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Searching for TeV Gamma-Ray Emission from SGR 1935+2154 during Its 2020 X-Ray and Radio Bursting Phase

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Abstract

Magnetar hyperflares are the most plausible explanation for fast radio bursts (FRBs)—enigmatic powerful radio pulses with durations of several milliseconds and high brightness temperatures. The first observational evidence for this scenario was obtained in 2020 April when an FRB was detected from the direction of the Galactic magnetar and soft gamma-ray repeater SGR 1935+2154. The FRB was preceded by two gamma-ray outburst alerts by the BAT instrument aboard the Swift satellite, which triggered follow-up observations by the High Energy Stereoscopic System (H.E.S.S.). H.E.S.S. observed SGR 1935+2154 for 2 hr on 2020 April 28. The observations are coincident with X-ray bursts from the magnetar detected by INTEGRAL and Fermi-GBM, thus providing the first very high energy gamma-ray observations of a magnetar 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 are derived. We here present the analysis of these observations and discuss the obtained results and prospects of the H.E.S.S. follow-up program for soft gamma-ray repeaters.

Unified Astronomy Thesaurus concepts: Soft gamma-ray repeaters (1471); Radio transient sources (2008); Gamma-rays (637); High energy astrophysics (739); Magnetars (992); Gamma-ray sources (633); Burst astrophysics (187); Gamma-ray transient sources (1853); Gamma-ray telescopes (634); Gamma-ray astronomy (628)

1. Introduction

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are associated with highly magnetized neutron stars or magnetars. They generate bursts of emission at irregular time intervals. The crust of the neutron star is thought to break owing to the intense shifts of the ultrastrong magnetic field causing the emission of hard X-rays and gamma rays. During these short (∼0.1 s) bursts, the brightness of these objects can increase by a factor of 1000 or more. Within this category, the most extreme giant flares are so intense that in the case of the 2004 December 27 event from SGR 1806−20 they can influence Earth's ionosphere and magnetic field (e.g., Inan et al. 2007).

1.1. SGRs and Nonthermal Emission

For many years it was unclear whether nonthermal emission mechanisms are involved in these burst activities. Recently the Large Area Telescope (LAT) aboard the Fermi satellite detected GeV gamma-ray emission from an extragalactic magnetar in the Sculptor galaxy group (Fermi-LAT Collaboration et al. 2021). The location of the recorded burst is consistent with several galaxies, including the starburst galaxy NGC 253 (the Sculptor galaxy) at 3.5 Mpc distance. The unusually long delay (19 s) of the GeV emission from the first spike and quasi-periodic oscillation seen in the MeV signal suggest a giant magnetar flare causing gamma emission well outside the magnetar's light cylinder radius. At present, the GeV radiation is attributed to optically thin synchrotron emission, suggesting the presence of relativistic electrons.

The potential for very high energy (VHE) gamma emission from extraordinary giant magnetar flares has been discussed, for example, in the context of SGR 1806−20 as a possible

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hadronic accelerator (Ioka et al. 2005). In the case of accelerated electrons, the strong magnetic field of the emission region could induce electron−positron pair cascades that can quench any VHE gamma-ray emission. This internal absorption of VHE photons can be avoided if the emission region is located far away from the surface of the magnetar. This is realized, for example, in the trapped fireball scenario (Thompson & Duncan 2001). So far, searches for VHE emission (variable or persistent) from the magnetars SGR 1806−20, 4U 0142+61, and 1E 2259+5864 have not revealed any detections (Aleksić et al. 2013; H.E.S.S. Collaboration et al. 2018).

1.2. Fast Radio Bursts and Magnetars

Fast radio bursts (FRBs) are powerful radio pulses with a duration of several milliseconds with high brightness temperatures suggesting a coherent emission mechanism (Petroff et al. 2019). It is believed that FRBs are of extragalactic origin. Over the past few years a rapidly growing number of FRBs have been detected in the radio band, including repeating ones (Petroff et al. 2016). Various theoretical emission and source models were put forward since the first detection of these enigmatic bursts (Zhang 2020). Magnetars are proposed as sources of FRBs (Popov & Postnov 2010). For example, some magnetars could produce FRBs through strongly magnetized pulses that interact with the material in the surrounding nebula and produce synchrotron maser emission (e.g., Lyubarsky 2014; Metzger et al. 2019; Beloborodov 2020). Some models suggest that repeating FRBs are generated not far from the surface of the magnetar through ultrarelativistic internal shocks and blast waves in the magnetar wind associated with flares (e.g., Beloborodov 2017).

