High energy neutrinos from fast winds in Novae

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ABSTRACT

We discuss a scenario in which TeV neutrinos are produced during explosions of Novae. It is argued that hadrons are accelerated to very high energies in the inner part of a Nova wind, as a result of reconnection of the strong magnetic field of a White Dwarf. Hadrons are expected to interact efficiently with a dense matter of the wind, either already during the acceleration process or during their advection with the equatorial wind. We calculate the neutrino spectra, and estimate the muon neutrino event rates in the IceCube telescope, in the case of a few Novae. In general, those event rates are unlikely to be detected with the present neutrino detectors. However, for favourable location of the observer, some neutrino events might be detected not only from the class of Novae recently detected in the GeV $\gamma$-rays by the Fermi-LAT telescope but also from novae not detected in $\gamma$-rays. The GeV $\gamma$-ray emission observed from Novae cannot originate in terms of the model discussed here, since protons are accelerated within a few stellar radii of the White dwarf, i.e. in the region in which GeV $\gamma$-rays are expected to be severely absorbed in the interactions with the radiation field and the matter of the wind.

Key words: stars: novae — stars: magnetic fields — radiation mechanisms: non-thermal — gamma-rays: stars

1 INTRODUCTION

Recently, GeV $\gamma$-ray emission has been detected by the Fermi-LAT telescope from explosions of several Novae (Abdo et al. 2010, Ackermann et al. 2014, see also Franckowiak et al. 2018 and the recent review by Chomiuk et al. 2021). It has been shown that in the case of a
few Novae, GeV \( \gamma \)-ray emission cannot extend with a simple power-law spectrum through the TeV energy range (Ahnen et al. 2015). However, the recurrent, symbiotic Nova RS Oph shows \( \gamma \)-ray emission extending up to sub-TeV energies (Wagner et al. 2021). Those \( \gamma \)-ray observations clearly indicate that the high energy processes play a very important role at the early phase of Nova explosion, i.e between a few to several days up to a few weeks after initial optical outburst.

In fact, acceleration of particles, up to TeV energies in the Nova shocks, has been expected already before these discoveries (see Tatischeff & Hernanz 2007). However localization of the emission region and the type of involved radiation processes are not clear up to now. Two mechanisms for the \( \gamma \)-ray production are usually considered, i.e. interaction of hadrons with the background matter and electrons with the optical radiation (Abdo et al. 2010, Sitarek & Bednarek 2012, Martin & Dubus 2013, Metzger et al. 2015, Ahnen et al. 2015, Vurm & Metzger 2018, Martin et al. 2018).

According to the present model of the Nova explosion, the thermonuclear runaway leads to ejection of a part of the layer of matter from the White Dwarf (WD) surface. The matter of the envelope, with the mass in the range \( \sim 10^{-7} - 10^{-3} \, M_\odot \) (Gallagher & Starrfield 1978, Shore 2012), moves with the velocity of the order of a thousand \( \text{km s}^{-1} \). However, nuclear reactions still continue in the rest of the layer turning to production of a fast wind from the hot surface of the WD. The radiation is emitted on the level close to (or even larger than) the Eddington limit (Kato & Hachisu 1994; Friedjung 2011). This fast wind, with the velocity of a few thousand \( \text{km s}^{-1} \), reaches slower expanding envelope in a few days, forming a strong shock (Li et al. 2017, Aydi et al. 2020a).

Production of \( \gamma \)-rays in hadronic processes, occurring in the external shocks, should be also accompanied by the emission of neutrinos with comparable energies (Razzaque et al. 2010). However, no significant neutrino excess could be identified from the direction of promising galactic source candidates and no significant excess was identified for the entire emission of the Galactic plane (Aartsen et al. 2017, Abbasi et al. 2021, Albert et al. 2018). In the case of Novae, neutrinos with GeV energies will be very difficult to detect with the present detectors, unless the \( \gamma \)-ray spectra do extend through the TeV energy range (Metzger et al. 2016, Fang et al. 2020). Neutrinos, with the TeV energies, are also expected provided that both electrons and hadrons are accelerated. However, hadrons reach clearly larger energies due to less efficient cooling (Sitarek & Bednarek 2012). In fact, the first upper limits on
Magnetic field reconnection region
WD
 Nova shock

Figure 1. Schematic representation of the model (not to scale) for the neutrino production in the inner region of the WD wind. We consider the binary systems with the parameters for which the energy density of the WD magnetic field dominates over the energy density of the wind close to the WD surface. Then, a part of the magnetosphere, close to the WD, has the dipole structure. However, at some distance, i.e. at the Alfven radius $r_A$, the wind starts to dominate, turning the magnetic field into reconnection. We argue that hadrons can be efficiently accelerated to the TeV energies in this reconnection region along the equatorial part of the wind. Relativistic hadrons are next captured in the random component of the turbulent wind. They are isotropised and slowly advected along the equatorial wind region. Hadrons suffer strong energy losses on the inelastic collisions with the matter of the wind producing pions. Neutrinos, produced from decay of charged pions, escape through the WD photosphere and the Nova ejecta without absorption.

the TeV neutrino fluxes from the Nova RS Oph has been already reported by the IceCube Collaboration (Pizzuto et al. 2021).

