PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

PoS(ICRC2021)783

Monitoring the magnetar SGR 1935+2154 with the MAGIC telescopes

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The Galactic magnetar SGR 1935+2154 was associated with a bright, millisecond-timescale fast radio burst (FRB) which occured in April 2020, during a flaring episode. This was the first time an FRB was unequivocally associated with a Galactic source, and the first FRB for which the nature of the emitting source was identified. Moreover, it was the first FRB with a counterpart at another wavelength correlated in time, an atypical, hard X-ray burst, which provides clear evidence for accompanying non-thermal processes. The MAGIC Telescopes are Imaging Air Cherenkov Telescopes (IACTs) sensitive to very-high-energy (VHE, E>100 GeV) gamma rays. Located at the center of the camera lies the MAGIC Central pixel, a single fully-modified photosensor-to-readout chain to measure millisecond-duration optical signals, displaying a maximum sensitivity at a wavelength of 350 nm. This allows MAGIC to operate simultaneously both as a VHE gamma-ray and a fast optical telescope. The MAGIC telescopes have monitored SGR 1935+2154 in a multiwavelength campaign involving X-ray, radio and optical facilities. In this contribution, we will show the results on the search for the VHE counterpart of the first SGR-FRB source in this multiwavelength context, as well as the search for fast optical bursts with the MAGIC Central Pixel.

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37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

1. Introduction

Magnetars are isolated neutron stars (NSs) with ultra-high magnetic fields (B =10^{14}-10^{15} G). About thirty objects, with spin periods between 0.3 and 12 seconds, have been detected in the Galaxy, most of them during transient episodes observed only once. These magnetars can display several types of emission:

Persistent: they show bright persistent X-ray emission, powered by magnetic field decay (see [1] for a review). This persistent emission is modeled by thermal radiation from the NS hot surface (about 0.2–0.6 keV), reprocessed in a twisted magnetosphere through resonant cyclotron scattering. This steady component has not been detected above few keV. Searchers for steady gamma-ray emission performed at high-energy (HE, E>100 MeV) by *Fermi*-LAT [2] set upper limits (ULs) on magnetar steady emission with the use of six years of data. Very-high-energy (VHE, E>100 GeV) observations performed by MAGIC of the magnetars 4U 0142+61 and 1E 2259+586 also resulted in non-detections, and ULs to the steady and pulsating emission were set [3]. These non-detections are in agreement with some theoretical models such as [4].

Transient: magnetars can emit flares and outbursts on different timescales, detectable in X-rays and radio. These are probably caused by large-scale rearrangements of the surface and/or magnetospheric field. They can either be accompanied or triggered by displacements of the NS crust. Magnetars can also display giant flares (GFs), which are among the most energetic (10^{44}-10^{47} erg s^{-1}) Galactic events. These GFs are short (lasting about a second) very-luminous hard spikes, followed by a softer pulsating tail (lasting hundreds of seconds) and a thermal afterglow (which typically lasts <1h) seen in hard X-rays. Only four GFs have been recorded in four decades of monitoring the high-energy sky: the most recent, a GF from an extragalactic magnetar, located in the Sculptor galaxy. The *Fermi*-LAT satellite discovered GeV emission during this GF event [5]. This is the most energetic emission ever recorded from these events, with two photons detected above 1 GeV.

SGR 1935+2154 is a Galactic magnetar, located at a distance of 6.6-12.5 kpc [6, 7]. It is embedded in the supernova remnant SNR G57.2+0.8 and it is likely associated with a molecular cloud (MC; Zhou et al. 2020). Since its discovery in 2014 by *Swift*-BAT (Stamatikos et al. 2014), SGR 1935+2154 has been very active, showing several outbursts in 2015 and 2016, each time more intense in terms of the total number of bursts per active episode and in terms of the total energy emitted and in the level of the persistent emission (Younes et al. 2017; Lin et al. 2020). The most interesting and unique outburst occurred in April 28, 2020, when an extremely bright, millisecond- timescale fast radio burst (FRB), namely FRB 200428, was detected by the CHIME telescope from a direction consistent with SGR 1935+2154 [8] and confirmed by STARE2 [9] and the European dishes including the 25-m single-dish at Westerbork (the Netherlands), the 25 m and 20 m telescopes at Onsala Space Observatory (Sweden) and the 32 m dish in Toruń (Poland) [10]. FRBs are bright transient flashes of millisecond duration, detected typically at GHz frequencies. FRBs were first discovered by [11] with the Parkes 64-m radio telescope. As of May 2021, a total of 147 FRB events have been detected (as reported in the FRB Community Newsletter Volume 2, Issue 05). 24 FRB repeaters have been localized and 14 host galaxies have been associated to FRB events. The FRB-event associated with SGR 1935+2154 is the only one of Galactic origin, being the rest of them originated outside of the Milky Way. Hence, SGR 1935+2154 has become the first source of FRBs identified with a known object and the first FRB with Galactic origin. Additionally, FRB 200428 was the first FRB accompanied by a more energetic counterpart, detected in X-rays by several instruments [12–16]. The X-ray burst had a significantly harder spectrum compared to other bursts usually observed from this and other magnetars [12].

