2001; Warner 2003; Knigge et al. 2011). Novae are usually discovered, following the eruption, in the optical band but it is hardly the only range in which a nova may be observed. Over the course of a nova cycle — accretion, eruption and decline — a nova producing system could possibly be observed in the infrared (IR), ultraviolet (UV), soft and hard X-rays and even $\gamma$-rays (MacDonald et al. 1985; Itoh & Hachisu 1990; Orio et al. 1994, 2009; Schaefer & Collazzi 2010; Hillman et al. 2014; Della Valle & Izzo 2020; Chomiuk et al. 2021; König et al. 2022). Each band, if observed, may provide clues as to the nature of the eruption, the system and its unique behavior that could help distinguish one system from the next. However, the capacity and technical capabilities of capturing observations in the different bands are not the same for all bands, resulting in mostly visual records. While the visual rise indicates the expansion of the WD’s envelope and ejection of the mass (e.g., Prialnik 1986), $\gamma$-rays, if observed, are detected only days after the visual peak (Sokolovsky et al. 2022), implying that they must be originating from somewhere other than the WD’s surface (Metzger et al. 2015; Martin et al. 2018).

In the past decade $\gamma$-rays were detected in a handful of systems emitting at energies higher than 100 MeV using the Fermi-Large Area Telescope (Fermi-LAT) (Razzaque et al. 2010; Ackermann et al. 2014; Cheung et al. 2016; Martin et al. 2018). Ackermann et al. (2014) investigated the likelihood of the $\gamma$-rays originating in both hadronic and leptonic processes, for the symbiotic nova (SymN) V407 Cyg and the three classical novae (CN) V1324 Sco, V959 Mon.
and V339 Del, but did not come to a firm conclusion regarding which emitting process is more likely to be the source. Cheung et al. (2016) explored detected γ-rays for an additional two CNe — V1369 Cen and V5667 Sgr (Li & Chomiuk 2016; Li et al. 2017), and interpreted that this high energy emission is due to particles accelerated up to ∼ 100 GeV at the reverse shock and undergoing hadronic interactions in the dense cooling layer downstream of the shock (Martin et al. 2018).

Recently, the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) and the H.E.S.S. (High Energy Stereoscopic System) telescopes have detected γ-rays of energies higher than 100 GeV from the 2021 outburst of RS Oph — a recurrent nova in a symbiotic system that erupts every ∼ 15 years (Acciari et al. 2022; H.E.S.S. Collaboration et al. 2022a). When a nova eruption occurs in a symbiotic system, the ejected mass will inevitably collide with the dense wind of the red giant (RG) companion, shocking a fraction of the particles and accelerating them, resulting in the emission of high energy radiation in the γ-ray range such as seen in RS Oph (H.E.S.S. Collaboration et al. 2022a) and V407 Cyg (Abdo et al. 2010; Martin et al. 2018).

Systems with a red dwarf (RD) donor (i.e., a cataclysmic variable (CV)) might also produce shocks in the event that the ejected mass is not expelled in a unified manner, but rather in stages or in clumps with different velocities, thus a fast clump of mass could collide with a previously ejected slower moving clump of mass. It is also plausible that the ejected mass shell may interact with an expanding mass shell that was ejected in a previous nova eruption, provided the recurrence period is short enough and enough mass was ejected. However, any of these options are not expected to produce detectable γ-rays since the gas cloud into which the ejected mass is colliding is much less dense than the wind from a red giant (RG) (Cheung et al. 2016), and in nova with short recurrence times the amount of ejected mass is low (Priahlk & Kovetz 1995; Yaron et al. 2005; Hillman et al. 2015, 2016; Shara et al. 2018; Hillman et al. 2019). Nevertheless, there are peculiar detections of γ-rays in some novae hosting a RD donor, as mentioned earlier (Ackermann et al. 2014; Cheung et al. 2016; Martin et al. 2018).