1.3. Past Observations of FRBs with Imaging Atmospheric Cerenkov Telescopes

The High Energy Stereoscopic System (H.E.S.S.) is an array of one 28 m and four 12 m imaging atmospheric Cerenkov telescopes (IACTs) located in the Khomas Highland in Namibia at an altitude of 1835 m. It is capable of detecting VHE gamma rays from energies of a few tens of GeV to 100 TeV. In the past, H.E.S.S. targeted two FRBs, FRB 20150215 (Petroff et al. 2017) and FRB 20150418 (H.E.S.S. Collaboration et al. 2017), with several hours to days of delay. No significant VHE emission was found from either observations. Simultaneous observations of repeating and nonrepeating FRBs with IACTs and radio telescopes did not reveal gamma-ray counterparts: VERITAS observed FRB 20121102 and FRB 180814.J0422+73 simultaneously with the Green Bank Telescope, detecting 15 radio bursts during the campaign (Holder et al. 2019). MAGIC observed FRB 20121102 simultaneously with Arecibo, which detected five radio bursts (Acciari et al. 2018).

1.4. SGR 1935+2154

Following its discovery in 2014 (Cummings et al. 2014), SGR 1935+2154 has probably become the most burst-active SGR, emitting dozens of X-ray bursts over the past few years (Lin et al. 2020a). SGR 1935+2154 is associated with the middle-aged galactic SNR G57.2+0.8 at a distance of about 6.6 kpc (Zhou et al. 2020). In 2020 late April and May SGR 1935+2154 showed renewed X-ray burst activity culminating with a “forest of bursts” as detected by BAT on board the Neil Gehrels Swift Observatory. Many other X-ray and soft gamma-ray telescopes (Fermi-GBM, INTEGRAL, sAGILE, HXMT, Konus–Wind, NICER) also reported sustained bursting activity into late May.

This situation became considerably more interesting with the detection of short, intense radio bursts from the direction of SGR 1935+2154. Two millisecond-duration radio bursts (FRB 20200428) were detected, the first burst being a double-peaked one detected by CHIME and STARE2 (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020) on 2020 April, at 14:34:33 UTC, and the second burst by FAST (Zhang et al. 2020a) on April 30, at 21:43:00 UTC. The radio energy released under the assumption of an isotropic emission of the bursts at 6.6 kpc is about 10^{34}–10^{35} erg, just below the low end of the extragalactic FRB distribution observed so far. After removing the radio dispersion delay, the timing of the first radio burst appears to line up very well with one of the bright X-ray bursts seen by AGILE (Tavani et al. 2021), Konus–Wind (Ridnaia et al. 2021b), INTEGRAL (burst G in Mereghetti et al. 2020), and Insight-HXMT (Insight-HXMT 2020; Zhang et al. 2020c). This coincidence is the first evidence that magnetars are linked to FRBs, or at least a subset of (repeating) bursts. It is also shown that the X-ray bursts overlapping the double-peaked CHIME radio burst have an unusually hard spectrum, and it is suggested that these X-rays and the radio bursts arise from a common scenario (Ridnaia et al. 2021b). Furthermore, the nonthermal nature of the Insight-HXMT burst (Li et al. 2021) points to the production of multi-TeV electrons. Multi-GeV to TeV gamma-ray emission via the inverse-Compton process may then accompany this X-ray emission.

We here report on searches for VHE gamma-ray emission associated with the flares of SGR 1935+2154 with H.E.S.S. during the period of high activity on 2020 April 28. This paper is organized as follows: Section 2 describes the H.E.S.S. observations and provides an overview of MWL observations of SGR 1935+2154. Section 3 presents the H.E.S.S. data analysis and results. Section 4 discusses our findings, which are concluded in Section 5.

2. Observation Summary

The top panel of Figure 1 gives an overview of the MWL bursts detected from SGR 1935+2154 over the years. The middle panel zooms in on the 2020 active period. The bottom panel zooms in on the period around the H.E.S.S. observations. The observations during the active period are summarized in the following.

Gamma rays and X-rays: Figure 1 (and references therein) shows detected bursts with AGILE, Fermi-GBM, INTEGRAL, Konus–Wind, HXMT, NuSTAR, NICER/XTI, and Swift-BAT from 2009 until the end of 2020. From the Konus–Wind-detected burst clusters on 2020 April 27 (Ridnaia et al. 2020f) we show only the most intense bursting activity that occurred around 18:33:01 (58,965.77293 MJD), with a duration of ∼23 s and a very high fluence of 1.09×10^{-4} erg cm^{-2}.