Here we investigate another scenario in which the high energy neutrinos are produced by hadrons accelerated in the inner, optically thick part of the fast wind as a result of reconnection of the magnetic field of strongly magnetized WD. We argue that such additional mechanism can accompany the process of acceleration of particles in the wind/ejected envelope shock which is likely responsible for the observed GeV $\gamma$-ray emission. In fact, $\gamma$-ray emission occurs simultaneously with the optical emission which is expected to be powered by the shocks (Aydi et al. 2020b).

2 MODEL FOR THE WIND IN NOVA

We consider the standard model for the Nova in which thermonuclear explosion occurs in the thick layer of matter on the surface of the WD. The layer of matter appears as a result of the accretion process from the companion star as observed in the Cataclysmic Variables. Since the WDs are characterised by a strong surface magnetic field (up to $\sim 10^8$ G), the accretion process, and the distribution of the matter on the WD surface, can be strongly inhomogeneous. During the explosion, a significant amount of the matter (of the order of
$10^{-5} - 10^{-3} M_\odot$) is expelled with the velocity which is typically below $10^3$ km s$^{-1}$ (see the review by Chomiuk et al. 2021). The surface of the WD is heated to temperature of the order of $\sim 10^6$ K. The nuclear reactions still continue in a layer of matter on the WD surface. Produced thermal radiation, with luminosity in the range $10^{38-39}$ erg s$^{-1}$, can even exceed the Eddington luminosity for the WD. Due to the pressure of this radiation, a fast wind with the velocity of the order of $\sim 2000 - 4000$ km s$^{-1}$ is launched. The kinetic energy of the wind is comparable to the thermal luminosity of this fast wind. It is expected that the fast wind can be aspherical due to the inhomogeneous layer on the WD surface and also strong magnetic field of the WD.

In fact, WDs are characterised by strong surface magnetic fields of the order of $\sim 10^7$ G in the case of isolated objects (Wickramasinghe & Ferrario 2000). In the case of accreting WDs of the AM Her type the average surface magnetic fields are $(38 \pm 6) \times 10^6$ G (Wickramasinghe & Ferrario 2000). The surface magnetic fields of the intermediate polars are expected to be comparable. For example, recent observations of the Nova Herculis 2021 show modulation of the soft X-ray emission which is interpreted as due to the presence of a strong magnetic field (Drake et al. 2021). The initial structure of the magnetic field of the WD is expected to be of the dipole type. During initial ejection of the WD envelope, the dipole structure of the magnetic field is modified by the dense moving plasma. However, during the phase of a fast and less dense wind, the magnetic field can recover its dipole structure starting from the WD surface. As a result, the magnetosphere of the WD can be characterised by a complex structure. It is similar to that postulated in the case of the early type massive stars with fast winds (Usov & Melrose 1992, Trigilio et al. 2004, Leto et al. 2006, Leto et al. 2017, Bednarek 2021). In general, two regions can be distinguished. Below the Alfven radius $R_A$, where the energy density of the magnetic field dominates over the kinetic energy density of the wind, the magnetosphere recovers its dipole structure. The winds launched from the Northern and Southern region, driven by the magnetic fields towards the equatorial plane, collide with each other forming a plasma with temperature of the order of several $10^6$ K (Shore & Brown 1990, Babel & Montmerle 1997, Gagne et al. 2005). The magnetic field lines in this part of the magnetosphere are closed. Above $R_A$, the energy density of the wind dominates over the energy density of the magnetic field. In such a case, the magnetic field is forced into reconnection in the equatorial region of the magnetosphere. Particles can be accelerated in this reconnection region to relativistic energies. The geometry of this scenario is shown in Fig. 1.
Here, we are interested in the radiation processes due to the protons accelerated in this reconnection region. The maximum energies of protons depend on the length scale of the reconnection region. Accelerated protons already interact with the matter either already in the acceleration region or after being injected into the equatorial region of the WD wind. In the second case, they can be effectively isotropised, provided that the wind shows significant level of turbulence. After injection to the equatorial wind, relativistic protons are slowly advected in the outward direction with the equatorial wind, suffering multiple interactions in a dense wind relatively close to the WD surface. We calculate the fluxes of neutrinos, produced in collisions of relativistic protons with the wind matter, and consider whether they can be detected by the present and future neutrino detectors. Note that, neutrinos, produced during the acceleration process in the reconnection region, are expected to be collimated along the equatorial wind. On the other hand, protons, escaping from the reconnection region into the equatorial wind, produce neutrinos in a much larger solid angle.

