An updated view and perspectives on high-energy gamma-ray emission from SGR J1935+2154 and its environment

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Abstract. SGR J1935+2154 was discovered in 2016 and is currently one of the most burst-active Soft Gamma-ray Repeaters (SGR), having emitted many X-ray bursts in recent years. In one of our previous articles, we investigated the contribution to high-energy and very high-energy gamma-ray emission (VHE, \( E > 100 \) GeV) due to cosmic-ray acceleration of SNR G57.2+0.8 hosting SGR J1935+2154 using the GALPROP propagation code. However, follow-up observations of SGR 1935+2154 were made for 2 hours on April 28, 2020, using the High Energy Stereoscopic System (H.E.S.S.). The observations coincide with X-ray bursts detected by INTEGRAL and Fermi/Gamma-ray Burst Monitor (GBM). These are the first high-energy gamma-ray observations of an SGR in a flaring state, and upper limits on sustained and transient emission have been derived. Now that new H.E.S.S. observations have been made, it is interesting to update our model with respect to these new upper limits. We extend our previous results to a more general situation using the new version of GALPROP. We obtain a hadronic model that confirms the results discussed by H.E.S.S.. This leads to an optimistic prospect that cosmic ray gamma rays from SGR J1935+2154 can contribute to the overall gamma energy density distribution and in particular to the diffusion gamma rays from the Galactic center.
1 Introduction

The Soft Gamma-ray Repeater (SGR) J1935+2154 was initially detected by the BAT (Burst Alert Telescope) instrument aboard the Swift satellite as an X-ray burst. Subsequent observations of this source allowed to classify it as a magnetar and they found that the source became active again in April 2020, whilst it exhibited multiple and severe X-ray burst activity (see [1–3] and references therein). SGRs are a diverse set of sources with huge magnetic fields of the order of \(10^{14} - 10^{15}\) G, rotational periods \(P \sim (2 - 12)\) s, slowing down rates \(\dot{P} \sim (10^{-15} - 10^{-10})\) s/s, persistent X-ray luminosity as large as \(10^{35}\) erg/s, transient activity in the form of outbursts of energy around \(10^{41} - 10^{43}\) erg, and, for some sources, the presence of giant flares, whose typical luminosities are \(10^{44} - 10^{47}\) erg (see, e.g., [4] and references therein). The emission nature of SGRs remains a cause for debate, and several scenarios were proposed to explain their observed spectra and properties [see 5–7, for detailed reviews]. Examples thereof are magnetars [8–13], accreting neutron stars [14, 15], rotation-powered pulsars [16], quark stars [17], or massive, fast-spinning and highly magnetized white dwarfs [18–23].

On April 28, 2020, a very bright radio outburst of SGR J1935+2154 was identified that turned out to be brighter than any radio burst seen from any galactic source to date. An extremely bright millisecond-duration radio burst was emitted by SGR J1935+2154 and detected with the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and STARE2 telescopes [24, 25]. The radio burst turned out to be temporally coincident with a bright hard X-ray burst detected with the NICER [26], INTEGRAL [2], Konus-Wind [27], Insight Hard X-ray Modulation Telescope - HXMT [28] and AGILE satellites [29].

Fast radio bursts are extremely intense millisecond-long radio pulses of primarily extragalactic origin and showcasing the characteristic dispersion sweep of radio pulsars. The physical nature of these bursts is unknown, and a variety of explanations have been considered, including synchrotron maser emission from young SGRs in supernova remnants (SNRs) [see 30, and references therein] and magnetospheric emission [see 31, for details]. SGRs have been proposed as sources of FRBs [see 32–35]. In particular, [36] suggest that repeating FRBs are generated not far from the surface of the source, as a result of ultrarelativistic internal shocks in the magnetar wind, which are launched by the magnetospheric flares.

In one of our previous articles we have obtained the contribution to the high energy and very high-energy gamma-ray (VHE, \(E > 100\) GeV) emission due to cosmic-ray acceleration from SNR G57.2+0.8 hosting SGR J1935+2154 with the use of the GALPROP propagation code\(^1\) [see 37]. We consider the SGR J1935+2154 and its environment as a single source.

