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<b>Authors</b>	TAVANI, MARCO; VERRECCHIA, Francesco; CASENTINI, CLAUDIO; PERRI, Matteo; URSI, ALESSANDRO; et al.
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## Gamma-Ray and X-Ray Observations of the Periodic-Repeater FRB 180916 During Active Phases

M. TAVANI,<sup>1,2</sup> F. VERRECCHIA,<sup>3,4</sup> C. CASENTINI,<sup>1,5</sup> M. PERRI,<sup>3,4</sup> A. URSI,<sup>1</sup> L. PACCIANI,<sup>1</sup>  
C. PITTORI,<sup>3,4</sup> A. BULGARELLI,<sup>6</sup> G. PIANO,<sup>1</sup> M. PILIA,<sup>7</sup> G. BERNARDI,<sup>8,9</sup> A. ADDIS,<sup>6</sup>  
L.A. ANTONELLI,<sup>4</sup> A. ARGAN,<sup>1</sup> L. BARONCELLI,<sup>6,10</sup> P. CARAVEO,<sup>11,12</sup> P.W. CATTANEO,<sup>12</sup>  
A. CHEN,<sup>13</sup> E. COSTA,<sup>1</sup> G. DI PERSIO,<sup>1</sup> I. DONNARUMMA,<sup>14</sup> Y. EVANGELISTA,<sup>1</sup> M. FEROCI,<sup>1</sup>  
A. FERRARI,<sup>15</sup> V. FIORETTI,<sup>6</sup> F. LAZZAROTTO,<sup>16</sup> F. LONGO,<sup>17</sup> A. MORSELLI,<sup>5</sup> F. PAOLETTI,<sup>18,1</sup>  
N. PARMIGGIANI,<sup>6,19</sup> A. TROIS,<sup>7</sup> S. VERCELLONE,<sup>20</sup> G. NALDI,<sup>8</sup> G. PUPILLO,<sup>8</sup> G. BIANCHI,<sup>8</sup> AND  
S. PUCCETTI<sup>14</sup>

<sup>1</sup>*INAF/IAPS, via del Fosso del Cavaliere 100, I-00133 Roma (RM), Italy*

<sup>2</sup>*Università degli Studi di Roma Tor Vergata, via della Ricerca Scientifica 1, I-00133 Roma (RM), Italy*

<sup>3</sup>*SSDC/ASI, via del Politecnico snc, I-00133 Roma (RM), Italy*

<sup>4</sup>*INAF/OAR, via Frascati 33, I-00078 Monte Porzio Catone (RM), Italy*

<sup>5</sup>*INFN Sezione di Roma 2, via della Ricerca Scientifica 1, I-00133 Roma (RM), Italy*

<sup>6</sup>*INAF/OAS, via Gobetti 101, I-40129 Bologna (BO), Italy*

<sup>7</sup>*INAF/OACa, via della Scienza 5, I-09047 Selargius (CA), Italy*

<sup>8</sup>*INAF/IRA, via Piero Gobetti 101, 40129 Bologna (BO), Italy*

<sup>9</sup>*Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa*

<sup>10</sup>*Dip. di Fisica e Astronomia, Università di Bologna, Viale Berti Pichat 6/2, 40127, Bologna, Italy*

<sup>11</sup>*INAF/IASF, via E. Bassini 15, I-20133 Milano (MI), Italy*

<sup>12</sup>*INFN Sezione di Pavia, via U. Bassi 6, I-27100 Pavia (PV), Italy*

<sup>13</sup>*School of Physics, Wits University, Johannesburg, South Africa*

marco.tavani@inaf.it  
francesco.verrecchia@inaf.it  
claudio.casentini@inaf.it

<sup>14</sup>ASI, via del Politecnico snc, I-00133 Roma (RM), Italy

<sup>15</sup>CIFS, c/o Physics Department, University of Turin, via P. Giuria 1, I-10125, Torino, Italy

<sup>16</sup>INAF/OAPd, vicolo Osservatorio 5, I-35122 Padova (PD), Italy

<sup>17</sup>Dipartimento di Fisica, Università di Trieste and INFN, via Valerio 2, I-34127 Trieste (TR), Italy

<sup>18</sup>East Windsor RSD, 25A Leshin Lane, Hightstown, NJ-08520, USA

<sup>19</sup>Università degli Studi di Modena e Reggio Emilia, DIEF - Via Pietro Vivarelli 10, 41125 Modena, Italy

