High-energy Neutrinos from Galactic Superbubbles

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Abstract

We study the propagation of cosmic rays (CRs) generated by sources residing inside superbubbles. We show that the enhanced magnetic field in the bubble wall leads to an increase in the interior CR density. Because of the large matter density in the wall, the probability for CR interactions on gas peaks there. As a result, the walls of superbubbles located near young CR sources efficiently emit neutrinos. We apply this scenario to the Loop I and Local Superbubble: these bubbles are sufficiently near such that CRs from a young source such as Vela interacting in the bubble wall can generate a substantial fraction of the observed astrophysical high-energy neutrino flux below ~few × 100 TeV.

Key words: astroparticle physics – cosmic rays – ISM: bubbles – neutrinos

1. Introduction

High-energy astrophysical neutrinos are a key tool for understanding the non-thermal universe (Gaisser et al. 1995). They are produced together with photons in interactions of cosmic rays (CR) on matter and background photons close to their sources and during propagation. These neutrinos travel undisturbed, being neither absorbed as high-energy photons nor deflected in magnetic fields as charged particles. These two properties distinguish neutrinos as a unique tracer of CR sources.

The discovery of astrophysical neutrinos in 2013 by the IceCube collaboration marked the beginning of neutrino astronomy (Aartsen et al. 2013, 2014). There are two main experimental channels to detect such neutrinos. Using the tracks of muons produced by the interactions of muon neutrinos, one can measure the neutrino arrival directions very precisely, while its energy can be only estimated within a factor of a few (Aartsen et al. 2016). To avoid the atmospheric neutrino background, the energy spectrum of astrophysical neutrinos in this channel is measured above 200 TeV. Because neutrinos of this energy are heavily absorbed in the Earth, the spectrum is dominated by a thin strip around the horizon. It is consistent with a 1/\(E^{-2.5}\) power law, which is predicted in many models of extragalactic neutrino sources (Stecker et al. 1991; Mannheim 1995; Waxman & Bahcall 1997; Loeb & Waxman 2006).

In a second channel using cascade events inside the IceCube detector, one can detect electron neutrinos interacting via the charge current and, additionally, all neutrino flavors interacting via neutral currents. In this channel, the energy of a neutrino can be measured with up to 10% accuracy but its derived arrival direction has an error that is typically larger than 10°. The energy spectrum of astrophysical neutrinos derived in this channel is close to 1/\(E^{-3}\) (Aartsen et al. 2017b). Such a steep spectrum challenges an extragalactic origin of this component, as the accompanying photons would overshoot the bounds on the diffuse background of extragalactic gamma-rays (Berezinsky et al. 2011; Murase et al. 2013). Moreover, the all-sky spectrum in this channel is consistent with a continuation of the all-sky spectrum in gamma-rays measured by Fermi-LAT (Neronov & Semikoz 2016c).

Gamma-rays observed at the highest energies, i.e., in the TeV range, are dominated by the Galactic contribution. Neronov & Semikoz (2016c) suggested that the four-year data set of IceCube (Aartsen et al. 2015) shows evidence for a Galactic component at the highest energies \(E > 100\) TeV in the cascade channel. Two-component models with galactic and extragalactic contributions were suggested by Neronov & Semikoz (2016b) and Palladino et al. (2017) to explain the data in both channels. Also, a non-zero Galactic contribution was obtained more recently in a multi-component fit performed in Palladino & Winter (2018). Finally, Neronov et al. (2018) uncovered the electromagnetic counterpart of the IceCube signal using Fermi-LAT data in the multi-TeV energy range. Because photons are strongly attenuated by pair-production on cosmic background photons at these energies, the detection of a TeV photon counterpart demonstrates that this signal has a largely Galactic origin.