Four Fermi-GBM bursts occurred during the H.E.S.S. follow-up observations of the source (Lin et al. 2020b). Moreover, INTEGRAL reported the detection of an X-ray burst at 03:47:52.2 UTC (burst A in Mereghetti et al. 2020 at 58,967.15824306 MJD) that coincides with the fourth Fermi-GBM burst during the last data-taking run by H.E.S.S. Therefore, the H.E.S.S. observations provide for the first time simultaneous VHE gamma-ray observational data with X-ray bursts emanating from an SGR.

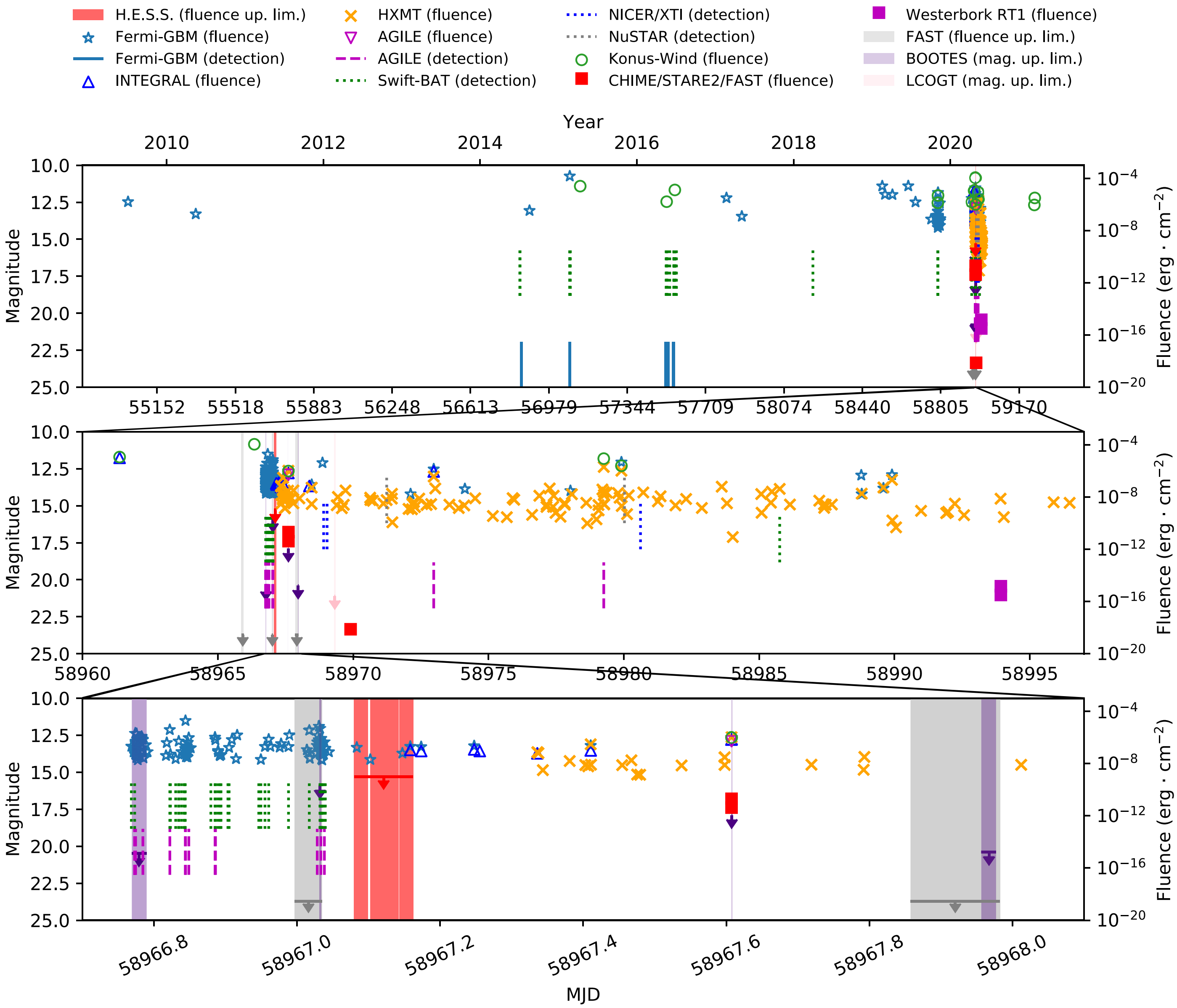

Figure 1. SGR 1935+2154 observations with gamma-ray, X-ray, optical, and radio telescopes. This plot presents X-ray bursts from the source detected by Fermi-GBM (Gruber et al. 2014; Kaneko et al. 2014; von Kienlin et al. 2014, 2020; Burns & Younes 2015; Bhat et al. 2016; Yu & Veres 2016; Younes 2016; Younes & Kouveliotou 2016; Younes et al. 2016; Lin et al. 2020b), Swift-BAT (Tohuvavohu 2020), NICER/XTI, NuSTAR (Borghese et al. 2020), INTEGRAL (Mereghetti et al. 2020), HXMT (Insight-HXMT 2020; Zhang et al. 2020b), AGILE (Ursi et al. 2020; Tavani et al. 2021), and Konus–Wind (Golenetskii et al. 2015; Frederiks et al. 2016; Kozlova et al. 2016a, 2016b; Ridnaia et al. 2019, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2021b) and radio bursts from CHIME (CHIME/FRB Collaboration et al. 2020; Scholz 2020), STARE2 (Bochenek et al. 2020), FAST (Zhang et al. 2020a), and the Westerbork (RT1), Onsala (25 m), and Toruń (30 m) dishes (Kirsten et al. 2020). The plot also shows the H.E.S.S., FAST, BOOTES, and LCOGT observations (Lin et al. 2020c) with upper limits from all shown instruments.

An X-ray burst is detected by AGILE, Konus–Wind, HXMT, and INTEGRAL (burst G in Mereghetti et al. 2020) simultaneously to the FRB from CHIME and STARE2 (FRB 20200428).