<sup>20</sup>INAF/OAB, via Emilio Bianchi 46, I-23807 Merate (LC), Italy

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## ABSTRACT

FRB 180916 is a most intriguing source capable of producing repeating fast radio bursts with a periodic 16.3 day temporal pattern. The source is well positioned in a star forming region in the outskirts of a nearby galaxy at 150 Mpc distance. In this paper we report on the X-ray and  $\gamma$ -ray observations of FRB 180916 obtained by *AGILE* and *Swift*. We focused especially on the recurrent 5-day time intervals of enhanced radio bursting. In particular, we report on the results obtained in the time intervals Feb. 3-8; Feb. 25; Mar. 5-10; Mar. 22-28, 2020 during a multiwavelength campaign involving high-energy and radio observations of FRB 180916. We also searched for temporal coincidences at millisecond timescales between the 32 known radio bursts of FRB 180916 and X-ray and MeV events detectable by *AGILE*. We do not detect any simultaneous event or any extended X-ray and  $\gamma$ -ray emission on timescales of hours/days/weeks. Our cumulative X-ray (0.3-10 keV) flux upper limit of  $5 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup> (obtained during 5-day active intervals from several 1-2 ks integrations) translates into an isotropic luminosity upper limit of  $L_{X,UL} \sim 1.5 \times 10^{41}$  erg s<sup>-1</sup>. Deep  $\gamma$ -ray observations above 100 MeV over a many-year timescale provide an average luminosity upper limit one order of magnitude larger. These results provide the so-far most stringent upper limits on high-energy emission from the FRB 180916 source. Our results constrain the dissipation of

magnetic energy from a magnetar-like source of radius  $R_m$ , internal magnetic field  $B_m$  and dissipation timescale  $\tau_d$  to satisfy the relation  $R_{m,6}^3 B_{m,16}^2 \tau_{d,8}^{-1} \lesssim 1$ , where  $R_{m,6}$  is  $R_m$  in units of  $10^6$  cm,  $B_{m,16}$  is  $B_m$  in units of  $10^{16}$  G, and  $\tau_{d,8}$  in units of  $10^8$  s.

## 1. INTRODUCTION

Fast Radio Bursts (FRBs) are impulsive outbursts of mysterious origin (typically lasting  $\sim 1$  msec) detected in the sub-GHz and GHz bands (e.g., Lorimer et al. 2007; Cordes & Chatterjee 2019). Most of the FRBs have been detected only once, but a special category of repeating FRBs has been recently revealed, demonstrating that a sub-class of sources can produce multiple radio outbursts over timescales of years (Cordes & Chatterjee 2019; Petroff et al. 2019).

We focus here on the remarkable repeater FRB 180916.J0158+65 (hereafter FRB 180916) for which 35 radio bursts have been detected with a periodic pattern during the time interval Sept. 2018 - Oct. 2019 (CHIME/FRB Collaboration et al. 2020, hereafter C20). This source, originally localized by CHIME/FRB with an uncertainty of about 0.09 square degrees (CHIME/FRB Collaboration et al. 2019c, hereafter C19) was later detected by VLBI observations a precise arcsec positioning (Marcote et al. 2020, hereafter M20). The source is positionally coincident with the outskirts of a spiral galaxy at the distance of about 150 Mpc. The 3-sigma significance of the proximity of FRB 180916 with a galaxy at a redshift  $z = 0.0337 \pm 0.0002$  and the a-posteriori determination of the intergalactic contribution to its observed excess dispersion measure (DM) strongly support the association of FRB 180916 with the galaxy SDSS J015800.28+654253.0 as reported in M20. This repeating FRB source is therefore located at a distance significantly smaller than that of the majority of FRBs showing  $DM_{excess} \geq 100 \text{ pc cm}^{-3}$  where  $DM_{excess}$  is the excess DM once the Galactic and halo contributions are taken into account.

Evidence of periodic activity of radio bursting from FRB 180916 provides important clues on the mechanism of FRB generation from this source (C20). Radio bursts are not randomly distributed but appear to concentrate especially in specific 5-day intervals recurring every 16.35 days. As noted

in C20, this period can be affected by aliasing<sup>1</sup> due to the CHIME/FRB regular exposure pattern of FRB 180916. A periodic behavior of an otherwise unpredictable emission is remarkable, and suggests either a "triggering" of the radio bursting from physical interactions in a binary system, or emission influenced by compact star precession.

FRB 180916 is then worth a careful study, given its relevance in terms of proximity, number of detected radio bursts, and periodic activity. Table 1 summarizes the relevant information on the 32 radio bursts so far detected from FRB 180916, providing topocentric arrival times and radio fluences on millisecond timescales. The (isotropic-equivalent) energy involved in the radio burst emissions is in the range  $E_{radio,iso} \simeq (10^{36} - 10^{38} \text{erg})$  at the source distance, that is a value million times larger than that of the brightest giant pulses observed from the Crab pulsar (Hankins et al. 2003). The object underlying FRB 180916 is therefore exceptional in its emission properties.