Note that the Galactic component may consist of two contributions: a component from the Galactic plane, and a local contribution at higher Galactic latitudes, \(10° < b < 50°\) (Neronov & Semikoz 2016a). The first one contains the "guaranteed" contribution from diffuse Galactic CRs scattering on gas in the Galactic plane, which is, however, both too small and too concentrated at small latitudes, \(|b| \lesssim 1°\), to explain the IceCube observations (Berezinsky et al. 1993; Evoli et al. 2007; Kachelrieß & Ostapchenko 2014). Additionally, the contribution from the Galactic plane was restricted by Astronomy with a Neutrino Telescope and Abyss environmental RESearch (ANTARES) measurements (Albert et al. 2017) and more recently by IceCube (Aartsen et al. 2017a). Taken at face value, these measurements seem to require an extragalactic origin of these astrophysical neutrinos. On the other hand, the most recent six-year cascade data of IceCube are still consistent with a soft 1/\(E^{-2.5}\) energy spectrum (Aartsen et al. 2017b). Last but not least, the TeV photon counterpart detected by Neronov et al. (2018) requires extended neutrino emission at large Galactic latitudes.

In this Letter, we suggest a resolution for this puzzle: that the soft 1/\(E^{-2.5}\) component in the astrophysical neutrino intensity is produced locally by CRs interacting in the walls of nearby superbubbles. We investigate as a possible realization of this.
scenario that CRs interact in the walls of the Local Bubble and the Loop I superbubble, in particular in the part that forms the interface between these two superbubbles. The large angular extension of Loop I on the sky explains why the arrival directions of this Galactic component are not concentrated in the Galactic disk. Moreover, the small distance to Loop I is the reason why a single source can dominate the Galactic neutrino flux. The required CR flux may be delivered by a recent young nearby supernova, such as Vela, close to or inside Loop I.

This Letter is organized as follows. We first examine the propagation of CRs emitted by a bursting source inside an idealized (super-) bubble. Then we discuss the case of the Loop I and the local superbubble. Combining our previous findings, we calculate the secondary fluxes produced by CR interactions in the wall of Loop I and show that the resulting neutrino flux can be a substantial fraction of the observed one below $\sim$few $\times$ 100 TeV.

2. CR Propagation in Idealized (Super-) Bubbles

Massive stars lose a significant fraction of their mass in the form of a stellar wind. As this wind expands, it collides with the gas in the interstellar medium (ISM), creating a low-density bubble that expands over time. Once the star explodes at the end of its fusion cycle as a core-collapse supernova, a shock wave is injected into the ISM. The shock expands quickly until it reaches the bubble wall, where it is typically stopped (van Marle et al. 2015). Because massive stars are formed in clusters, the wind-blown bubbles of the individual stars encounter each other as they expand and merge to form a single superbubble (van Marle et al. 2012; Krause et al. 2013). The shape of these superbubbles is determined in particular by the pre-existing density inhomogeneities and magnetic fields, as well as the positions of the first supernovae (SNe). Simulations (Breitschwerdt et al. 2000; Schulreich et al. 2017) show that the bubble walls are fragmented and twisted, and outflows away from the Galactic plane may open up the bubble (Breitschwerdt et al. 2000).

In view of this intricate geometry, we idealize the bubble in our numerical simulations as follows: we assume for the magnetic field $B(x)$ and density $n(x)$ profiles perpendicular to the Galactic plane $(x, y)$ a cylindrical symmetry. Inspired by van Marle et al. (2015) we set the magnetic field strength inside the bubble to $B_{\text{ext}} = 0.1, 12 \, \mu G$ in the wall and $5 \, \mu G$ outside of the wall. We assume that the energy density in the regular and turbulent field are equal. For the direction of the regular field inside the bubble, we use a clockwise field for $y > 0$ and an anticlockwise field for $y < 0$. Such a configuration corresponds to the naïve picture that a uniform field is driven by a central explosion toward the south and north side of the bubble, which is supported by analytical and numerical arguments (van Marle et al. 2015).