3 ACCELERATION OF HADRONS IN THE WD WIND

We consider the acceleration region in the fast wind of a Nova. The Alfven radius in the windy magnetosphere of the WD can be estimated from the balance, $B^2/8\pi = \rho v^2_w/2$, where $\rho$ is the density of the wind and $v_w = 3 \times 10^3 v_3$ km s$^{-1}$ is the WD wind velocity. The magnetic field strength of the WD is of the dipole type, $B = B_s/r^3$, where $R = rR_{\text{WD}}$ is the distance from the WD and $B_s = 10^7 B_7$ G is the magnetic field strength on the surface of WD at the equator. We assume the radius of the WD $R_{\text{WD}} = 6 \times 10^8$ cm (Nauenberg 1972). Density of the matter is given by the WD mass loss rate,

$$\rho = \frac{2L_w}{4\pi r^2 R_{\text{WD}}^2 v^3_w} \approx 10^{18} \frac{L_{38}}{v^3 v_3} \text{ cm}^{-3}.$$  \hfill (1)

The mass loss rate, $\dot{M}$, determines the power of the wind $L_w = \dot{M} v^2_w/2 = 10^{38} L_{38}$ erg s$^{-1}$. Then, the Alfven radius (expressed in units of the radius of the WD) is located at,

$$r_A = \left[R_{\text{WD}}^2 B^2_s v_w/(2L_w)\right]^{1/4} \approx 2.7[B^2_t v^3_t/L_{38}]^{1/4}. \hfill (2)$$

The energy density of the wind dominates over the energy density of the magnetic field in the whole region above the surface of the WD for the condition $B_7 < 0.13(L_{38}/v_3)^{1/2}$. Then, the wind expands freely everywhere above the surface of the WD. However, when the magnetic field of the WD is stronger, then the structure of the wind changes. Above the distance estimated in Eq. 2, the magnetic field of the WD wind can be forced into
the reconnection in the equatorial region of the dipole magnetic field (see Fig. 1). In such a reconnection region, particles can reach relativistic energies. Since the wind is expected to be turbulent, the reconnection region is characterized by some degree of coherence. We assume that the dimension of the reconnection region is proportional to its distance from the WD, i.e. \( L_{\text{rec}} = \eta r_{\text{WD}} \), where the scaling factor \( \eta = 1 \eta_1 \) has to be less than unity.

The maximum energies of protons accelerated in the reconnection region can be estimated from,

\[
E_{\text{max}} = e \beta_w \alpha B L_{\text{rec}} \approx 1.8 v_3 \eta_1 B r^{-2} \text{ PeV},
\]

where \( \beta_w = v_w/c = 0.01 v_3 \) is the velocity of the wind in units of the velocity of light, \( \alpha \) is the reconnection efficiency of the order of \( \alpha \sim 0.1 \) (e.g. Uzdensky 2007), and \( e \) is the elemental charge. At the bottom border of the reconnection region, determined by the Alfven radius \( r_A \), the maximum energies of particles are

\[
E_{\text{max}} \approx 240 \eta_1 (v_3 L_{38})^{1/2} \text{ TeV}.
\]

Already during the acceleration process, hadrons might be able to lose energy on the pion production in collisions with the dense radiation and matter of the wind. We estimate the importance of those processes on the final energies of hadrons.

The electromagnetic luminosity of a typical Nova is in the range, \( L_{\text{WD}} = 10^{38} - 10^{39} \text{ erg s}^{-1} \). We assume that the Nova emission is close to the Eddington luminosity of the White Dwarf, i.e. \( \sim 10^{38} \text{ erg s}^{-1} \) is emitted from the surface of the White Dwarf. Then, the surface temperature has to be \( T_{\text{WD}} \approx 8 \times 10^5 \text{ K} \) (see Kahabka & van den Heuvel 1997 and also the recent case of the Nova RS Oph, Pei et al. 2021). The energies of thermal photons are equal to \( \varepsilon = 3 k_B T_{\text{WD}} \sim 200 \text{ eV} \). The density of these photons is calculated assuming that the emission from the WD surface is of the black body type with temperature \( T_{\text{WD}} \). It is equal to \( n_{\text{ph}} \approx 10^{19} r_{-2} ^{-2} \text{ cm}^{-3} \). The minimum energies of protons, required for production of pions in collisions with such thermal photons, have to be \( E_{\text{p}}^{\text{min}} = E_{\gamma \rightarrow \pi}^{\text{th}} m_p c^2/\varepsilon \sim 700 \text{ TeV} \), where \( E_{\gamma \rightarrow \pi}^{\text{th}} = 140 \text{ MeV} \) is the threshold energy for the pion production in collision of the \( \gamma \)-rays with the proton. We conclude that protons, accelerated in the reconnection region, are not able to lose energy in collisions with dense radiation field due to too low energies.