We recently presented in Casentini et al. (2020) preliminary results of *AGILE* observations of FRB 180916 based on the first 10 detected radio bursts. In this paper we extend our search for high-energy emission from the source considering *Swift* X-ray observations as well as *AGILE*  $\gamma$ -ray data both focused on specific active 5-day repetition intervals. Our observations are part of a multi-frequency campaign involving *AGILE*, *Swift* and radio observations of FRB 180916 during the periods Feb. 3 – Feb. 8 and Feb. 19 – Feb. 25, 2020 carried out at the Sardinia Radio Telescope (Prandoni et al. 2017) and at the Northern Cross in Medicina (Locatelli et al. 2020). Our improved upper limits on X-ray and  $\gamma$ -ray emissions from FRB 180916 provide significant constraints on the physical nature of FRB 180916.

## 2. *AGILE* OBSERVATIONS

The *AGILE* mission is an ASI (Italian Space Agency) space project dedicated to X and  $\gamma$ -ray astrophysics (Tavani et al. 2009; Tavani 2019). The instrument consists of four different detectors

<sup>1</sup> The resulting period could be in the range of a few hours to a day as discussed in C20. However, C20 discuss several possibilities that support the hypothesis that this is not the case.

onboard the satellite: an imaging  $\gamma$ -ray Silicon Tracker sensitive in the range 30 MeV - 30 GeV (GRID; Barbiellini et al. 2002), a coded mask X-ray imager sensitive in the 18-60 keV band (Super-AGILE; Feroci et al. 2007), the Mini-Calorimeter sensitive in the 0.4-100 MeV band (MCAL; Labanti et al. 2009) and the anti-coincidence (Perotti et al. 2006) system. Currently, AGILE operates in spinning mode (Pittori et al. 2019), with the instrument axis rotating every  $\sim 7$  minutes around the satellite-sun direction; for each satellite revolution, an exposure of about 80% of the entire sky is obtained. For a summary of the AGILE mission features, see Tavani (2019).

AGILE is capable of quasi-continuously monitoring a source positioned in the accessible portion of the sky. Source visibility depends on solar panel constraints (a seasonal effect that makes about 20% of the sky near the Sun or in the opposite direction not available for observations at any given time), Earth occultations (affecting source visibility with  $\sim 10^3$  s timescales), and South Atlantic Anomaly (affecting about 10% of the  $\sim 95$ -min satellite orbit). Despite these limitations, AGILE can be very effective in detecting transient and steady X-ray and  $\gamma$ -ray emissions from cosmic sources.

In this paper we focus on AGILE and *Swift* observations of the FRB 180916 location (Galactic coordinates  $l = 129.7^\circ$ ,  $b = 3.7^\circ$ ) that turns out to be somewhat influenced by diffuse Galactic emission. The results of the analysis of radio observations (Pilia et al. 2020a) will be reported in a separated paper (Pilia et al. 2020b). In the following we report the results of searches for high energy emission in coincidence with the arrival times ( $T_0$ ) of Table 1 within time windows of 200 seconds centered at  $T_0$ . Due to dispersive delay, radio waves reach detectors on Earth or in orbit several seconds after X-rays or  $\gamma$ -rays. In our searches we take as  $T_0$ 's the de-dispersed topocentric arrival times<sup>2</sup> at infinite frequencies for the different radio telescopes of Table 1.

### 2.1. Super-A flux upper limits

Super-AGILE detects steady and transient emission from sources in the 18-60 keV energy band within a field of view of  $107^\circ \times 68^\circ$ . Due to the spinning of the AGILE satellite, we analyzed time

<sup>2</sup> The difference between the actual AGILE arrival time and the radiotelescopes' de-dispersed topocentric times is of order of 20-40 msec, and it is negligible for our adopted window search of 200 sec.