\(^1\)http://galprop.stanford.edu
near to the Galactic center. Then, we have proposed that the above setting can provide a more comprehensive scenario for the generation of GeV-TeV gamma-rays. In fact, the diffuse gamma-ray emission from the Galactic plane was first detected by EGRET [38] and then followed by Fermi LAT measurements [39]. Additionally, a TeV diffuse emission originated in the central part of our Galaxy was detected by ground-based imaging atmospheric Cherenkov telescopes [40–42]. The observations by the High Energy Stereoscopic System (H.E.S.S.) of a gradient in the cosmic-ray (CR) profile derived from the diffuse VHE gamma-ray emission, with a peak at the inner regions, imply an injection by a steady source located at the center of the Milk Way [43].

The main goal of the present paper is to extend our previous study where we have investigated particle acceleration models for SNR G57.2+0.8 hosting SGR J1935+2154 [see 37, for details] motivated by H.E.S.S., Fermi-GBM and INTEGRAL VHE gamma-ray observations [see 44, 45]. Here, we have used GALPROP propagation code [46–48] in its enhanced version [49] performing 3D diffusion/re-acceleration model simulations. Further, we use the new flux from the pulsar spin-down timescale for SGR J1935+2154. It is assumed that the SGR J1935+2154 is injecting accelerated particles into the interstellar medium (ISM) in equal numbers with a fraction of its spin-down power converted to pairs. After injection, the particles propagate via a diffusive process [see e.g., 50]. The mechanism we demonstrate here is an indication that improves the understanding of the leptonic and hadronic origins of the gamma-ray emission. Also, such analysis would show whether the gamma-ray emission around this region is due to leptonic or hadronic processes. H.E.S.S. measurements at VHE - TeV energies of SGR J1935+2154 are crucial for constraining SGR particle acceleration scenarios up to the knee. As a result, they may provide independent properties of the magnetospheric regions of SGRs and hence unveil some of the physics taking place in their outermost regions. To do so this paper is organized as follows. Section 2 is devoted to an update and brief summary of H.E.S.S. observations. In Section 3 and Section 4 we present how the calculations are done and discuss the obtained results.

2 High-energy gamma-ray emission from SGR J1935+2154

Follow-up observations of SGR 1935+2154 were carried by H.E.S.S. for 2 hr on 2020 April 28. The observations are coincident with X-ray bursts detected by INTEGRAL and Fermi-GBM, thus providing the first very high energy gamma-ray observations of a SGR in a flaring state. High-quality data acquired during these follow-up observations allow us to perform a search for short-time transients. No significant signal at energies $E > 0.6$ TeV is found, and upper limits on the persistent and transient emission were derived [see 45, for details].

The integral upper limits derived from the 2 hr of H.E.S.S. observation, assuming a spectral index of $E^{-2.5}$, can be translated into upper limits on the flux $F(E > 600 \text{ GeV}) < 2.4 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}$. SGR 1935+2154 is associated with the middle-aged galactic SNR G57.2+0.8 at a distance of about 6.6 kpc (see [37, 51] and references therein). Assuming this distance, [45] derive a luminosity upper limit $L(E > 600 \text{ GeV}) < 1.3 \times 10^{34} \text{ erg/s}$. This places constraints on persistent VHE emission from SGR 1935+2154 during the H.E.S.S. observations.