In symbiotic systems, where high energy γ-rays are plausible (as explained above), it is still not entirely clear what nuclear process is emitting them. The main interpretation of this high energy emission has been claimed to be due to hadronic particle acceleration in shocks (Stecker & Metzger 2020; Acciari et al. 2022; H.E.S.S. Collaboration et al. 2022a). High energy protons, accelerated in the shock region may interact with other protons in the dense environment, giving rise to neutral pions (π⁰) that then decay to high energy γ-rays. A proton-proton interaction will also produce charged pions (π±) that will decay into high energy neutrinos. Modeling γ-ray emission from an astrophysical source with a π⁰ model thus inevitably predicts a high-energy neutrino flux from the same source (e.g., Stecker 1970). Therefore, if the high energy γ-ray emission has an hadronic origin, we expect the process to be accompanied by the production of neutrinos.

This work aims to test the origin of the physical processes responsible for the γ-ray emission that is sometimes observed in nova eruptions. If the high-energy emission observed in these transients has an hadronic and/or leptonic origin, it follows that it should be accompanied by a flux of neutrinos (Razzaque et al. 2010; Metzger et al. 2016; Bednarek 2022). In this work we estimate the neutrino flux that might be associated with the recent eruption of nova RS Oph and thus we predict the number of events that, in principle, could be detected during nova explosions by the present and future neutrino telescopes.

In §2 we specify the technical capabilities of each neutrino detector that we refer to in this work. §3 specifies our method of calculation for the different energy ranges of neutrino flux followed by our results in §4. We discuss the implications of our results and compare the expected number of neutrino events with those derived in previous works in §5 and provide our conclusions in §6.

2. NEUTRINO TELESCOPES

High-energy neutrinos interact with nucleons, producing secondary particles which travel faster than the speed of light in the sea or ice inducing Cherenkov radiation inside the detector. The photons that are emitted by this process are detected by optical sensors that are deployed in the sea or ice (depending on the detector). In the following we briefly describe the basic characteristics of each telescope considered in this work.

2.1. IceCube and DeepCore

The IceCube high-energy neutrino telescope is a neutrino detector located at the geographic South Pole (IceCube Collaboration et al. 2006). In the final detector configuration, the digital optical modules, deployed in the Antarctic ice, are arranged on 86 vertical strings of 60 sensors each, spread over depths between 1450 m and 2450 m with vertical distances of 17 m between adjacent sensors. Seventy-eight strings have a horizontal spacing of about 125 m and cover a hexagon with a surface area of roughly 1 km². Eight additional strings together with the seven strings surrounding IceCube, form
the more densely instrumented central DeepCore detector (Abbasi et al. 2009, 2010). The module density in DeepCore is about five times greater than the rest of IceCube, which allows for the much lower energy detection threshold of a few GeVs. The IceCube detector has been collecting data since 2006, and so far no neutrino event has been associated with a nova eruption. The effective areas vs. neutrino energy for IceCube and DeepCore are shown in Figure 1.

2.2. ANTARES

The ANTARES neutrino detector is located in the Northern Hemisphere and is currently the only deep sea high energy neutrino telescope (Ageron et al. 2011) that exists to date. The telescope covers an area of about 0.1 km² on the sea bed, at a depth of 2475 m, 40 km off the coast of Toulon, France. In its full configuration, it is composed of 12 detection lines, each comprising up to 25 triplets of photo-multiplier tubes (Aguilar et al. 2005). Each triplet is located in one of the storeys, regularly distributed along 350 m, the first storey being located 100 m above the sea bed. The telescope reached its nominal configuration, with 12 lines immersed and taking data, in May 2008. Figure 1 shows the effective area of the ANTARES neutrino detector, with selection and reconstruction criteria optimized for the search of point like sources, as a function of the neutrino energy (Adrián-Martínez et al. 2012).