**Table 1.** FRB180916.J0158+65 bursts and *AGILE* observations

Burst no.	FRB parameters					Event in the <i>AGILE</i> FoV		
	Day (yymmdd)	Arrival times <sup>*</sup> (UTC)	Instr. <sup>†</sup>	bandwidth (MHz)	Fluence (Jy ms)	MCAL	GRID	Super-A
1	180916	10:15:10.746748	C	400-800	>2.3	NO	NO	NO
2	181019	08:13:13.695545	C	400-800	>3.5	-	-	-
3	181019	08:13:13.759080	C	400-800	>2.0	-	-	-
4	181104	06:57:09.522136	C	400-800	>2.8	YES	NO	NO
5	181104	07:06:52.655909	C	400-800	6.8	YES	NO	NO
6	181120	05:55:57.158955	C	400-800	8.0	YES	NO	NO
7	181222	03:59:14.238510	C	400-800	9.6/15/16.5/7.2	YES	YES	NO
8	181223	03:51:19.892113	C	400-800	10.4/3.6	YES	YES	NO
9	181225	03:52:54.884107	C	400-800	3.1	YES	NO	NO
10	181226	03:43:21.063337	C	400-800	2.9/1.6	YES	NO	NO
11	190126	01:32:41.297440	C	400-800	6.4	-	-	-
12	190518	18:13:33.601287	C	400-800	1.0	-	-	-
13	190518	18:20:56.937173	C	400-800	7.7	NO	NO	NO
14	190519	17:50:16.601726	C	400-800	>1.3/>2.2	YES	YES	NO
15	190519	18:08:52.454119	C	400-800	3.1/5.3	-	-	-
16	190519	18:10:41.139009	C	400-800	4.4	NO	NO	NO
17	190603	17:09:14.367599	C	400-800	2.1	YES	NO	NO
18	190604	17:11:30.757683	C	400-800	37	-	-	-
19	190605	16:55:55.866635	C	400-800	>7.0	NO	NO	NO
20	190605	17:02:21.845335	C	400-800	11.5/5.4	NO	NO	NO
21	190619	02:24:19.980000	E	1636-1764	0.72	YES	NO	NO
22	190619	02:46:06.367000	E	1636-1764	0.20	YES	YES	NO
23	190619	03:36:59.608000	E	1636-1764	0.62	-	-	-
24	190619	06:46:56.344000	E	1636-1764	2.53	YES	NO	NO
25	190809	12:50:40.150674	C	400-800	7.3	YES	NO	NO
26	190810	12:49:34.408294	C	400-800	>1.7	-	-	-
27	190825	11:48:18.617542	C	400-800	24	NO	NO	NO
28	190825	11:51:53.904598	C	400-800	2.8	NO	NO	NO
29	190825	11:51:53.967298	C	400-800	1.4	NO	NO	NO
30	190825	11:53:35.794063	C	400-800	>2.6	NO	NO	NO
31	191030	07:33:47.920217	C	400-800	2.3	-	-	-
32	191030	07:41:43.668377	C	400-800	>2.3	YES	YES	YES
33	200220	13:27:35.57	S	296-360	37	YES	YES	-
34	200220	13:36:49.57	S	296-360	13	-	-	-
35	200220	13:36:49.57	S	296-360	19	-	-	-

Notes:

\*: De-dispersed topocentric arrival times at the CHIME , Effelsberg or SRT locations.

†: Radio instruments which detected each specific burst, where C is for CHIME/FRB, E for EVN and S for SRT.

Unmarked detector FoV labels are for radio events occurring when the *AGILE* instrument was in idle mode with no data acquisition mostly due to passages over the SAA.

periods with the source within  $10^\circ$  from the instrument on-axis direction. The resulting time windows have a duration of about 10-20 s. We excluded events taken during the passage above the South Atlantic Anomaly, and events collected when the source was occulted by the Earth. We searched for hard X-ray emission during the 5-day active periods of FRB 180916 during the intervals Feb. 3 – 8, 2020, and Feb. 19 – 25, 2020. The corresponding effective exposures of 5.6 and 2.4 ks lead to  $5\sigma$  ULs of  $2.4$  and  $5.0 \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$  for the two observing intervals. For the sum of observations during the interval Feb. 3 – 25, 2020, we obtain an upper limit of  $1.8 \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$  for a total exposure of 13.5 ks.

## 2.2. MCAL fluence upper limits

The *AGILE*/MCAL (Labanti et al. 2009; Marisaldi et al. 2008) is an all-sky monitor with a  $4\pi$  FoV, sensitive in the 400 keV – 100 MeV energy range. It is a segmented detector, composed of 30 CsI(Tl) scintillation bars, with a total geometrical area of  $\sim 1400$  cm $^2$  (on-axis). The *AGILE* MCAL is a triggered detector: its onboard trigger logic acts on different energy ranges and timescales (ranging from  $\sim 300$   $\mu$ s to  $\sim 8$  s). The sub-millisecond logic timescale allows MCAL to trigger on very short-duration impulsive events. MCAL is then capable of efficiently detecting long and short transients such as GRBs (Galli et al. 2013) as well as Terrestrial Gamma-ray Flashes (TGFs) on millisecond timescales (Marisaldi et al. 2015). A detailed discussion about MCAL triggering and upper limit capabilities is reported in (Casentini et al. 2020; Ursi et al. 2019).

We checked the possible detections by MCAL of transient emission at or near the times of arrival of all accessible radio burst events marked with a "YES" label in the MCAL column of Table 2. Our search was within  $\pm 100$  seconds from the topocentric arrival times of Table 1.