Radio: FRB 20200428 associated with SGR 1935+2154 is detected by CHIME (CHIME/FRB Collaboration et al. 2020; Scholz 2020) at 2020 April 28 14:34:33 UTC and STARE2 (Bochenek et al. 2020) at 2020 April 28 14:34:25 UTC (∼58,967.60733 MJD). Several X-ray instruments detected coincident X-ray bursts as shown in Figure 1. Follow-up observations by the FAST radio telescope (Pingtang, China) in the 1.25 GHz band did not reveal radio bursts down to a fluence of < 22 mJy ms (Lin et al. 2020c); however, a weak, highly linearly polarized radio burst was detected on April 30 (Zhang et al. 2020a; 58,969 MJD). Moreover, no radio bursts were detected in the observation campaigns by the Arecibo, Effelsberg, LOFAR, MeerKAT, MK2, and Northern Cross radio telescopes (not shown in Figure 1) reported in Bailes et al. (2021). The upper limits derived from these observations are between 18 and 25 mJy. Two additional radio bursts separated by ∼1.4 s on 2020 May 24 (Kirsten et al. 2020; 58,993 MJD) were detected following an X-ray burst detected by HXMT during a joint campaign between the Westerbork (RT1), Onsala (25 m), and Toruń (30 m) radio dishes. The burst fluences are several orders of magnitude lower than the two bursts detected by CHIME and STARE2, with values of 112 ± 22 Jy ms and 24 ± 5 Jy ms, respectively. The four FRBs

Table 1
Summary of the H.E.S.S. Observations of SGR 1935+215

Start Time (UTC)	Duration	Average Zenith Angle
2020 Apr 28 01:55:00	28 minutes	55.0 deg
2020 Apr 28 02:26:55	28 minutes	51.0 deg
2020 Apr 28 02:56:08	28 minutes	48.1 deg
2020 Apr 28 03:25:24	28 minutes	46.2 deg

Note. The observations overlapped with magnetar bursts detected by INTEGRAL and Fermi-GBM.

detected from SGR 1935+2154 thus span around seven orders of magnitude in fluence. No FRBs were detected during the time of the H.E.S.S. data acquisition.