We choose the radius $R$ of the bubble as $R = 50 \, \text{pc}$ and set the width of the bubble wall to $2 \, \text{pc}$. Then we inject CRs at the center of the bubble, calculate their trajectories using the Lorentz equation, and record the resulting surface density $n = \, dN/\, dS = \, dN/(2\pi r \, dr)$. We consider two cases for the injection history: a continuous source and a bursting source. In the latter case, we record the CR density $n$ after $t = \{300, 1000, 3000, 10,000\} \, \text{years}$.

In Figure 1 we show the normalized CR surface density of a bursting and a continuous source (right) as function of distance in units of the bubble radius for three different energies (Andersen 2016). Let us first discuss the case of a bursting source shown in the left panel after the time $t = 3000 \, \text{years}$: at low energies, $E \lesssim 0.1 \, \text{PeV}$, the Gaussian diffusion front $\propto(2D_0)^{1/2}$ (with $D$ as the diffusion coefficient inside of the bubble) has not yet reached the bubble wall. The small fraction of CRs that have already left the bubble feels the stronger magnetic field outside, leading to a slower decrease of the CR density at $r > R$. Thus, the CR density is described by a quasi-Gaussian density profile with two effective diffusion coefficients inside and outside of the bubble. In contrast, at the highest energy considered, $E = 10 \, \text{PeV}$, CRs propagate inside of the bubble close to the ballistic regime, being then “slowed” down by the increased diffusion in the bubble wall. Thus, the bubble wall acts as a kind of “semi-permeable membrane” increasing the CR density inside of the bubble. After a drop in the CR density, a quasi-Gaussian tail is visible outside of the bubble. Finally, for the intermediate energy $E = 1 \, \text{PeV}$, CRs also diffuse inside of the bubble, and a quasi-Gaussian density profile with two effective diffusion coefficients inside and outside of the bubble is visible. The main difference between the bursting and the continuous source shown in the right panel is the absence of a characteristic energy below which CRs have not yet reached the bubble wall. As a result, the production of low-energy secondary photons is not suppressed.

3. Loop I and Local Superbubble

We next consider the special case of our local neighborhood. The Sun is situated inside of the Local Superbubble, an irregularly formed volume of the ISM with an extremely low density and radius $\sim 100 \, \text{pc}$. Egger & Aschenbach (1995) noted the possibility of a collision of the nearby Loop I superbubble with the Local Bubble, forming a wall of neutral and dense material in the interaction zone. In this Letter, we will use the geometry sketched in their Figure 5. In particular, we will assume that the Sun is close to the wall, choosing as the smallest distance $d = 25 \, \text{pc}$. We assume that the interface between the Local Bubble and Loop I has the density $n = 20 \, \text{cm}^{-3}$, while the remaining bubble wall of Loop I has the density $n = 10 \, \text{cm}^{-3}$.

Compared to our calculations of CR propagation in our toy model, Loop I has a radius that is three times larger. Moreover, we are interested in a source such as Vela, which is $\approx 11,000 \, \text{years}$ old. From the scaling law $L \propto (2D_0)^{1/2}$ we estimate that we can use the results presented in Figure 1 as a proxy for the case $t \approx 11,000 \, \text{years}$ and $R \approx 100 \, \text{pc}$ appropriate for the distance of Vela to the center of Loop I. Alternatively, the CR source may be older and the magnetic field strength in Loop I higher than we assumed.

Note that in a two-dimensional geometry as the Galactic disk, sources inside of a ring with distance $\rho$ to the observer contribute $1/\rho$ to the observed flux. Therefore, nearby sources contribute strongly even assuming a uniform source distribution $n_\nu$. More explicitly, one can calculate the flux from 100 sources distributed uniformly in the Galactic disk. In Figure 2, we show the cumulative flux from sources within the distance $d$ normalized such that the total flux is one (magenta line). While one expects on average the nearest source at the distance $d \approx 1.5 \, \text{kpc}$, the distance to Vela is $d = 0.3 \, \text{kpc}$, leading to an enhancement of its flux by a factor 25. This