No significant event was detected for a typical fluence UL obtained for millisecond timescales of  $10^{-8}$  erg cm $^{-2}$ . Table 2 provides the typical MCAL fluence ULs obtained at different trigger timescales. When compared with the radio fluences of FRB 180916 bursts, our ULs in the MeV range set the constraint that the energy detectable in the MeV range and emitted on millisecond timescales have to be less than  $\sim 10^8$  times the energy emitted in the GHz band ( $E_r \sim 3 \times 10^{37}$  erg).

**Table 2.** Average *AGILE*/MCAL fluence ULs in  $\text{erg cm}^{-2}$ 

sub-ms	1 ms	16 ms	64 ms	256 ms	1024 ms	8192 ms
$1.13 \times 10^{-8}$	$1.29 \times 10^{-8}$	$3.72 \times 10^{-8}$	$4.97 \times 10^{-8}$	$7.95 \times 10^{-8}$	$1.59 \times 10^{-7}$	$4.49 \times 10^{-7}$

### 2.3. GRID flux upper limits

Gamma-ray observations of FRB 180916 focused on day-long exposures of the source during the reportedly active time intervals following the 16.3 periodicity of C20. Table 3 summarizes the *AGILE*/GRID ULs obtained above 100 MeV for 5-day integrations corresponding to 10 contiguous active intervals of FRB 180916 covering the period 25 Aug. 2019 – 28 Mar. 2020. Typical 5-day GRID flux ULs are  $10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  (obtained by the *AGILE* multi-source maximum likelihood analysis for a power-law spectral model of spectral photon index of 2) corresponding to isotropic-equivalent  $\gamma$ -ray luminosity ULs of  $3 \times 10^{44} \text{ erg s}^{-1}$ .

In addition to the latter integrations, we also performed a deep exposure of the FRB 180916 region including both pointing (2007–2009) and spinning (2010–today) mode data. We find an integrated flux UL  $\sim 8.2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ , corresponding to an isotropic long-term averaged  $\gamma$ -ray luminosity  $L_{\gamma, UL, ave} \sim 2 \times 10^{42} \text{ erg s}^{-1}$ .

**Table 3.** Average *AGILE*/GRID flux ULs in  $\text{erg cm}^{-2} \text{ s}^{-1}$ .

$\Delta T = 10^1 \text{ s}$	$\Delta T = 10^2 \text{ s}$	$\Delta T = 10^3 \text{ s}$	$\Delta T = 10^0 \text{ d}$	$\Delta T = 10^1 \text{ d}$	$\Delta T = 10^2 \text{ d}$
$4.0 \times 10^{-7}$	$3.5 \times 10^{-8}$	$1.5 \times 10^{-8}$	$4.0 \times 10^{-10}$	$1.0 \times 10^{-10}$	$1.7 \times 10^{-11}$

Notes:

$2\sigma$  flux ULs ( $\text{erg cm}^{-2} \text{ s}^{-1}$ ) obtained for emission in the range 50 MeV–10 GeV for the short integration timescales and 100 MeV–10 GeV for the long ones, at the FRB 180916 position.

## 3. *Swift* OBSERVATIONS

The Neil Gehrels Swift Gamma-ray Burst Observatory has three instruments (Gehrels et al. 2004); namely, the Burst Alert Telescope (BAT, Markwardt et al. 2005), the X-ray Telescope (XRT, Burrows

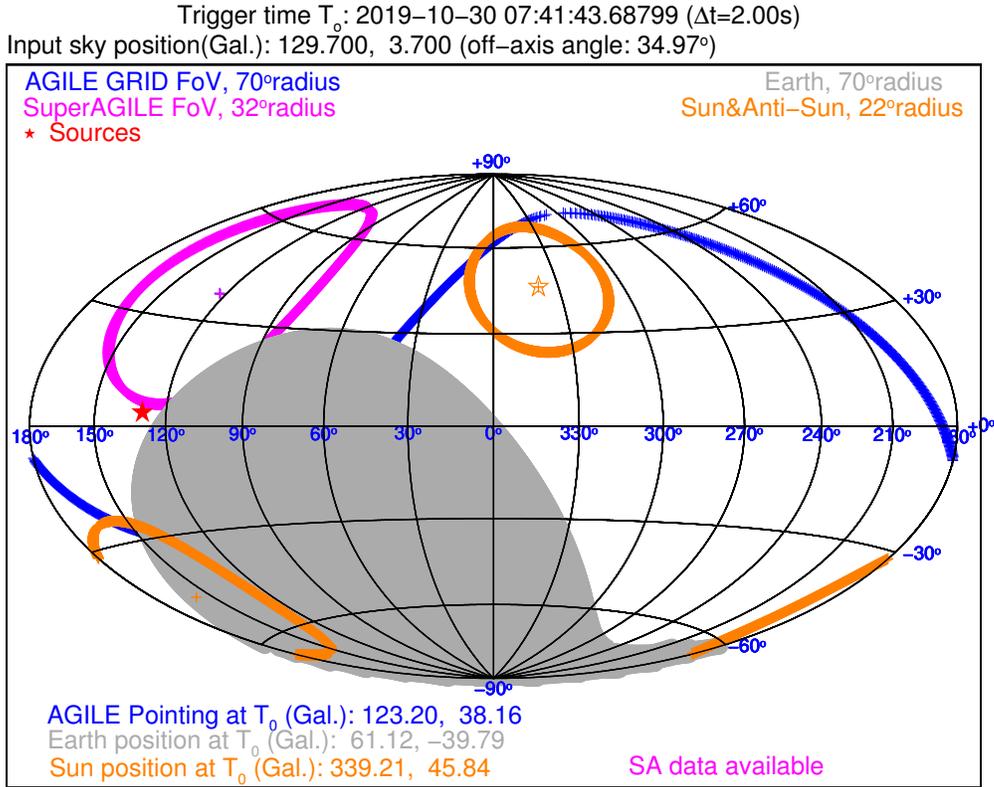
**Table 4.** *AGILE*/GRID flux upper limits on 5-day integrations centered on single activity cycles. Flux integrations are centered on radio burst activity cycles derived from C20.