VHE gamma rays: The H.E.S.S. transients' follow-up system triggered Target of Opportunity follow-up observations on SGR 1935+2154 after the reception of a first Swift-BAT alert, indicating a high-intensity X-ray burst from SGR 1935+2154 at 2020 April 27 18:26:19.95 UTC (58,966.76828646 MJD). A second Swift-BAT alert arrived ∼6.5 minutes later (Barthelmy et al. 2020). Darkness and visibility constraints only allowed follow-up observations to commence ∼7.5 hr later. The observations lasted 2 hr and consisted of four runs taken with *wobble* offsets whereby the source is alternately offset by 0.5 deg in opposite directions of the R.A. and decl. The positions reported by Swift-BAT have a $3'$ uncertainty and are thus fully comprised within the H.E.S.S. field of view of 2.5 deg radius. A summary of the observations is presented in Table 1, and we put them in context with the MWL observations of the burst activity of SGR 1935+2154 in Figure 1.

Optical: No optical emission has been detected by the BOOTES-3 (New Zealand) telescopes observing contemporaneously to the first detected FRB, and 3σ upper limits in the *Z*-band are given as >17.9 mag during this epoch (Lin et al. 2020c). No optical emission was seen by LCOGT (California, USA), other BOOTES telescopes, or the MeerLICHT (not shown in Figure 1) optical telescope (Bailes et al. 2021).

3. Data Analysis and Results

The H.E.S.S. results presented here use data from all four 12 m telescopes. The quality of the obtained data has been thoroughly verified, and standard quality selection criteria (Aharonian et al. 2006) are applied. The data are then analyzed using the *standard cuts* of the semianalytical *Model Analysis* described in de Naurois & Rolland (2009). The standard *Ring background* technique (Berge et al. 2007) is used to determine the background with a radial acceptance and a 0.1 deg ON region. We obtain a total number of ON events $N_{\mathrm{ON}} = 26$ and OFF events $N_{\mathrm{OFF}} = 270$ in the source region, with $\alpha = 0.0813$ leading to an excess value of 4.0. We derive the significance map shown in Figure 2 using the formalism described in Li & Ma (1983) and an oversampling radius of 0.1 deg. In this map no significant signal above 5σ can be found at the position of the SGR or elsewhere in the covered region. We therefore conclude that no significant VHE gamma-ray emission has been detected by H.E.S.S. during the follow-up observations of SGR 1935+2154.

A low-energy threshold is defined as the energy where the effective area is at least 10% of its maximum value. Influenced by the relatively high zenith angle of the observations, a value of $E_{\mathrm{thr}} = 600$ GeV is found. Assuming a generic $E^{-2.5}$ energy spectrum, we compute 95% confidence level differential upper limits shown in Figure 3 at the position of SGR 1935+2154 using a Poisson likelihood method described in Rolke et al. (2005). Integrating above 600 GeV gives a value of $\Phi_\gamma(E > 600\,\mathrm{GeV}) < 1.5 \cdot 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. If we consider an E^{-2} spectrum, this value drops by ∼13%, and for an E^{-3} spectrum it increases by ∼7%. The analysis presented in this section has been cross-checked and validated with an independent event calibration and reconstruction analysis (Parsons & Hinton 2014).

In addition to the standard analysis, we perform the Cumulative Sum, ON-OFF, and Exp- tests described in Brun et al. (2020) to search for a variable or transient VHE signal. For that we use the gamma-candidate events that are selected after the cut applied by the *Model Analysis*. No significant variability was detected at minute to hour timescales. Furthermore, a search for gamma-candidate doublets arriving within millisecond time windows from the direction of

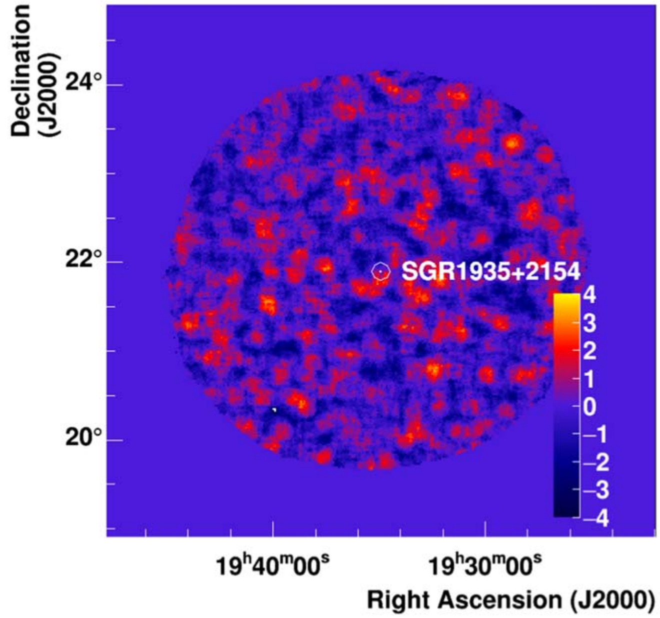

Figure 2. Significance map computed from the H.E.S.S. observational data taken on SGR 1935+2154.