On the other hand, the mean free path for the energy losses of relativistic protons, in collisions with the matter of the wind, is

\[
\Lambda_{\text{pp}} = (\kappa_{\text{pp}} \rho \sigma_{\text{pp}})^{-1} \approx 6.7 \times 10^7 v_3^3 r_{-2}^2 / L_{38} \text{ cm},
\]
where the inelasticity coefficient is $\kappa_{pp} = 0.5$. This mean free path is shorter than the length scale of the reconnection region, $L_{rec} = \eta R_{WD} r = 6 \times 10^{8} \eta_1 r$ cm, at distances $r < 10 \eta_1 L_{38}/v_3^3$. Then, the maximum energies of protons due to the energy losses are

$$E_{\text{pp max}}^{\text{vp}} = e^\beta_w \alpha B_\Lambda_{pp} \approx 200 v_3^4 B_7/(L_{38} r) \text{ TeV.}$$

(6)

For the bottom edge of the reconnection region at $r_\Lambda$ (see Eq. 2), the maximum energies of protons, due to the energy losses, are

$$E_{\text{pp max}}^{\text{vp max}} \approx 74 v_3^{15/4} B_7^{1/2}/L_{38}^{3/4} \text{ TeV.}$$

(7)

We conclude that the maximum energies, to which protons can be accelerated, are given by Eq. 4 for $\Lambda_{pp} < L_{rec}$ (acceleration limited by the energy losses on pion production), and by Eq. 7 (for the acceleration not limited by the energy losses). These maximum energies ($E_{\text{max}}^{\text{vp}}$) are reported for a few considered example Novae in Table. 1. The maximum energies are calculated for the surface magnetic field of the WD equal to $10^7$ G and $10^8$ G (values in brackets). The scaling factor of the reconnection region is assumed to be $\eta = 1$.

4 PRODUCTION OF NEUTRINOS

Here we show the results of a simple estimation of the muon neutrino event rates in the neutrino telescope, in terms of the above defined model, in the case of protons injected with the mono-energetic spectrum. Next, a more detailed numerical calculations, in the case of acceleration of protons with the power-law spectrum (spectral index -2), are presented. These two extreme models are investigated since acceleration of particles in the reconnection regions is expected to produce flat power-law spectra. The calculations of the neutrino spectra are done applying simulated spectra of muons and pions produced by relativistic protons at a given energy using CORSIKA Monte Carlo package with the QGSJET-II model for the high-energy interactions (Heck et al. 1998).

4.1 Quasi-monoenergetic injection of protons

At first, we provide very simple estimates of the neutrino event rates in the IceCube telescope by assuming that, particles escape from the reconnection region into the equatorial wind. They are isotropised due to the turbulence in the wind. The Larmor radius of protons, with energies given by Eq. 7, in the local magnetic field is equal to $R_L \approx 4.4 \times 10^5 v_3^{9/2}/L_{38}^{3/2} B_7$ cm. It is clearly shorter than the typical distance scale considered in the model, $rR_{WD}$. Therefore,
particles are frozen into the wind being slowly advected with the velocity of the equatorial wind. Due to a very large density of the wind in this region (see Eq. 1), we assume that all injected relativistic protons interact producing pions. We estimate analytically the number of muon neutrinos in a very simple way by assuming that two mono-energetic muon neutrinos are produced from the decay of a single pion. On the other hand, the number of pions, from a single mono-energetic proton-proton interaction, is given by the multiplicity $\mu$. Every muon neutrino takes on average one forth of the energy of produced pion and the average number of produced pions depends on their multiplicity (which depends on the energy of interacting proton) and on the inelasticity coefficient. So then, in the case of the interaction of mono-energetic protons we do not take into account the spectrum of produced secondary particles. However, it is taken into account in our more realistic model for protons injected with the power-law spectrum (see next section). The energies of neutrinos, from decay of those pions, can be roughly estimated from,

$$E_\nu \sim \kappa_{pp} E_p/(4\mu) \approx 0.36v_3^{15/4} B_7^{1/2} / L_{38}^{3/4} \text{ TeV},$$

(8)

where the inelasticity coefficient $\kappa_{pp} = 0.5$, the average multiplicity of the charged pion production in collisions of protons with the matter changes slowly with the proton energy. It is equal to $\mu \approx 25.8$ for the protons with the characteristic energies given by Eq. 7 (see Grosse-Oetringhaus & Reygers 2010). When estimating neutrino energies, we do not take into account energy losses of pions and muons before their decay to neutrinos. In fact, they are expected to be negligible in the case of charged pions (due to their short decay time scale) but might be important in the case of muons. In such a case, the predicted fluxes of muon neutrinos should be reduced by a factor of two. We calculate the number of muon neutrinos from, $N_\nu \sim 2\mu N_p$, where the total number of accelerated protons is $N_p = L_p/E_p$, $L_p$ is the total energy in accelerated protons and $E_p$ is the energy of mono-energetic protons. We assume that protons take a part of the wind energy which fall onto the surface of the reconnection region in the range of distances between $r_A$ and $2r_A$. This surface defines a part of the solid angle, $\Omega = 0.1\Omega_{-1}$, of the wind ejected from the WD surface. If the efficiency of proton acceleration is of the order of $\chi = 0.1\chi_{-1}\%$, then $L_p = 0.01\chi_{-1}\Omega_{-1} E_w$. The typical lifetime of $\gamma$-ray emission from Novae is of the order of $\tau = 10\tau_{10}$ days. The total wind energy can be estimated on $E_w = 10^{38}L_{38}\tau_{10}\Omega_{-1}$ ergs, and the energy in relativistic protons is

$$L_p = 8.6 \times 10^{41} L_{38} \chi_{-1} \tau_{10} \Omega_{-1} \text{ ergs}.$$  (9)
Then, the total number of emitted neutrinos is,

\[ N_\nu \sim 2 \mu N_p \sim 3.7 \times 10^{41} \chi_{1-1} \Omega_{-1} \tau_{10} L_{38}^{7/4} / (B_{1/2} v_3^{15/4}) \nu, \]  