Cycle no.	Date* (UTC)	UL value ( $\times 10^{-10}$ erg cm $^{-2}$ s $^{-1}$ )
3	25/03/2020 09:00	2.06
2	09/03/2020 00:36	1.42
1	21/02/2020 16:12	1.36
0	05/02/2020 07:48	0.90
-1	19/01/2020 23:24	2.30
-2	03/01/2020 15:00	0.74
-3	18/12/2019 06:36	0.89
-4	01/12/2019 22:12	1.00
-5	15/11/2019 13:48	2.10
-6	30/10/2019 05:24	1.20
-7	13/10/2019 21:00	1.00
-8	27/09/2019 12:36	0.76
-9	11/09/2019 04:12	1.50
-10	25/08/2019 19:48	1.10

Notes:

\*: Dates refer to the centers of the 5-day time intervals.

et al. 2005), and the Ultraviolet/Optical Telescope (UVOT, Roming et al. 2005). A request for *Swift* ToO observations of FRB 180916 was granted, and a first 6-day period of pointings started on Feb. 3, 2020. An additional observation on Feb. 25, 2020 was also carried out (solar panel constraints did not allow *Swift* to monitor the corresponding active time interval). Additional *Swift* data were collected during the active time intervals Mar. 5 – 10 and Mar. 22 – 28, 2020.



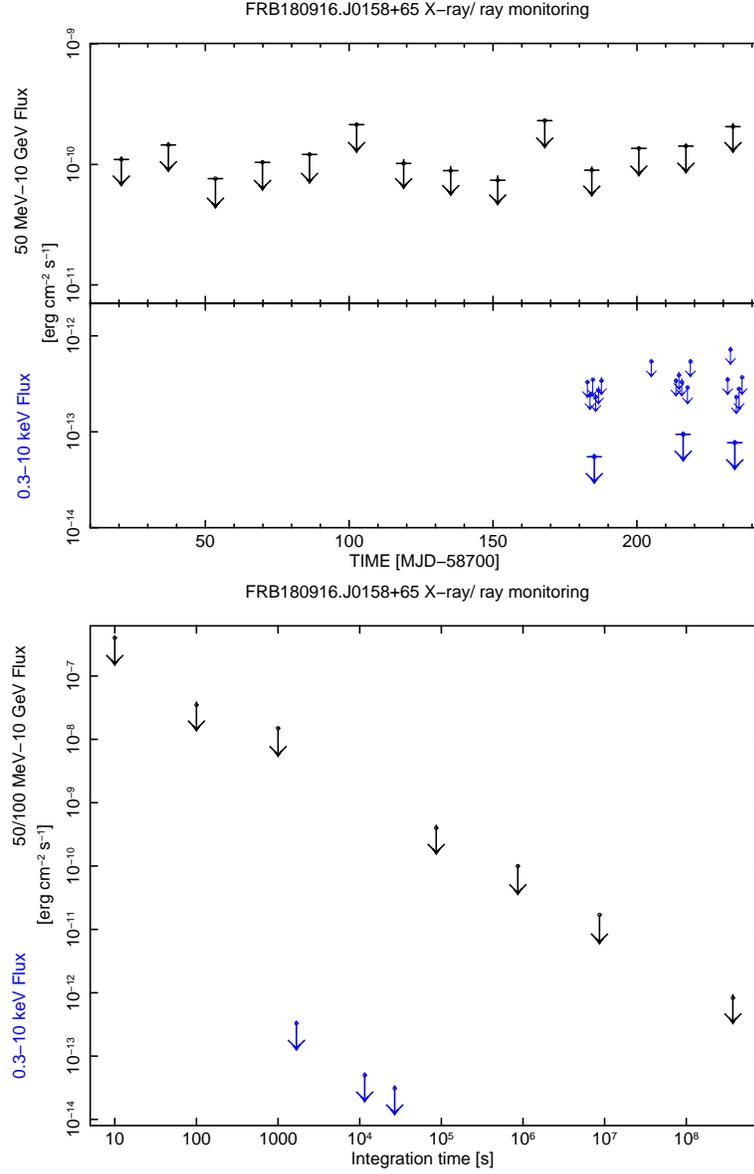
**Figure 1.** Galactic coordinate map showing the *AGILE*/GRID FoV (in blue color) and the Super-A FoV (in magenta color) at the time of arrival  $T_0$  of the FRB 180916 radio burst no. 32 of Table 1 on Oct. 30 2019 07:41:43.668 UTC. The position of FRB 180916 is marked with a red star. The shaded gray area shows the portion of the sky occulted by the Earth at  $T_0$ .