2.3. KM3NeT

The KM3NeT detector (Adrián-Martínez et al. 2016) is the future generation of under water neutrino telescopes. The infrastructure will consist of three so-called building blocks, each made of 115 strings of 18 optical modules, that have 31 photo-multiplier tubes each. KM3NeT will be comprised of the KM3NeT/ARCA which will consist of two building blocks each that will be deployed at a depth of 3500 m at a site 80 km South-East of Porto Palo di Capo Passero, Italy, and of a third building block, called KM3NeT/ORCA, which will be located at a depth of 2200 m in a site close to ANTARES (Toulon). KM3NeT/ARCA will have large spacings between adjacent strings in order to target astrophysical neutrinos at TeV energies. The KM3NeT/ORCA will be sensitive to neutrinos down to energies of a few GeV thanks to the denser and compact array. Figure 1 shows the effective areas of KM3NeT/ARCA and KM3NeT/ORCA as a function of the neutrino energy (Adrián-Martínez et al. 2016; Zegarelli et al. 2022).

2.4. Hyper-Kamiokande (Hyper-K)

The Hyper-Kamiokande is a next generation underwater Cherenkov detector with a sensitivity that is far beyond that of the Super-Kamiokande (Super-K) detector. The Hyper-K is designed to detect proton decays, atmospheric neutrinos, and neutrinos from astronomical origins. The baseline design of Hyper-K is based on the highly successful Super-K, taking full advantage of a well-proven technology (Abe et al. 2011). In Figure 1 we show the effective area of Hyper-K as a function of the neutrino energy. As may be seen in this figure, the detector has good low energy performance, which should allow detection down to a few GeV.

Figure 1. The effective areas vs. energy (on a log-log scale) for the six detectors, reproduced from: Aartsen et al. (2014) (IceCube); Zegarelli et al. (2022) (DeepCore and KM3NeT/ORCA); Adrián-Martínez et al. (2012) (ANTARES); Adrián-Martínez et al. (2016) (KM3NeT/ARCA); and Abe et al. (2011) (Hyper-K).

3. EXPECTED NEUTRINO FLUXES

In this section, we derive the neutrino flux expected from RS Oph based on the assumption that the high energy photon emission is due to hadronic processes. Relativistic protons may produce > GeV γ-rays either by photo-meson production or inelastic nuclear collisions. In Bednarek (2022) the authors show that p-p interactions are the most likely mechanism for pion production in novae. A possible mechanism that can produce the very high energy (VHE) photons that were de-
ected by H.E.S.S. (H.E.S.S. Collaboration et al. 2022a) and MAGIC (Acciari et al. 2022) may be the decay of neutral pions ($\pi^0$) produced through nuclear collisions of relativistic protons. The same process that produces the neutral pions, and subsequently the sub-TeV photons, would also generate charged pions ($\pi^\pm$) that decay into neutrinos of similar energy. The following equation describes the three processes:

$$p + p \rightarrow \pi^0, \pi^+, \pi^- p, n, ...$$ (1)

From this kind of interaction we expect almost the same number of $\pi^+, \pi^0$ and $\pi^-$ particles, due to isospin symmetry (e.g., Povh et al. 2004). $\pi^0$ particles decay into two $\gamma$-rays, having, in the pion rest frame, an energy equal to half of the $\pi^0$ mass as described below:

$$\pi^0 \rightarrow \gamma + \gamma \ \ \ \ \ \ \ \ \ \ \ (2)$$

On the other hand, the charged pions decay into neutrinos as follows:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$ \hspace{0.5cm} (3)

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$ \hspace{0.5cm} (4)

where $\nu_\mu$ and $\nu_e$ are the muon and electron neutrinos respectively. Considering the relation between the photon flux and the neutrino flux given in Eq. 4 of Razzaque et al. (2010) we derive that (Di Palma et al. 2017):

$$\frac{dN_{\nu^+\nu}}{dE_\nu} = \frac{dN_\gamma}{dE_\gamma}$$ \hspace{0.5cm} (5)

and therefore

$$\int_{E_{\gamma}^{\min}}^{E_{\gamma}^{\max}} E_\nu \frac{dN_{\nu}}{dE_\nu} dE_\nu = \int_{E_{\nu}^{\min}}^{E_{\nu}^{\max}} E_\nu \frac{dN_\gamma}{dE_\gamma} dE_\gamma$$ \hspace{0.5cm} (6)

where $E_{\gamma}^{\min}$ ($E_{\nu}^{\min}$) and $E_{\gamma}^{\max}$ ($E_{\nu}^{\max}$) are the minimum and maximum photon (neutrino) energies respectively.