(10)

The neutrino flux on the Earth from the example Nova, which exploded at a typical distance of 3 kpc, is

\[ F_\nu = \frac{N_\nu}{4\pi D^2} \sim 3.8 \times 10^{-4} \chi_{1-1} \Omega_{-1} \tau_{10} L_{38}^{7/4} / B_{1/2} v_3^{15/4} D_3^2 \nu \text{ cm}^{-2}. \]  

(11)

The number of neutrino events produced by such a Nova in the IceCube type neutrino detector is estimated as,

\[ N_{\nu_{\text{det}}} = SF_\nu \approx 0.38 \chi_{1-1} \Omega_{-1} \tau_{10} L_{38}^{7/4} / B_{1/2} v_3^{15/4} D_3^2 \nu / \text{Nova}, \]  

(12)

where we used the effective detection area of the IceCube with a Deep Core, \( S \approx 10^3 \text{ cm}^2 \) at \( E_\nu = 0.36 \text{ TeV} \) (Abbasi et al 2012). The above simple estimate of the neutrino event rate from the example Nova is done for the lower limit on the wind power and the energy conversion efficiency from the WD wind to relativistic protons equal to 1%. In such a case, the IceCube neutrino detector has a chance to observe a few neutrino events from the whole population of Novae, which are already detected in the GeV \( \gamma \)-rays by the Fermi-LAT telescope. In case of no detection, the parameters of the considered model such as, the acceleration efficiency of protons \( \chi \), the solid angle of the wind which falls into reconnection region, or the activity period of the energetic wind \( \tau \), will be constrained.

In the next subsection, we also consider more realistic scenario in terms of the proposed model in which protons are injected from the reconnection region with the power-law spectrum. They cool completely in the dense WD wind. In this case we make use of a more detailed numerical calculations.

## 4.2 Protons with the power-law spectrum

In this scenario, we calculate the muon neutrino event rates assuming complete cooling of relativistic protons, since the column density of the matter in the WD wind is very large. This column density is estimated on \( X_{p\gamma} = \int_{R'}^{\infty} \rho(R)R_{WD} dr \sim 350 L_{38}/v_3^3 \) gram. Relativistic protons are advected with the wind with a relatively low velocity, \( v_w \ll c \). Therefore, they have time to cool completely in the interactions with the matter. Protons are injected with the power-law spectrum from the reconnection region up to the maximum energies as estimated in Sect. 3.1. The spectrum of protons is normalized to its power \( L_p \) (see Eq. 9),
$L_p = A \int_{E_{\text{min}}}^{E_{\text{max}}} E_p^{-\beta} E_p dE_p$, where $E_{\text{max}}$ is the maximum energies of protons (see Eq. 4 and Eq. 7) and $E_{\text{min}}$ is equal to 10 GeV. In this way, the normalization coefficient 'A' is obtained.

The muon neutrino fluxes expected on the Earth from a few example Novae (see their parameters reported in Table 1) are shown in Fig. 2. These neutrino spectra are compared to the Atmospheric Neutrino Background (ANB) within $1^\circ$ of the source (Lipari 1993). We also calculate the muon neutrino event rate in the IceCube neutrino telescope, for two example models of proton acceleration, following the formula,

$$N_\nu = \int_{E_{\nu\text{min}}}^{E_{\nu\text{max}}} S(E_\nu) \frac{dN_\nu}{dE_\nu} dE_\nu,$$

where $S(E_\nu)$ is the effective area of the IceCube neutrino detector as a function of neutrino energy (Abbasi et al. 2012) and $dN_\nu/dE_\nu$ is the neutrino spectrum produced by protons in collisions with the matter.