### 3.1. *Swift*/XRT flux upper limits

The XRT data were taken within the framework of the planned coordinate multi-instrument campaign. The FRB 180916 position was monitored in the X-rays (0.3–10 keV) during a first interval with daily observations between MJD 58882 and MJD 58887 (Tavani et al. 2020a,b). A single observation was carried out on MJD 58904. Additional pointings were obtained during the time windows MJD 58913 – 58918, and MJD 58921 – 58926. All observations were carried out in the Photon

Counting (PC) readout mode, with a typical exposure of  $\sim 1.5$  ks per pointing. The data were processed using the XRTDAS software package (v.3.5.0), developed by the ASI Space Science Data Center (SSDC) and released by HEASARC in the HEASoft package (v.6.26.1). The data were calibrated and cleaned with standard filtering criteria using the `xrtpipeline` task and the calibration files available from the Swift/XRT CALDB (version 20190910). The imaging analysis was executed selecting events in the energy channels between 0.3 keV and 10 keV and within a 10-pixel ( $\sim 46$  arcsecond) radius, which contains 80% of the point spread function (PSF). The background was estimated from an annular region with radii of 25 and 60 pixels. No X-ray source was detected. We extracted the  $3\text{-}\sigma$  countrates UL using the XIMAGE package (*sosta* command) and converted to fluxes using a standard single power-law spectral model with photon index  $\alpha = 2.0$  (with the photon number flux defined as  $dN/d\varepsilon \propto \varepsilon^{-\alpha}$ , with  $\varepsilon$  the photon energy). We corrected the flux for absorption with a neutral-hydrogen ( $N_H$ ) column density fixed to the Galactic 21 cm value in the direction of the source,  $7.1 \times 10^{21} \text{ cm}^{-2}$  (HI4PI Collaboration et al. 2016), and redshifted the single spectral component for the known value  $z = 0.0337$  (M20)<sup>3</sup>. Combining all the *Swift*/XRT observations we obtain an overall 3-sigma flux upper limit of  $3.1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  for the total exposures of 26.8 ks. The X-ray ULs are reported in Table 5.

<sup>3</sup> We verified that variations in photon index of  $\pm 0.5$  leads to flux values within -20%/+30% with respect to the one reported above; variations of  $N_H$  from  $10^{21}$  to  $10^{22} \text{ cm}^{-2}$  correspond to variations in flux values within  $\lesssim 30\%$ .



**Figure 2.** (*Top panel:*) *Upper plot:* *AGILE*/GRID 5-day  $\gamma$ -ray flux ULs (100 MeV - 10 GeV) obtained at active cycles of FRB 180916 during the period August 2019 - March 2020. *Bottom plot:* *Swift*/XRT flux ULs marked in blue color (shown for integrations larger than 900 s) in the 0.3–10 keV energy range; they are obtained for individual observations during cycle 0, 2 and 3 of Table 5 (Feb. 3-8, Feb. 25, Mar. 5-10 and Mar. 23-28, 2020). The lowest values of the ULs are for the summed observations of cycle 0 (10.2 ks), cycle 2 (7.9 ks) and cycle 3 (7.8 ks). (*Bottom panel:*) *AGILE* and *Swift* flux ULs obtained with different integration time intervals of observations of FRB 180916. The GRID ULs (in black color) in the range 50 MeV - 10 GeV are for integrations of 10, 100 and 1000 s centered on radio bursts of FRB 180916, and in the range 100 MeV - 10 GeV for integrations of 1, 2, 100 days. The lowest value UL is obtained for a deep GRID integration of  $\sim 11.5$  years. *Swift*/XRT ULs in the 0.3–10 keV energy range (in blue color) are shown for typical single 1.5 ks integrations, summed integration during an active cycle (cycle 0), and for the sum of all observations during cycles 0-3 with total exposure of 26.8 ks.