X-ray observatories NICER [17] and Swift [18] detected different forests of bursts contemporaneously to the FRB event from SGR 1935+2154, which extended for several hours. [19] reported the detection of several millisecond-duration burst few days after the CHIME/FRB discovery, indicating the bursting phase was still active. Two days after the FRB detection, a highly-polarised, transient radio burst was reported by FAST [20].

Three more millisecond duration radio bursts were detected by CHIME/FRB on October 8, 2020 [21]. This radio emission was confirmed by FAST [22]. Several bright X-ray bursts were again detected from SGR 1935+2154 in January-February 2021 [23–25]. The several episodes of activity have been detected along almost a year.

One of the questions that intrigue the gamma-ray community is whether magnetars can emit VHE radiation. Can VHE gamma-rays be produced during GFs? Can FRB-like flares produce VHE emission? The detection of hard X-ray bursts with a non-thermal spectrum show that, at least some FRBs are able to accelerate particles and produce high-energy non-thermal emission. Also, the *Fermi-LAT* detection of GeV emission from an extragalactic magnetar GF demonstrates that magnetars can indeed produce high-energy gamma-ray emission. Different scenarios propose that VHE gamma-ray emission could be produced correlated with FRBs on millisecond timescales. FRBs could be produced via synchrotron maser mechanism, as proposed by [26, 27]. The emission would be triggered by strong magnetic disturbances that arise in the magnetosphere and propagate outwards, until they dissipate by interacting with the ambient nebula. TeV emission could be produced on millisecond (or even longer, according to [27]) timescales, but it could reach luminosity levels to be detected by IACTs. In the case of SGR 1935+2154 , similar synchrotron maser shock models propose that the dissipation of disturbances within the magnetar wind is the cause of the hard X-ray burst from SGR 1935+2154 associated with FRB 200428 [28–30]. TeV emission could be produced in this case via a non-thermal tail [31].

FRBs may be potentially accompanied by "fast optical bursts" (FOBs) via different mechanisms [32]. Even if very few optical counterparts have been associated to magnetars (e. g. [33]), a very fast optical flaring episode was associated to a soft gamma repeater candidate [34]. This episode reported sub-second very-bright optical variability resembling the light-curve profiles seen during magnetar outbursts. Ra

2. The MAGIC telescopes: gamma-ray and optical detectors

The Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes are a stereoscopic system composed of two 17m-diameter telescopes, located at 2200 m above sea level in the Roque de los Muchachos observatory in La Palma (Canary Islands, Spain). They detect VHE gamma-rays from as low as 50 GeV up to 100 TeV [35].

The MAGIC cameras are composed of 1039 highly-sensitive photomultipliers. They are able to detect the dim flashes of Cherenkov light created by gamma-initiated electromagnetic showers. The central pixel of the MAGIC camera (namely *central pixel* or *cpix*) has been adapted to measure

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millisecond-duration optical signals. It is a single fully-modified photosensor-to-readout chain, reaching a maximum sensitivity at a wavelength of 350 nm [36]. This allows MAGIC to operate simultaneously both as VHE gamma-ray and fast optical telescope. Since the predictions for both the most luminous FOBs associated with relatively bright FRBs and the fast optical flaring episodes seen on a SGR candidate are well within the sensitivity of the central pixel, it might be possible to detect putative emission from a FRB event from SGR 1935+2154 . The central pixel has already been proven useful in the search of FRBs, as i.e., constraining the optical emission from FRB 121102 [37].