5 SPECIFIC EXAMPLES OF $\gamma$-RAY NOVAE

We performed example calculations of the expected muon neutrino flux from a few Novae detected in the GeV $\gamma$-rays by the Fermi-LAT. These Novae differ in basic parameters (e.g. the total kinetic energy) allowing acceleration of protons to different maximum energies. Thus, they are different representative cases from the Nova population. The parameters of these Novae, needed for the modelling, are collected in Table 1. In our calculations, we estimate the lower limit on the total energy of the Nova explosion as a product of the power of the wind and duration of $\gamma$-ray emission from Nova. The optical bolometric luminosity of the Nova ($L_{\text{Bol}}$) is estimated as the ratio of the $\gamma$-ray power and the coefficient describing the ratio of the $\gamma$-ray emission to the observed optical bolometric emission (the parameter $\xi$ in Table 1). The results of observations in the optical energy range of the novae considered by us in this work are reported in Aydi et al. (2020b) and Abdo et al. (2010). The maximum energies, to which protons can be accelerated, are estimated in Eq. 4 (in the case of unsaturated acceleration) and by Eq. 7 (in the case of saturation of the acceleration process by proton energy losses in collisions with the matter). In the case of unsaturated acceleration, protons are ejected from the reconnection regions into the equatorial wind. They are isotropised producing neutrinos in the whole solid angle. In the case of saturated acceleration, neutrinos are mainly produced in the general plane of the reconnection region (see Fig. 1), i.e. in a relatively small solid angle. In this case neutrinos are emitted anisotropically. For the Novae,
Neutrinos from Novae

Figure 2. The spectra of muon neutrinos from the wind regions of a few Novae: V906 Car (solid curves), V407 Cyg (dotted-dashed), and V339 Del (dashed). The parameters of the Novae are listed in Table 1. It is assumed that 1% of the energy of the Nova wind is transferred to relativistic protons. Two models, for the surface magnetic field, equal to $10^7$ G and $10^8$ G, are considered for the estimation of the maximum energies of accelerated protons. In the case of V407 Cyg: For the weaker magnetic field the acceleration of protons is limited by their energy losses on pion production (see Eq. 7, thick curves), but for stronger magnetic field, the acceleration is not limited by the energy losses. (see Eq 4, thin curves). In the case of V906 Car and V339 Del, for both surface magnetic fields of the WD, the acceleration process is limited by their energy losses. The scaling factor of the reconnection region is assumed to be $\eta = 1$. The neutrino spectra are confronted with the atmospheric neutrino background (ANB) within $1^\circ$ of the source collected during the period of 10 days (thin, dotted curves, see Lipari 1993). Two curves correspond the the horizontal ANB (upper flux) and vertical ANB (lower flux).

V407 Cyg, V906 Car, and V339 Del, we show the expected spectra of neutrinos (Fig. 2) and their event rates in the IceCube neutrino telescope (Tab. 1). It is assumed that 1% of the Nova total energy ($E_{\text{Nova}}$) is converted to relativistic protons ($L_p = 0.01E_{\text{Nova}}$), with the power-law spectrum and spectral index equal to $\beta = 2$. This value for the spectral index has been selected since the modelling of the acceleration of reconnection regions postulate the spectra of particles with the spectral index even lower than 2 (e.g. Guo et al. 2016). Since we do not know what is the detailed geometry of the reconnection region, and also the collimation of produced neutrinos, the event rates of neutrinos are calculated assuming isotropy. Note, that in the case of a significant collimation of protons, interacting already during the acceleration process in the reconnection region, and favourite location of the observer, the neutrino event rates can be enhanced.

5.1 A moderate Nova V407 Cyg

V407 Cyg is the first Nova detected in the GeV $\gamma$-rays (Abdo et al. 2010). It is relatively nearby symbiotic Nova with a fast wind and a relatively low wind power (see Table. 1). Such features allow acceleration of protons in the reconnection region to energies above hundred TeV. We consider acceleration of protons in two cases, i.e for the surface magnetic field
of the WD $10^7$ G and $10^8$ G. In the first case, protons lose efficiently energy in collisions with the matter on the pion production already in the reconnection region (acceleration limited by the energy losses). In the second case, acceleration of protons is not limited by the energy losses since the maximum energies, which can be reached by protons, are below the limit given by Eq. 4. They are injected into a turbulent equatorial wind region. They become isotropised. They collide with the matter producing neutrinos quasi-isotropically. As an example, we consider the WD with the coherence scale of the reconnection region described by $\eta = 1$. The expected spectra of neutrinos in those two cases are shown in Fig. 2. Around TeV energies, the neutrino spectra from those example Nova are comparable to the ANB. The neutrino event rates, for the energy conversion efficiencies mentioned above and assuming isotropic emission, are less than one (Table 1). Therefore, their detection by the IceCube size detector will be extremely challenging. Note however, that in the first model (saturated acceleration), neutrino emission is expected to be significantly collimated. This effect can increase the neutrino event rates from specific sources at a cost of decreasing the chance of observability.