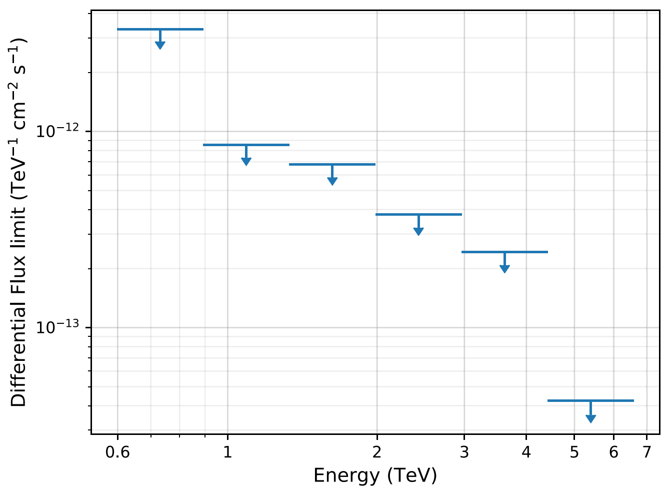

Figure 3. Differential 95% C.L. upper limits derived from the H.E.S.S. observational data taken on SGR 1935+2154.

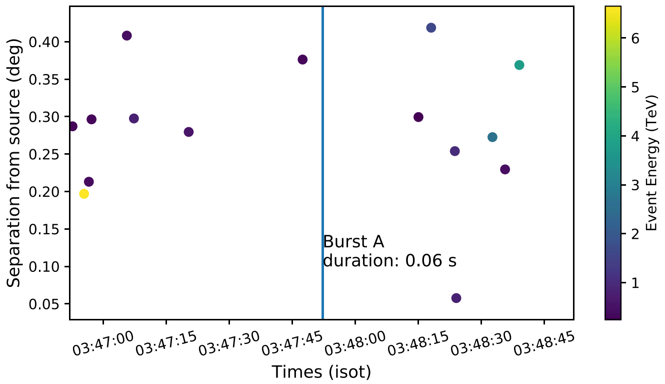

Figure 4. VHE gamma candidates detected by H.E.S.S. from SGR 1935+2154 at the time of the X-ray burst A detected by INTEGRAL (Mereghetti et al. 2020). The vertical line designates the burst. The gamma candidates are expected background events.

SGR 1935+2154, which could be associated with a magnetar burst, is conducted. No such doublets are detected. This search is extended to clusters of gamma candidates around the Fermi-GBM and INTEGRAL bursts. As an example, Figure 4 shows the arrival times of gamma candidates around the INTEGRAL burst. No gamma-candidate events from the source region are found within less than 9 s of any Fermi-GBM or INTEGRAL burst occurring during our observations. We note that the gamma candidates are expected background events that passed the selection cuts from the *Model Analysis* and should not be misinterpreted with gamma rays.

The H.E.S.S. sensitivity for this kind of fast transient phenomena, i.e., assuming detection of gamma-candidate multiplets at millisecond-scale time windows, is at the order of $\sim 10^{-9}$ erg cm^{-2} depending on the zenith angle of the observations.

4. Discussion

The H.E.S.S. observations described here present the first VHE gamma-ray observations of a magnetar during a high-activity phase. Our observations are coincident with four X-ray bursts detected by two instruments (Fermi-GBM and INTEGRAL) and put stringent upper limits on the VHE emission during the active phase of the magnetar.

With a spectral index of 2, the INTEGRAL burst (burst G from Mereghetti et al. 2020) coincident with the FRB detected by CHIME and STARE2 has a harder spectral shape than from other bursts detected by INTEGRAL. It is also more energetic than burst A that occurred during the H.E.S.S. observations: $F_G/F_A = 5.3$, with F_G and F_A the fluence values of bursts A and G, respectively. Assuming that burst A could be connected to another coincidental FRB half an order of magnitude less energetic than the detected radio burst, FRB 20200428, this hypothetical FRB would still be within the sensitivity of radio instruments. The fact that several X-ray bursts happened during FAST radio observations and the lack of radio burst detection (UL $\sim 2.75 \times 10^{-19}$ erg cm^{-2}) leads us to believe that these ordinary SGR bursts (including burst A) are different from burst G. Moreover, the HXMT burst associated with the FRB is dominated by a power law and is therefore primarily nonthermal in nature according to Li et al. (2021), which is very rare for SGRs (6% of SGR bursts as per Li et al. 2021).