The number of photons per unit energy interval, time, and surface area can be written as:

$$\frac{dN_\gamma}{dE_\gamma} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma}$$ \hspace{0.5cm} (7)

where $N_0$, $E_0$ and $\Gamma$ are the amplitude at reference energy, reference energy and spectral index respectively, computed from observations.

Following the line of the work by Alvarez-Muñiz & Halzen (2002), Guetta & Amato (2003) and Di Palma et al. (2017), we compute the high energy neutrino flux at Earth and estimate the number of events that may be detected by the telescopes described in §2.

The total number of expected astrophysical events during an exposure time $T$ of a neutrino telescope is given by:

$$N = \int_{0.1 \text{ TeV}}^{100 \text{ TeV}} T \frac{dN_\nu}{dE_\nu} A(E_\nu) dE_\nu$$ \hspace{0.5cm} (8)

where $dN_\nu/dE_\nu$ can be derived from $dN_\gamma/dE_\gamma$ according to Equation 5 for the given TeV spectrum (and used in Equation 7) and $A(E_\nu)$ is the effective area of the considered neutrino telescope, as a function of the neutrino energy $E_\nu$ as shown in Figure 1.

The effective area of a detector may depend on the declination of the observed celestial object. The declination of RS Ophiuchi is $-06^\circ 428.5''$, and we use the corresponding effective areas of the relevant detectors where applicable.

VHE ($>100$ GeV) $\gamma$-rays were reported by H.E.S.S. and MAGIC from the recurrent nova RS Ophiuchi up to a month after its 2021 outburst (Acciari et al. 2022; H.E.S.S. Collaboration et al. 2022a). The VHE emission has a temporal profile similar to lower-energy GeV emission (H.E.S.S. Collaboration et al. 2022b, Fig. 3), indicating a common origin, with a two-day delay in peak flux.

Referring to tables S1 and S2 in H.E.S.S. Collaboration et al. (2022a) we consider the five days of detection (August 9-12 2021). We use their amplitude at reference energy, reference energy and spectral index from their table S2 ($N_0$, $E_0$ and $\Gamma$ respectively) and their exposure times from table S1, in Equations 7 and 8 in order to obtain an hourly average.

We estimate the neutrino flux in the energy range 100 GeV-100 TeV, which is the range in which IceCube, and ANTARES operate. We assume the same range for the future KM3NeT/ARCA detector.

We also extend our estimate to lower energies and consider the 1–500 GeV energy range data taken by the Fermi-LAT instrument over the same time period as the H.E.S.S. and MAGIC observations (Acciari et al. 2022; H.E.S.S. Collaboration et al. 2022a).

The H.E.S.S. collaboration find that the best fit for the energy range observed photon flux is given by a log-parabola spectral function of the form:

$$\frac{dN_\gamma}{dE_\gamma} = N_0 \frac{E}{E_0}^{-\alpha - \beta \ln(E/E_0)}$$ \hspace{0.5cm} (9)

We refer to the joint Fermi-LAT and H.E.S.S. calculation in H.E.S.S. Collaboration et al. (2022a) and take $N_0$ and $E_0$ from their table S3, as well as the spectral index and curvature ($\alpha$ and $\beta$ respectively). This data is used to estimate the expected number of neutrinos in
the energy range 1-500 GeV for the IceCube-DeepCore, the KM3NeT/ORCA and the Hyper-Kamiokande detectors.

4. RESULTS OF CALCULATIONS

In this section we show the results of our calculations regarding the 2021 RS Oph eruption for the high and low energy ranges. We also apply our analysis to additional novae (elaborated in §1) that were detected in $>0.1\text{GeV}$ by Fermi-LAT.