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4. Andersen (2016) discussed fits of various analytical toy models to the CR density inside and outside of the bubble.
enhancement becomes stronger if one takes into account the known spatial distribution of pulsars and supernova remnants (SNRs). For instance, Figure 14 of Neronov & Semikoz (2012) shows the location of known pulsars with age \(<30,000\) years (see also their Table 3). Except for Vela, no other pulsar is known within \(1\) kpc, and many have distances as large as \(3–5\) kpc. Using this distribution, one obtains the green line for the cumulative flux within the distance \(d\). We conclude that Vela (or other sources in Loop I) that are at an exceptionally small distance compared to other known pulsars or young SNRs can dominate the total flux from all Galactic sources. This also implies that the extragalactic flux from normal galaxies gives a negligible contribution.

### 4. Neutrino and Photon Fluxes

We use the Monte Carlo generator QGSJET-II (Ostapchenko 2008, 2011) to calculate the photon and neutrino secondary fluxes. We assume a mass fraction of 24% of helium in the target gas and calculate the average intensity of the secondaries as

\[
I_i(E) = \frac{c}{4\pi} \sum_{A \in \{1,4\}} \int_0^\infty dE' \frac{d\sigma_{\text{inel}}^{PA \rightarrow i}(E', E)}{dE} \times \int d^3x \frac{n_p(E', x) n_A^{\text{helium}}(x)}{d^2},
\]

where \(\sigma_{\text{inel}}^{PA}\) is the production cross section of secondaries of type \(i\) in interactions of protons on nuclei with mass number \(A\), \(d\) denotes the distance from the Sun to the interaction point \(x\), \(n_p(E, x)\) is the differential number density of CR protons, and \(n_A^{\text{helium}}(x)\) is the density of protons and helium in the bubble wall of Loop I, respectively. We use \(dN/dE \propto E^{-2.2} \exp(-E/E_0)\) as injection spectrum of CR protons with \(E_0 = 3 \times 10^{15}\) eV, normalized such that the total energy emitted in CRs is \(E_{\text{CR}} = 2.5 \times 10^{50}\) erg. Then we use the normalized CR surface density shown in Figure 1 to obtain the relevant CR density inside of the bubble wall.

The red line in Figure 3 shows the resulting intensity \(I(E)\) multiplied by \(E^2\) of neutrinos on Earth obtained in our model.
An extragalactic component with spectral shape $1/E^{2.1}$ as fit to the muon data is shown by an orange line. Finally, the total intensity as sum of the two components is shown by a violet line. While the neutrino intensity of the Galactic component drops below $10^{14}$ eV, because CRs with energy lower than $10^{15}$ eV have not yet reached the bubble wall, it is suppressed at high energies because of the assumed cutoff in the CR injection spectrum. The combined neutrino intensity of the Galactic and extragalactic contributions gives a good fit of the experimental data (Aartsen et al. 2017b). In most concrete models for extragalactic neutrinos, the predicted intensity is not a pure power law. For instance, the neutrino intensity predicted in Kachelrieß et al. (2017) becomes steeper than an $1/E^{2}$ power law below $10^{14}$ eV, thus leading to a more pronounced neutrino bump. Because photon absorption is considered to play no role at the small distances considered, the corresponding photon flux is uniquely determined. An important constraint on our model comes therefore from the limits on the diffuse gamma-ray flux in the 100 TeV–1 PeV energy range (Ahlers & Murase 2014), which was imposed in particular by the KASCADE-Grande Collaboration, taking into account post-Large Hadron Collider (LHC) hadronic models.

In Figure 4 we show that the integral photon intensity $I(E)$ obtained in our model as a function of energy $E$ obeys the upper 90% C.L. derived from KASCADE data (Apel et al. 2017). Note, however, that the predicted photon flux is only a factor of a few below the KASCADE limit, which makes it detectable by future experiments. Additionally, the arrival directions of photon-like events in the KASCADE data could be used now to constrain a possible flux enhancement toward Loop I.