Moreover, the simultaneous X-ray emission and radio bursts offered the missing link to correlate FRBs with SGRs. The X-ray emission can be an indication that protons and electrons are being accelerated at TeV scales via interactions with matter in the region or through inverse Compton scattering, respectively, and H.E.S.S. observations can help better
understand this scenario. As well discussed in [37], if SGRs are cosmic-ray sources at the TeV-PeV energy range, they could contribute to the diffuse gamma-ray emission in the Galaxy given that it is expected to originate from the interactions of cosmic rays with Galactic interstellar gas and radiation fields. It is also worth noting that H.E.S.S. has shown a strong correlation between the Central Molecular Zone (CMZ) and the brightness distribution of diffuse emission, possibly indicating that these gamma rays originate from VHE protons interacting with matter in these regions. It has been argued that the origin of these CRs via Inverse Compton scattering is likely prevented by the strong radiative losses of TeV electrons that limit their propagation in the CMZ [52]. Moreover, H.E.S.S. has observed a high-energy CR density in the CMZ that is an order of magnitude larger than in the rest of the Galaxy and that could be interpreted by the existence of more than one accelerating source in the Galactic center [52]. This clearly motivates studies considering G57.2+0.8 and/or SGR J1935+2154 as such sources. Recently, the Tibet AS$\gamma$ collaboration reported the first detection of sub-PeV diffuse gamma rays in the Galactic disk. The lack of correlation between the observed events and known TeV sources virtually rules out a leptonic origin for this diffuse emission, and argues for an origin by hadrons accelerated in this region at PeV energies [see 53, for details].

3 Simulations

In this section, we briefly review the main features of the model to highlight the relevant improvements of our simulations compared with previous results reported in [37]. In order to assess the distribution of gamma rays from the propagation of cosmic rays (CRs) for SNR G57.2+0.8, which hosts SGR J1935+2154, we used GALPROP code [46–48] in its latest version v57 [49] performing 3D diffusion/re-acceleration model simulations. The corresponding spectra of gamma rays reaching the Earth taking into account the propagation effects and interactions with background radiation were determined. For a given source distribution and boundary conditions, GALPROP solves the transport equation. Energy loss, fragmentation and decay, convection, diffusion, and re-acceleration processes are included in the simulations. Based on the input CR source abundances, GALPROP computes a comprehensive network of isotope production. A second-order implicit Crank-Nicholson approach is used for the numerical solution. The spatial boundary conditions are based on the assumption that free particles escape. The diffusion coefficient for a given halo size is defined by the B/C nuclear ratio as a function of rigidity and dispersion parameter [46–48]. To a better comprehension, in this paper we improve the model described in [37] with its environment and GALPROP parameters, used to better describe the SNR G57.2+0.8 hosting SGR J1935+215.

However, the calculation of the spectral energy distribution of the total gamma-ray emission uses parameters of the source SGR J1935+2154. The modelling assumes that accelerated particles are injected into the ISM and the spectral model for the injected particles is obtained with a power law $dq(p)/dp \propto p^{-\alpha}$, where $\alpha$ is the spectral index and $q(p)$ the injection energy spectrum and, the total spectrum is normalized so that the total injected power is given by the expression [49, 50, 54]

$$L = L(t) + L' \quad \text{and} \quad L(t) = \eta L_0 \left(1 + \frac{t}{\tau_0}\right)^{-2}, \quad (3.1)$$

where $L_0$ is the initial spin-down power of the SGR, $\eta = 1.0$ is the efficiency factor, $\tau_0 = 3.37 \text{ yr}$ is the pulsar time scale defined as the ratio of the initial rotational energy to the
initial spin-down luminosity [see 54] and $L'$ is the gamma-rays luminosity of the burst state from H.E.S.S. upper limits [45]. The initial spin-down power is calculated using the current spin-down power of $1.7 \times 10^{34}$ erg s$^{-1}$ assuming the characteristic age of $3.6 \times 10^{3}$ yr$^2$. The luminosity $L$ represents the total emission of particles from SGR J1935+2154. We assume that this emission is caused by the rotational energy loss of the pulsar [see e.g., 54], and by the luminosity in a flaring state from the magnetar. Then, we have considered the magnetic energy injection rate (for both quiescent and flaring/outburst emissions). The distance of the SGR J1935+2154 is $6.6 \pm 0.7$ kpc [51, 55, 56].

Calculations are performed in a Cartesian grid, with the Galactic plane assumed to be the X-Y plane at whose origin the GC is located. The Galactic volume spans up to 18 kpc in the X and Y directions, with a halo height (h) of 8 kpc in the X-Y direction. We use the treatment of inhomogeneous diffusion properties in the space around CR sources, modelling two-zone diffusion scenarios, as described in [37].