4.1. RS Oph - High energy ($>100\text{GeV}$)

For the high energy regime we use Equations 7 and 8 and the data from CT1-4 stereo analysis from H.E.S.S. Collaboration et al. (2022a) to calculate estimates of the total number of neutrinos expected to have been detected from the latest RS Oph eruption by IceCube, ANTARES and KM3NeT/ARCA. For each detector, we calculate the average number of events per hour over the five exposure epochs. According to H.E.S.S. Collaboration et al. (2022a) the source was observed in eruption for $\sim 30$ days. In order to obtain an upper limit of the total number of expected neutrino events, we multiply the average number that we obtained by 30 days. Since the errors given in H.E.S.S. Collaboration et al. (2022a) are very large, of order 30%, we do not calculate a range, but regard our results as estimates. We find the total expected number of neutrino events for IceCube, ANTARES and KM3NeT/ARCA to be $\sim 1.4 \times 10^{-3}$, $\sim 3.6 \times 10^{-4}$ and $\sim 2.1 \times 10^{-2}$ respectively. These numbers indicate a detection to be highly improbable.

4.2. RS Oph - Low energy ($\sim 0.1 - 100 \text{ GeV}$)

Next we calculate the expected flux for the case that the neutrinos could have originated in $\pi$ decays resulting in lower energies. We use Equations 8 and 9 and data from H.E.S.S. Collaboration et al. (2022a) as described in §3. As with the high energy data, here too, the Fermi-LAT data from H.E.S.S. Collaboration et al. (2022a) has large error bars, thus our results here are estimates for $\sim 30$ days. We obtain 0.014, 0.061 and 0.046 for Hyper-K, DeepCore and KM3NeT/ARCA respectively — these values, although higher than those derived via the high energy calculation, are still too low for any of the current or future telescopes to be able to detect.

We also use the joint spectral fit of H.E.S.S. and Fermi-LAT for the total energy range ($>0.1\text{GeV}$) to compute the expected number of neutrino events that would have been detected by the high energy detectors, and derive $\sim 4.6 \times 10^{-4}$, $\sim 1.5 \times 10^{-4}$ and $\sim 7.5 \times 10^{-3}$ for IceCube, ANTARES and KM3NeT/ARCA respectively. These are $1 - 2$ orders of magnitude lower than the expected detection from the low energy telescopes.

All our methods of calculation, considering both energy ranges yield neutrino fluxes for RS Oph that seem to be too low for any of the current or future telescopes to be able to detect.

4.3. Additional novae

We now consider the Fermi-LAT detections of the six novae specified in §1. We take the photon fluxes from Ackermann et al. (2014) and Cheung et al. (2016) and use them in Equations 7 and 8 to determine the expected number of neutrino events, while assuming, as before, that the energy emitted in neutrinos is of the same order as the energy emitted in photons. We used $E_0 = 1 \text{ GeV}$ as the reference energy and $\Gamma = 2.1$ as the spectral index. The values for exposure time and amplitude at reference energy (extracted from Ackermann et al. (2014) and Cheung et al. (2016)) are specified in Table 1 as well as our resulting number of expected neutrino detections by each of the low energy telescopes up to 100 GeV.

Our results predict, for the six novae, substantially smaller numbers of expected events relative to RS Oph, and within the six novae, we expect a higher detection rate for the SymN V407 Cyg relative to the five CNe. We note that none of the low energy telescopes yield a feasible number of expected events for any of these novae.

Additionally, we extrapolate the above calculation to predict the number of neutrino events for the hypothetical case that those novae may emit in the high energy range ($> 100 \text{ GeV}$). We accomplish this by extending the Fermi-LAT photon flux to higher energies. Our results are shown Table 2, where it seems as though the high energy telescopes would have a good chance of detecting neutrinos from these six novae, while not for RS Oph, which actually emitted in high energy. We discuss this further in §5.