Finally, let us comment on the deviation expected in our scenario from an isotropic neutrino flux. The sky region in the direction of the Loop I superbubble is approximately circular with radius $60^\circ$, centered at the Galactic coordinates $l = 329^\circ.5$ and $b = 17^\circ.5$. In the six-year IceCube data set, 15 out of 28 events (54%) with $E > 100$ TeV are located in this region, while one expect 8.6 events according to the IceCube exposure for an isotropic flux (or 31%). Thus, the current data set shows an excess in this region corresponding to 23% of the total number of events. Dedicated data analyses by the IceCube and the ANTARES Collaborations will have the potential to constrain or to favor this scenario in the future.

5. Conclusions

The explanation of the IceCube data requires, in addition to an extragalactic component with a hard spectrum $1/E^{\alpha}$ and $\alpha = 2.0–2.2$, a soft Galactic component with the spectral slope $\alpha \simeq 2.5$ (Neronov & Semikoz 2016a, 2016b; Palladino et al. 2017; Neronov et al. 2018). The bounds on the diffuse extragalactic gamma-rays suggest that such a soft component has a Galactic origin. A Galactic neutrino component can be decomposed into two contributions, depending on their angular distribution: neutrinos from sources in the Galactic plane that are not nearby, and neutrinos from local sources. The first component is strongly limited by the recent bounds on the neutrino contribution from the Galactic plane (Aartsen et al. 2017a).

In this Letter we have studied the possibility that a nearby CR source contributes to the astrophysical neutrino flux. In particular, we studied a model where the CR source is located inside or nearby a superbubble, created by previous supernovae. Both the magnetic field strength and the gas density are enhanced in the wall of a superbubble. As a result, neutrinos are preferentially produced in the wall of the superbubble. If the observer is close to such a superbubble, neutrino events are distributed over a considerable fraction of the sky. We then applied this mechanism to the case of our local neighborhood in the Galaxy. In particular, we considered the Local and the Loop I superbubbles that are interacting and have an “interaction wall” between them. As an example, a young nearby CR source may serve the Vela supernova, which exploded 11,000 years ago. The neutrino flux resulting in this model shown in Figure 3 can be responsible for a significant part of the IceCube neutrino flux at $\sim$few × 100 TeV and below. Other sources should provide only one half of the flux predicted for Vela (compare with the green line in Figure 2). A signature of this scenario is the correlation of the arrival direction of Galactic astrophysical neutrinos with the matter distribution in the walls of the Local and the Loop I superbubbles. The contribution to the neutrino signal from the former source would be rather isotropic, and thus resemble the extragalactic component because we are inside of this superbubble (but not at its center).

An important constraint on any Galactic neutrino model comes from the limits on high-energy gamma-rays in the 100 TeV–1 PeV energy range. We showed that the predicted photon flux in our model is only a factor few below the KASCADE limits, which makes a detection possible for future experiments. Such a detection, which would add additional angular information, could confirm that both neutrinos and gamma-rays are produced by CR interactions in the wall between the Local and Loop I superbubbles. However, the connection to a concrete CR source model has to be additionally proven. For instance, secondary acceleration on the wall of the Loop I superbubble may be operating as an additional acceleration mechanism (Bykov & Toptygin 2001; Parizot et al. 2004; Ackermann et al. 2011). With or without secondary acceleration, the identification of a fraction of IceCube neutrinos as Galactic ones implies the existence of a nearby CR PeVatron. As a young nearby SNR, Vela is a good candidate for this source. In this case, the CR spectrum in the energy region of the knee can be dominated by a single source such as Vela, as suggested, for example, by

![Figure 4. Integral photon intensity $I(E)$ from Loop I as a function of energy $E$ compared to upper 90% C.L. derived from KASCADE data (Apel et al. 2017).](image-url)
Erlykin & Wolfendale (1997). Such a scenario naturally complements the “local source” proposal of Kachelrieß et al. (2015, 2018), where a 2–3 Myr-old source dominates the CR energy spectrum in the 1–100 TeV range.

We conclude that our scenario—if confirmed by future observations—opens up the possibility for studying a nearby PeVatron at work through multi-messenger observations with neutrinos, gamma-rays, and CRs.