The generation of $\gamma$-rays is determined by the propagating CR distributions, including primary, secondary, and inelastically scattered protons. Inverse Compton scattering is calculated by the interactions between anisotropic background photon distribution with a Galactic interstellar radiation field. As well as different contributions of the pion-decay and bremsstrahlung are calculated from emission levels using the column densities of $H$ gas. Models of the Galactic magnetic field are used to determine the synchrotron emission. The $\gamma$-ray and synchrotron sky maps result from integrating the relevant emissivities with gas distributions, interstellar radiation, and magnetic fields [see 46]. The gamma-ray flux is calculated from G57.2+0.8 hosting SGR J1935+2154 and compared with those published in [37].

4 Discussions
Gamma-ray emission can be produced by hadronic and leptonic processes triggered by the interaction of CRs accelerated in the molecular cloud region and ISM. We simulate the CR flux as a result of SGR J1935+2154 injecting particles into the surrounding space and account the contribution of gamma-ray emission by the propagation of CRs for SNR G57.2+0.8.

In order to fix the same environment as in [37] we choose diffusion constant $D_0 = 2.5 \times 10^{28}$ cm$^2$ s$^{-1}$, slope of the diffusion coefficient $\delta = 0.6$, Alfvén velocity $v_a = 28.0$ km s$^{-1}$ and spectral slope $\alpha = 2.2, 2.4, 2.6$. The results are described in Figure 1. The Figure displays the behavior of the S0 model described in [37], in which the VHE gamma-ray emission from SNR G57.2+0.8 and SGR J1935+2154 was normalized as the sum of pion decay and inverse Compton spectra, with an upper limit on the integral flux of TeV gamma rays from H.E.S.S. Observatory up to 99.5% CL [52]. The model presented in [37], although consistent, shows a lower flux than the current model. This is because the flux calculation in previous work is associated with the upper limits of the gamma integral measured by H.E.S.S. [52], which was updated in [45].

Figure 1 shows the data of diffuse TeV energy gamma-ray emission from the Galactic Center of H.E.S.S. [43, 52] and MAGIC models [42]. According to our findings, gamma-rays of CRs from SGR J1935+2154 can make contribution to the total gamma energy density 2

In the magnetic dipole approximation, we can use $\Omega/2 \dot{\Omega} = -(t + \tau)$ [see Eq. A5 of 54], the characteristic age $t$, and the current values of $\Omega$ and $\dot{\Omega}$ to calculate that its pulsar time scale $\tau_0 = 3.37$ yr. Assuming NSs canonical parameters (moment of inertia $I \sim 1.4 \times 10^{45}$ gcm$^2$) we can derive the initial rotational energy. The similar approach was developed by [54] to estimate the initial energy by using the current spin-down luminosity [see also 49, 50].
distribution and, in special, to the diffusion gamma-ray from Galactic Center. Up to $10^4$ MeV, the pion emission component dominates. The differences in the spectral indices show that smaller indices make a larger contribution to the Galactic diffuse gamma, see Fig. 1 - (a,b,c). The figure 1 also describes the production of the VHE gamma-ray emission from particles following the method discussed in [37]. The method makes a conservative connection between the upper limit of the integral flux of TeV gamma-rays detected by H.E.S.S. [45] and the cosmic-ray luminosity at the source. The red line on figure 1 shows this result. We suggest that the flare was the result of the interaction of particles accelerated, producing $p - p$ collisions and generating gamma-ray emission and, therefore, dominating the VHE spectrum, figure 1-(b,c). This emission is below than the quiescent one, described by the orange line, figure 1-(a), because the spectral index is harder, consequently generating more pions at higher energies.

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**Figure 1**: Spectral energy distribution of the gamma-ray emission. The total gamma-ray spectrum is the sum of pion decay, inverse Compton, and bremsstrahlung from the spin-down model, $L(t)$, and the H.E.S.S. 2021 model, described from the flaring state $L'$, of the SGR J1935+2154. See text for details. The models use the 2D gas distribution [48].
This simple model presented is an interesting window that improves the understanding about the hadronic origins of gamma-ray emission at high energies, as discussed by H.E.S.S. [45]. The approach presented here becomes more predictive considering the energy losses during the CRs propagation, magnetic field, distance and the spin-down age of SGR J1935+2154.

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