4.4. Expected atmospheric events

We have presented quantitative estimations concerning detection prospects of low-energy neutrinos from novae with current (IceCube-DeepCore) and under construction (KM3NeT/ORCA and Hyper-Kamiokande) neutrino telescopes. At multi-GeV energies the atmospheric background severely limits the identification of cosmic signals. The main component for the background is the flux of atmospheric neutrinos, which is caused by the interaction of cosmic rays, high energy protons and nuclei, with particles in the Earth’s atmosphere. Decay of charged pions and kaons produced in cosmic ray interactions generates a flux of atmospheric neutrinos and
Table 1. Summary of six novae. D and T are the distance to the system and the exposure time (Ackermann et al. 2014; Cheung et al. 2016) and \( N_0 \) is given in units of \( 10^{-11} \text{erg}^{-1}\text{cm}^{-2}\text{s}^{-1} \). Columns 3–5 are the derived expected number of neutrinos for the three low energy detectors. In the last column we give the total energy emitted in neutrinos in units of \( 10^{41} \) erg. The data of RS Oph are included for comparison.

| Novae       | D [kpc] | T [days] | \( N_0 \) | \( N_{\nu}^{\text{DeepCore}} \) | \( N_{\nu}^{\text{Hyper-K}} \) | \( N_{\nu}^{\text{ORCA}} \) | \( E_{\nu}^{\text{TOT}} \) |
|-------------|---------|----------|-----------|-------------------------------|-------------------|---------------------|-----------------|
| V339 Del    | 4.2     | 5.0      | 27        | 0.013                         | 0.0026            | 0.009               | 6.0             |
| V959 Mon    | 3.6     | 7.0      | 22        | 0.015                         | 0.0030            | 0.011               | 7.1             |
| V1324 Sco   | 4.5     | 10.0     | 17        | 0.016                         | 0.0033            | 0.012               | 13              |
| V407 Cyg    | 2.7     | 10.0     | 22        | 0.021                         | 0.0043            | 0.015               | 6.1             |
| V1369 Cen   | 2.5     | 2.5      | 18        | 0.004                         | 0.0009            | 0.003               | 3.0             |
| V5568 Sgr   | 2.0     | 1.0      | 47        | 0.005                         | 0.0009            | 0.003               | 1.2             |
| RS Oph      | 2.3     | 7.1      | 30        | 0.060                         | 0.0140            | 0.046               | 20              |

Table 2. Summary of six novae. The first three columns are the derived hypothetical expected number of neutrinos for the three high energy detectors. The fourth and fifth columns are the sum of events for high and low energy ranges and the sixth column is the average number of atmospheric background neutrino events from Metzger et al. (2016). The last two columns are the computed maximum distances at which the systems would need to be in order to allow for a 3\( \sigma \) detection above the atmospheric background neutrinos, for IceCube+DeepCore (\( D_1^{3\sigma} \)) and KM3NeT (\( D_2^{3\sigma} \)). The 3\( \sigma \) confidence levels for the background were calculated using Gehrels’ (1986) prescriptions for small numbers of events. The data of RS Oph are included for comparison.

| Novae       | \( N_{\nu}^{\text{IceCube}} \) | \( N_{\nu}^{\text{ANTARES}} \) | \( N_{\nu}^{\text{ARCA}} \) | IceCube+DeepCore | KM3NeT | \( N_{\nu}^{\text{Bkgnd}} \) | \( D_1^{3\sigma} \) [kpc] | \( D_2^{3\sigma} \) [kpc] |
|-------------|-------------------------------|-------------------------------|-------------------------------|-------------------|--------|--------------------------|---------------------------|---------------------------|
| V339 Del    | 0.467                         | 0.026                         | 2.163                         | 0.552             | 2.172  | 1.9                      | 0.94                      | 1.9                       |
| V959 Mon    | 0.533                         | 0.029                         | 2.467                         | 0.630             | 2.478  | 1.6                      | 0.89                      | 1.8                       |
| 1324 Sco    | 0.588                         | 0.033                         | 2.724                         | 0.696             | 2.736  | 1.2                      | 1.2                       | 2.4                       |
| V407 Cyg    | 0.761                         | 0.042                         | 3.525                         | 0.900             | 3.540  | 1.6                      | 0.8                       | 1.6                       |
| V1369 Cen   | 0.156                         | 0.009                         | 0.721                         | 0.185             | 0.724  | 1.2                      | 0.35                      | 0.7                       |
| V5568 Sgr   | 0.163                         | 0.009                         | 0.753                         | 0.193             | 0.756  | 3.3                      | 0.25                      | 0.5                       |
| RS Oph      | 0.0014                        | 0.0004                        | 0.020                         | 0.061             | 0.045  | 2.2                      | 0.2                       | 0.15                      |
In order to reduce the effect of the background, the search of neutrinos with energies in the multi-GeV range from novae should be performed only for upward going neutrinos. Indeed, Earth-filtered events allow to reduce the atmospheric muon background significantly. Moreover, only events due to $\nu_\mu$ charged current (CC) interactions should be considered. The muons that originate in such interactions indeed lead to a long track that allows to define the direction of an incoming neutrino with good accuracy, pointing back to the source.