### 5.2 A powerful Nova V906 Car

V906 Car is one of the most powerful Nova observed up to now in GeV $\gamma$-rays (Aydi et al 2020b). It belongs to the class of classical Novae. It has the mild wind velocity but the large wind power (see Tab. 1). In such a case, acceleration of protons is saturated at a relatively low energies (a few to several TeVs) for the magnetic field of the WD in the range $10^7 - 10^8$ G. The calculated neutrino spectra are below (but not very far) from the ANB (see Fig. 2). The predicted neutrino event rates (assuming again isotropic production) are comparable to that expected from V407 Sgr. Detection of such low neutrino fluxes with the IceCube is challenging. However, in both models, acceleration is limited by the energy

| Nova   | $d$ (kpc) | $\tau$ (days) | $L_\gamma$ (erg s$^{-1}$) | $\xi$ | $E_{\text{Nova}}$ (erg) | $v_w$ (km s$^{-1}$) | $L_w = L_{\text{Bol}}$ (erg s$^{-1}$) | $E_{\text{max}}^p$ (TeV) | $N_{\text{IceCube}}^\nu_{\text{det}}$ | $\nu_{\text{e}}$ events | Ref. |
|--------|-----------|---------------|-----------------|------|-----------------|-----------------|-----------------|-----------------|------------------|-----------------|-------|
| V407 Cyg | 2.7 | 15 | $2.8 \times 10^{35}$ | $4 \times 10^{-3}$ | $10^{44}$ | 3200 | $7 \times 10^{37}$ | 130 (207) | 0.14 (0.16) |
| V906 Car | $4.0 \pm 1.5$ | $> 20$ | $1.7 \times 10^{36}$ | $2 \times 10^{-3}$ | $1.5 \times 10^{45}$ | 2500 | $8.5 \times 10^{38}$ | 67 (22) | 0.125 (0.4) |
| V339 Del | $4.5 \pm 0.6$ | 27 | $6.7 \times 10^{34}$ | $4 \times 10^{-4}$ | $3.9 \times 10^{44}$ | 2000 | $1.7 \times 10^{38}$ | 11.5 (38) | 0.05 (0.14) |

*Table 1.* Estimated muon neutrino event rates in the IceCube neutrino detector $(N_{\text{IceCube}}^\nu_{\text{det}})$ from a few Novae: $d$ - the distance to Nova, $\tau$ - the duration of $\gamma$-ray emission phase, $L_\gamma$ - the average $\gamma$-ray luminosity, $\xi$ - the ratio of $\gamma$-ray power to bolometric luminosity $L_{\text{Bol}}$, $E_{\text{Nova}} = \tau \cdot L_{\text{Bol}}$ the total energy of Nova, $v_w$ - the wind velocity, $L_w = L_{\text{Bol}}$ - the wind power equal to the bolometric luminosity, $E_{\text{max}}^p$ - the maximum energies of accelerated protons for $B_s = 10^7$ G and $10^8$ G. References: (a) Abdo et al. (2010), (b) Aydi et al. (2020b), (c) Schaefer et al. (2014), (d) Shore et al. (2013b).
losses of protons. Therefore, neutrino emission is expected to be collimated within a part of the celestial sphere. The collimation should increase the event rates for the observer located within this solid angle. This effect is difficult to take into account since it depends on the details of the process of proton acceleration and subsequent interaction.

5.3 A weak Nova V339 Del

V339 Del is the case of a less powerful Nova with slower wind velocity and low GeV $\gamma$-ray emission (Ackermann et al. 2014). Protons are accelerated in the reconnection region to the intermediate energies (several to a few tens of TeV) for the range of magnetic field strengths $10^7 - 10^8$ G. For such magnetic field strengths, the acceleration process is limited by the energy losses. So, neutrinos should show some level of collimation which might increase the event rates reported in Table 1 in the case of the observer with the neutrino emission cone. Predicted neutrino event rates (if re-calculated for the isotropic case) are a factor of a few lower than expected in the case of considered above Novae.

We conclude that the neutrino event rates (expected in this model) are below unity in the case of specific Novae. Their detection by the present neutrino detectors is extremely challenging unless the neutrino flux is not strongly beamed in the direction towards the observer. However, some muon neutrinos might be observed if the whole population of Novae (including those not observed in GeV $\gamma$-rays by Fermi-LAT) is considered. We see some effects which can increase predicted here neutrino event rates. For example, neutrino production is expected to be anisotropic which might increase the event rates from specific novae above unity. Moreover, the active phase of the proton acceleration might last longer than applied here the period of the GeV $\gamma$-ray emission. Note that, the surface of the WD shows strong soft X-ray emission. This is the evidence of a hot WD surface and extended activity period of the fast wind. Therefore, acceleration of protons, in the inner magnetosphere of the WD, may last longer than applied here activity period of the $\gamma$-ray emission.

6 $\gamma$-RAYS FROM HADRONIC COLLISIONS IN THE WIND

$\gamma$-rays and leptons are unavoidable products of collisions of hadrons with the matter of the wind. However, in contrast to neutrinos, $\gamma$-rays strongly interact with the soft radiation field of the Nova, and its dense wind, since they are produced deep within the photosphere. We assume that locally within the photosphere, the medium is dense enough that the radiation
field can be locally approximated by the radiation in thermal equilibrium. Then, the local temperature of the radiation, as a function of distance from the WD, can be described between the WD surface and the outer radius of the photosphere by the condition,

\[ L_{\text{ph}} = 4\pi R^2 \sigma_{\text{SB}} T^4, \]