The lack of VHE gamma rays is consistent with expectations from regular magnetar bursts (Kaspi & Beloborodov 2017) when thermal emission mechanism is involved. 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 $F(E > 600\,\mathrm{GeV}) < 2.4 \times 10^{-12}$ erg cm^{-2} s^{-1}. Assuming a distance of 6.6 kpc, we derive a luminosity upper limit $L(E > 600\,\mathrm{GeV}) < 1.3 \times 10^{34}$ erg s^{-1}. This places constraints on persistent VHE emission from SGR 1935+2154 during the H.E.S.S. observations. The sensitivity to gamma-ray multiplets can be transformed into sensitivity to the isotropic energy from a VHE burst $E_{\mathrm{VHE,iso}}(E > 600\,\mathrm{GeV}) \leqslant 5.2 \times 10^{36}$ erg. This sensitivity is higher than the isotropic energies of the FRB bursts detected from the source ($\sim 10^{34}$–10^{35} erg). However, it can be compared to the energy released in the X-ray domain during the coincident Fermi-GBM and INTEGRAL bursts ($\sim 10^{38}$–10^{39} erg), indicating that if there were an isotropic VHE emission related to these X-ray bursts during the time of H.E.S.S. observations, it would have been detected.

The nondetection by H.E.S.S. may suggest that the inverse-Compton process is suppressed in the magnetar surroundings, making the VHE emission too weak to be detected. An explanation for that is that the gamma-ray emission is happening too close to the magnetar surface and pair production and photon splitting result in significant energy losses for the VHE gamma rays, leading to strong cutoffs in the MeV to GeV energy range. This flux suppression could be avoided in scenarios where the gamma rays are generated well away from the magnetar's intense magnetic field (Hu et al. 2019) or in scenarios involving axions (Archer & Buckley 2021). In case of detection, the H.E.S.S. observations could therefore also probe the particle transport aspects (such as outflows) in the vicinity of SGR 1935+2154 during the recent flaring episode. Further MWL observations of flaring magnetars are needed for a robust conclusion on the nature of the observed bursts. We cannot draw any conclusions concerning VHE counterpart emissions from FRBs since the H.E.S.S. data presented here are not contemporaneous with any radio burst and the coincident X-ray bursts seem to be different in nature from the bursts associated with FRB 20200428. The predicted energy released during a VHE pulse from magnetar nebulae by Lyubarsky (2014) is detectable at distances of roughly hundreds of Mpc. The derived sensitivity of H.E.S.S. to TeV photons suggests that such VHE bursts would be detectable by H.E.S.S. This motivates further observations of magnetars and FRBs in the VHE domain.

5. Conclusions

H.E.S.S. observed SGR 1935+2154 during its period of high activity on 2020 April 28. We gather MWL information on the source from the time of discovery until the high-activity period recorded in 2020. Four X-ray bursts were detected by INTEGRAL and Fermi-GBM during the H.E.S.S observation period. The data analysis does not show any significant detection of VHE gamma rays from the source, and variability searches do not show emission of gamma rays on the minute, second, and millisecond scales. We thus use H.E.S.S. observations to derive upper limits. SGR 1935+2154 established the link between FRBs and X-ray bursts thanks to the coincident radio and X-ray bursts. While the H.E.S.S. upper limits cannot be used to constrain VHE emission from the source's FRBs, they place for the first time constraining upper limits on the persistent and transient VHE emission coincident with magnetar X-ray bursts. The details of the underlying emission mechanism are still unclear, and further MWL observations of these objects are necessary. We note that SGR 1935+2154 renewed its activity in the beginning of 2021 with bursts detected by INGTERAL (Mereghetti et al. 2021), Fermi-GBM (Roberts et al. 2021a, 2021b), CGBM (Ricciarini et al. 2021), and Konus–Wind (Ridnaia et al. 2021a). The H.E.S.S. program on transient phenomena includes various triggered and untriggered campaigns and aims at providing additional pieces to the puzzle of the origin of FRBs and the mechanisms of magnetar flares.

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