An approximate estimate of the background events has been given in Metzger et al. (2016). They estimate the number of background events to be $\sim 1$ neutrino over a two week duration of typical nova LAT emission for DeepCore-IceCube. Following their work we have estimated the background events and report them in Table 2 for comparison, demonstrating them to be of the same order as the high energy and total energy calculations. This means that even if these nova were emitting in high energy, it would be difficult to distinguish source events from the background events.

5. DISCUSSION

In this paper we estimate the neutrino flux from RS Oph and other novae that emitted energy in the GeV range. We find that no nova to date has provided a strong enough neutrino signal to be detected by any of the present or future neutrino telescopes. The systems are either too far away or the interactions in the ejecta are not energetic enough. Being more energetic means the basic system parameters (e.g., WD mass, donor type or mass or evolutionary stage, separation, accretion rate, kinetic energy etc.) would have to be different. However, understanding what system parameters may produce sufficiently energetic interactions is not so simple. For instance, let us consider the extreme, rapidly recurring nova, M31N 2008-12a (Darnley et al. 2016) that erupts every year. It should be producing multiple mass shells that expand away from the WD, and they would not all be expanding at the exact same velocity, inevitably leading to collisions between different shells. In-homogeneity in the ejecta can form clumping which can lead to collisions as well. This interpretation can mislead to the simplistic conclusion that a system with a shorter recurrence period should be the place to look for highly energetic shocks. However, the amount of mass ejected in a nova decreases with decreasing time between eruptions. This means that being a recurrent nova is not necessarily the only requirement. RS Oph, being a SymRN, is embedded in the dense wind coming from its companion, so the nova eruption sends the ejected shell hurling into it, which is the source of the GeV radiation. This being the case, perhaps we should expect to find this range of energy in all SymNe? Ackermann et al. (2014) and Razzaque et al. (2010) have investigated the SymN V407 Cyg and found, for the relevant energy range, lower fluxes than found for RS Oph (based on kinetic energy considerations). We find similar results here for the low energy detectors. The difference between these two systems (RS Oph and V407 Cyg) that leads to different energy range output will require deep investigation of the many system parameters that determine the outcome of the eruption, as mentioned above.

Considering the GeV flux given in Ackermann et al. (2014) and Cheung et al. (2016) for five CNes, we estimate the expected number of neutrino events in the low energy range using the method described in §4.2 and find them to be substantially lower than for RS Oph — entirely undetectable with any current or future planned neutrino telescope. These results are consistent with those found by Metzger et al. (2016) for V1324 Sco in the low energy range. They also extrapolated the low energy flux to high energies and reported that they have obtained an extremely overestimated number of expected events. We followed this procedure for the six novae and obtained the hypothetical high values shown in Table 2. We used this method to calculate an expected number of neutrinos from RS Oph and obtained the entirely unrealistic prediction of $\sim 14$ neutrinos, whereas when we use the actual values obtained from observations of RS Oph, our expected number of events remains low. (See §4.3 and the last row of Tables 1 and 2). This emphasizes that such extrapolations should be carried out with great caution.

We note that we may have been systematically underestimating the neutrino emission from RS Oph due to the fact that we have not considered absorption of GeV—TeV photons from the surrounding environment. This calculation is not straightforward, since it involves modelling of the environment, including possible ancient shells that have expanded parsecs away from the source.