MAGIC can perform observations in two different modes. In the so-called *wobble* mode, the source is located off-axis from the center of the camera (typically 0.4° away). In this scenario, the source position is swapped 90° every 15 to 20 min of observation, allowing to simultaneously record OFF data under the same conditions that is used for background estimation. This mode is optimal for VHE observations. In the ON mode, the MAGIC telescopes track the source at the center of the camera. This allows for simultaneous observations with the central pixel. However, no simultaneous background is taken, hence dedicated OFF observations need to be scheduled or the background needs to be estimated from observations of regions in the sky with no gamma-ray detection.

3. A multi-wavelength campaign on SGR 1935+2154

The SGR-FRB connection established with the detection of FRB 200428, have made SGR 1935+2154 a highly interesting source to be studied. Considering the uniqueness of the 2020 event, we started a multi-wavelength (MWL) campaign to monitor the status of the magnetar and potentially detect either gamma or FOB emission for the first time. Unfortunately, the April 2020 event took place during the COVID19 lockdown, when MAGIC was under shutdown. During the following months, we organized coordinated MWL observations with radio (Westerbork and Onsala), optical (SiFAP2 camera [38] mounted on the Telescopio Nazionale Galileo; TNG) and X-ray (*Swift*) facilities to monitor the behavior of this magnetar while it was visible from the MAGIC site. This campaign took place between July and October 2020. The second detection of millisecond radio emission by CHIME six months after the first event, confirmed that SGR 1935+2154 was still active and that FRB-like emission was still possible any time.

The strategy was to monitor the source at least twice per month and trigger additional observations whenever flaring emission or outbursts were detected in other frequencies (namely X-rays or radio). The list of performed coordinated observations is collected in Table 1.

No VHE counterpart has been identified in a daily basis in MAGIC data. Likewise, the overall VHE emission is not significant. We have calculated upper limits (ULs at 95% confidence level) to the flux and the corresponding lightcurve above 100 GeV. Similarly, no radio bursts were reported by Westerbork or Onsala. Optical TNG/SiFAP2 observations could not identify any optical burst either. On the contrary, *Swift* reported several burst episodes on different nights (Borghese et al. in prep).

MAGIC observations were scheduled both in wobbling and ON modes, to increase VHE sensitivity and allow simultaneous central-pixel observations, respectively. Simultaneous gamma-ray/optical cpix observations started to be taken from October 9, 2020, one night after the new millisecond radio detections reported by CHIME. Also on October 9, FAST reported the presence of pulsed-emission and several radio bursts [22]. Simultaneous MAGIC and *Swift* observations were scheduled via ToO for that night. A forest of bursts was detected in *Swift* (Borghese et al. in prep). The analysis does not reveal any persistent VHE emission from MAGIC data. A detailed analysis is ongoing for the identification of burst-like signals within both the short-timescale VHE and optical regimes. The Onsala radio telescope observed later on that night for 50 min, but no bursting activity was detected.

Date (MJD)	**MAGIC (gamma/optical cpix)**	**Swift (X-rays)**	**TNG/SiFAP2 (optical)**	**Westerbork/Onsala (radio)**
59053.96-59054.04	yes/no	yes	no	yes/no
59080.88-59080.97	yes/no	no	no	no/no
59102.95-59103.03	yes/no	no	yes	yes/no
59109.95-59110.03	yes/no	yes	no	yes/no
59110.86-59110.94	yes/no	yes	no	yes/no
59111.85-59111.93	yes/no	yes	no	yes/no
59131.89-59131.98	yes/yes	yes	no	no/yes

Table 1: MWL observations of SGR 1935+2154 .

4. Conclusions

SGR 1935+2154 is the first source identified as a FRB emitter of a known nature. In addition, it is the source associated to the first FRBs with detected multi-wavelength counterparts, and it is located within the Milky Way. Due to these extremely unique characteristics, we have started a monitoring campaign to follow-up its behavior in a MWL context. No VHE emission has been detected yet with MAGIC. A detailed analysis for the search of burst-like VHE or FOB events is still ongoing. Coordinated multi-frequency observations of SGR 1935+2154 will help us better understand magnetars and FRBs. A positive detection either in the VHE or optical regimes would be a paramount discovery for both the Galactic transients and VHE fields.

5. Acknowledgements

We acknowledge the support from the agencies and organizations listed here:
https://magic.mpp.mpg.de/acknowledgments_ICRC2021/

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