\( \sigma_{\text{SB}} \) is the Stefan-Boltzmann constant. From the recent observations of the Nova RS Oph, the surface temperature of the WD is estimated on \( T_{\text{WD}} = 7 \times 10^5 \) K, assuming the radius of WD \( R_{\text{WD}} = 6 \times 10^8 \) cm). Then, the gradient of temperature within the photosphere is \( T(r) = 7 \times 10^5/r^{1/2} \) K, where \( r \) is the distance in units of WD radius. \( \gamma \)-rays, produced close to the WD surface, should be effectively absorbed in the local radiation field on their way outside Nova wind since the optical depth should be very large. In fact, the local optical depth for \( \gamma \)-rays, with energies corresponding to the peak of the \( \gamma-\gamma \) cross section is \( \tau_{\gamma\gamma} \sim n_{\text{ph}} R_{\text{WD}} \sigma_{\gamma\gamma} \approx 870/r^{1/2} \) for \( \sim \)TeV \( \gamma \)-rays. Therefore, we conclude that those \( \gamma \)-rays with energies above a few GeV are completely absorbed. On the other hand, \( \gamma \)-rays with energies below a few GeV can be absorbed in the matter of the wind. The optical depth for \( \gamma \)-rays on this process can be estimated from \( \tau_{p\gamma} = \sigma_{p\gamma} X \sim 6 L_{38} v_3^{-3} r^{-1} \), where the cross section for \( \gamma \)-ray absorption in collision with a proton is \( \sigma_{p\gamma} = 10^{-26} \) cm\(^2\) (in the case of complete screening) and the column density of the matter in the wind is \( X = R_{\text{WD}} \int_r^\infty n(r) dr \approx 6 \times 10^{26} L_{38} v_3^{-3} r^{-1} \) cm\(^{-2}\).

This absorption effects concern \( \gamma \)-ray photons with energies clearly above the threshold for \( e^\pm \) pair production. Therefore, we conclude that the GeV \( \gamma \)-rays, observed from Novae by the Fermi-LAT telescope, have to originate in another region than considered by us reconnection of the magnetic field, e.g. either in the shock region of expanding Nova or in the internal shock due to collision of fast wind with slow ejecta (see e.g. models mentioned in the Introduction). The GeV \( \gamma \)-ray production has to be located outside photosphere of the Nova. So, in fact our calculations of the neutrino emission from Novae are not related to their GeV \( \gamma \)-ray emission. Therefore, in principle also Novae not detected in GeV \( \gamma \)-rays can be interesting targets for the neutrino telescopes.

7 CONCLUSION

We considered the production of neutrinos in collisions of relativistic protons with the matter of the fast wind emanating from the White Dwarf after Nova explosion. The acceleration process of protons occurs in the reconnection regions of the strong magnetic field of the WD driven by the dense winds. We show that protons can reach TeV energies for the
parameters of the Nova explosions, as observed in the case of Novae showing GeV $\gamma$-ray emission. For reasonable conversion factor of energy from the Nova wind to the relativistic protons (of the order of 1%), we obtained neutrino spectra which are close to the level of the Atmospheric Neutrino Background. The predicted muon neutrino event rates in the IceCube detector, from a few specific Novae, are not so far but less than one (assuming isotropic production of neutrinos). Therefore, detection of predicted in this model neutrino event rates will be extremely challenging with the current neutrino telescopes. We argue that, for the parameters of the considered models, the acceleration of protons is limited by their energy losses already in the reconnection region. Then, neutrinos, from collisions of relativistic protons with the matter, should be strongly collimated along the direction of the reconnection region. For the location of the observer within the neutrino emission cone, the neutrino fluxes (and event rates in the detector from the specific Novae reported in Table. 1) should be enhanced in respect to the isotropic case by the factor corresponding to the reciprocal of the solid angle in which neutrinos are emitted from the reconnection region. We conclude that Novae, whose reconnection regions are accidentally directed to the observer on the Earth, might provide the chance to produce correlated events in the neutrino detector of the IceCube size.

We note, that the estimated neutrino event rate is proportional to the time scale of the activity of the Nova wind. In our example calculations, we identify this time scale with the duration of the phase of the $\gamma$-ray emission in Novae (typically of the order of several days). However, observations of the super-soft X-ray emission from the WD surface (Kahabka & van den Heuvel 1997) indicate that the fast wind phase of the Nova might last longer, of the order of months. In such a case, the neutrino fluxes reported in Table. 1 will be proportionally increased, even by a factor of a few.

We also show that the $\gamma$-rays, produced in these same interactions as neutrinos, are not likely responsible for the observed GeV $\gamma$-ray emission from the Novae. In this scenario, the cooling process of relativistic protons occurs deep in the wind region of Nova, i.e. close to its hot surface and in dense wind. Therefore, $\gamma$-rays, from decay of pions, are expected to be completely absorbed. This high energy $\gamma$-ray emission requires another acceleration site of particles, e.g. in the initial shock wave propagating in the surrounding medium of the Nova or in the region of collision of the fast wind with the initially ejected material (see references for models mentioned in the Introduction).
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DATA AVAILABILITY

The simulated data underlying this article will be shared on reasonable request to the corresponding author.

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