It has been suggested that the expected signal event rate may be increased by combining search among low and high energy neutrino detectors, i.e., KM3NeT/ORCA + KM3NeT/ARCA and DeepCore + IceCube (Zegarelli et al. 2022). Another option that can greatly increase the signal detection is summing the contribution of many novae (stacking). However, the same holds for the atmospheric background, such that complex stacking techniques are required in order to obtain a significant detection level. (See Zegarelli et al. (2022) for a detailed description of this procedure).

6. CONCLUSIONS
In this paper we have estimated the number of neutrino events expected for RS Oph and other novae observed at both low and high energy ranges. A number of interesting results have emerged:

(i) Given the current telescope sensitivity we cannot put any constraint on whether the GeV–TeV emission is a result of an hadronic process or a leptonic one. Our predictions for the number of neutrino events, both for the high and low energy ranges, are quite low. For the IceCube-DeepCore detections we estimate that the distance that a nova eruption similar to RS Oph must occur in order to obtain a 3$\sigma$ detection above the background, must not be larger than $\sim 1$ kpc. All the novae in the sample explored in this work are characterized by distances greater than 2 kpc. Our calculations imply the situation should improve with KM3NeT, whose higher sensitivity expands the detection threshold up to $\sim 2$ kpc. This would still not be sufficient to detect any of the novae in our sample, but given the current rates of nova explosions in the Milky Way, it will make the neutrino observations from nova explosions a realistic scenario (see item iv).

(ii) In the low energy regime, we find an expected number of events that is lower than found by Razzaque et al. (2010) and consistent with Metzger et al. (2015). The discrepancy with Razzaque et al. (2010) may be due to the fact that these authors did not have sufficient information on the actual effective area of the detector at the time. On the basis of our results we can estimate that the total energy from neutrino flux emitted by novae is of the order of $\sim 10^{41/42}$ erg, which corresponds to about $10^{-3/-5}$ the bolometric nova energy budget estimated for a nova explosion (Gallagher & Starrfield 1978).

(iii) In the high energy range we find a result lower than what was found by Metzger et al. (2016) due to the fact that we use the observed high energy photon flux while Metzger et al. (2016) extrapolated the low energy flux to high energies. Since we do not have any observations at $> 100$ GeV for the other novae that were detected at GeV by Fermi-LAT, we have extrapolated the low energy flux to high energy, following the approach taken by Metzger et al. (2016). The expected number of events that we derive at high energies are consistent with what was found by Metzger et al. (2016) for V1324 Sco. However, we stress that extrapolating the calculation in this way can introduce very large errors, as we have shown by computing the expected number of events for RS Oph by both methods.

(iv) The global nova rate in the Milky Way has been measured many times by several authors over the past decades (see Della Valle & Izzo (2020) for a summary). Currently, the frequency of occurrence of novae within the Galaxy is typified by a factor of two of uncertainty. Today we believe that its value is between 20 (Della Valle & Livio 1994) and 50 novae/year (Shafer 2017). Given the relatively low neutrino fluxes expected from novae (see Table 2), only nearby objects have the potential to be observed by neutrino observatories. A close inspection of Table 2 reveals that IceCube has the potential to reveal neutrino fluxes from novae up to a distance of $\sim 1$ kpc, whereas KM3NeT may be able to detect up to a distance of $\sim 2$ kpc. Our location in the Galaxy, in the outskirts of the galactic disk together with the requirement of distances less than 2 kpc, limit our interest only to the disk nova component. Following Della Valle & Duerbeck (1993) and using modern values for nova rates, we compute an upper limit for the nova eruption density in the disk of $\sim 1 \times 10^{-10}$ pc$^{-3}$ yr$^{-1}$. This figure, implies a rate of about $1^{+2.3}_{-0.8}$ novae every 4 years within 2 kpc and every $\sim 15$ years within 1 kpc. These values are not unrealistic and may provide, in the near future, a valuable test bed for assessing the validity of the physical processes, described in the literature, which are believed to underlie the high-energy emission observed in novae.

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