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References

Aartsen, M. G., Abbasi, R., Abdou, M. G., et al. 2013, Sci, 342, 1242856
Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2015, ApJ, 809, 98
Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2016, ApJ, 833, 3
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014, PhRvL, 113, 101101
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2017a, ApJ, 849, 67
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2017b, arXiv:1710.01191
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, Sci, 334, 1103
Ahlers, M., & Murase, K. 2014, PhRvD, 90, 023010
Albert, A., André, M., Anghinolfi, M., et al. 2017, PhRvD, 96, 062001
Andersen, K. J. 2016, Master’s thesis, NTNU Trondheim
Apel, W. D., Arteaga-Velázquez, J. C., Bekk, K., et al. 2017, ApJ, 848, 1
Berezinsky, V., Gazizov, A., Kachelrieß, M., & Ostapchenko, S. 2011, PhLB, 695, 13
Berezinsky, V. S., Gaisser, T. K., Halzen, F., & Stanev, T. 1993, APh, 1, 281
Breitschwerdt, D., Freyberg, M. J., & Egger, R. 2000, A&A, 361, 303
Bykov, A. M., & Toptygin, I. N. 2001, AstL, 27, 625
Egger, R. J., & Aschenbach, B. 1995, A&A, 294, L25
Erlykin, A. D., & Wolfendale, A. W. 1997, JPhG, 23, 979
Evoli, C., Grassi, D., & Maccione, L. 2007, ICAP, 0706, 003
Gaisser, T. K., Halzen, F., & Stanev, T. 1995, PhR, 258, 173, [Erratum: Phys. Rept. 271, 355(1996)]
Kachelrieß, M., Kalashev, O., Ostapchenko, S., & Semikoz, D. V. 2017, PhRvD, 96, 083006
Kachelrieß, M., Neronov, A., & Semikoz, D. V. 2015, PhRvL, 115, 181103
Kachelrieß, M., Neronov, A., & Semikoz, D. V. 2018, PhRvD, 97, 063011
Kachelrieß, M., & Ostapchenko, S. 2014, PhRvD, 90, 083002
Krause, M., Charbonnel, C., Decressin, T., Meynet, G., & Prantzos, N. 2013, A&A, 552, A121
Loeb, A., & Waxman, E. 2006, JCAP, 0605, 003
Mannheim, K. 1995, APh, 3, 295
Murase, K., Ahlers, M., & Lacki, B. C. 2013, PhRvD, 88, 121301
Neronov, A., Kachelrieß, M., & Semikoz, D. V. 2018, arXiv:1802.09983
Neronov, A., & Semikoz, D. V. 2012, PhRvD, 85, 083008
Neronov, A., & Semikoz, D. V. 2016a, APh, 75, 60
Neronov, A., & Semikoz, D. V. 2016b, PhRvD, 93, 123002
Neronov, A., & Semikoz, D. V. 2016c, APh, 72, 32
Ostapchenko, S. 2008, PhRvD, 77, 034009
Ostapchenko, S. 2011, PhRvD, 83, 014018
Palladino, A., Mascaretti, C., & Vissani, F. 2017, EPJC, 77, 684
Palladino, A., & Winter, W. 2018, arXiv:1801.07277
Parizot, E., Marcowith, A., van der Swaluw, E., Bykov, A. M., & Tatischeff, V. 2004, A&A, 424, 747
Schulreich, M. M., Breitschwerdt, D., Feige, J., & Dettbarn C. 2017, A&A, 604, A81
Stecker, F. W., Done, C., Salamon, M. H., & Sommers, P. 1991, PhRvL, 66, 2697, [Erratum: PhRvL 69, 2738(1992)]
van Marle, A. J., Meliani, Z., & Marcowith, A. 2012, A&A, 541, L8
van Marle, A. J., Meliani, Z., & Marcowith, A. 2015, A&A, 584, A49
Waxman, E., & Bahcall, J. N. 1997, PhRvL, 78, 2292