**Table 5.** *Swift*/XRT 3- $\sigma$  flux ULs.

Start Date (UTC)	Effect.Exposure (s)	0.3–10 keV UL value ( $\times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ )
2020-02-03 18:43:55	1677	3.3
2020-02-04 15:43:59	1966	2.4
2020-02-05 15:23:58	1304	3.5
2020-02-06 15:29:51	2006	2.3
2020-02-07 15:23:35	2016	2.7
2020-02-08 15:16:35	1264	3.4
2020-02-25 14:00:01	920	5.4
2020-03-05 13:08:00	1828	3.4
2020-03-06 14:23:00	1241	3.9
2020-03-07 14:16:00	1392	3.3
2020-03-08 14:12:13	303	15.0
2020-03-09 14:04:46	1597	2.9
2020-03-10 13:57:52	920	5.4
2020-03-23 12:20:41	1795	3.5
2020-03-24 12:40:46	727	7.2
2020-03-25 12:40:34	318	18.0
2020-03-26 12:20:14	1938	2.3
2020-03-27 11:53:55	1738	2.8
2020-03-28 11:48:08	1254	3.7

#### 4. DISCUSSION

Our X-ray and  $\gamma$ -ray observations of FRB 180916 provide valuable constraints on the nature of the source. The (isotropic equivalent) energy of radio bursts is  $E_{radio,iso} \simeq (3 \times 10^{37} \text{ erg}) S_{\nu,Jy} \delta t_{ms} \Delta\nu_{GHz} d_{150M}^2$ , where the measured radio flux density is  $S_{\nu,Jy}$  in units of Jansky,  $\delta t_{ms}$  is the temporal width in units of milliseconds,  $\Delta\nu_{GHz}$  is the radio bandwidth in units of GHz,

and  $d_{150\text{Mpc}} = d/150\text{Mpc}$  with  $d$  the source distance from Earth. Note from Table 1 that the radio bursts of FRB 180916 have radio spectral fluences  $F'_{\text{GHz}}$  in the range  $0.1\text{ Jy ms} \lesssim F'_{\text{GHz}} \lesssim 10\text{ Jy ms}$  for frequencies in the interval  $0.3 - 1.5\text{ GHz}$ . We therefore have  $E_{\text{radio,iso}} \simeq (10^{36} - 10^{38})\text{ erg}$  that is radiated on millisecond timescales. These energies are 6 orders of magnitude larger than those of the giant pulses from the Crab pulsar (Hankins et al. 2003). It is therefore unlikely that the underlying source of FRB 180916 is a neutron star of the type associated with radio pulsars in our Galaxy. Alternative possibilities to provide the required energies rely on compact objects, either strongly magnetized objects such as magnetars, or black holes (BHs). In both cases, the energetics involved in the impulsive radio emission might be a small fraction of a much larger latent power. The process of radio burst emission in FRB 180916 is probably "triggered" by the presence of a companion star. We can envision different possibilities for the generation of radio pulses induced by a wind or plasma flow originating from a companion (main sequence, O-B or Be) star: magnetospheric events, accretion events, or shock interactions with mass outflows under the form of isotropic or equatorial winds as in the case of Be stars. Alternative scenarios include periodicities induced by a compact star precession or localized "spots" in accretion disks. In case of an aliased period shorter than the 16.35 day value, precession or spin of a magnetar-like object should be considered in addition to the binary hypothesis.

We notice that no super-intense radio pulses of the type of FRB 180916 have been detected from binary systems in our Galaxy. Probably the Galactic compact objects that might generate intense radio pulses do not have the right conditions to be "triggered" or induced in a proper way. For example, Galactic magnetar-like objects might miss the right combination of magnetic field energy and external "trigger" to be effective as FRB sources. Furthermore, no accreting BH in the Galaxy has ever been detected producing short millisecond radio bursts such as those of FRBs. Again, this might be the consequence of external conditions not easily applicable to Galactic systems. We are therefore dealing with an "exotic source" capable of transcending the properties of known compact objects and their environments, either Galactic neutron stars or black holes. Note, however, that rare Galactic radio bursts generated by FRB-like sources might escape detection in searches by multiple-

beam receivers as noticeably pointed out by (Tendulkar et al. 2016). In this case, the radio flux might be so intense as to saturate momentarily a receiver and be classified as radio frequency interference. It is an interesting possibility for future searches to associate high-energy outbursts with simultaneous (within the delay times) very intense radio events classified as interference.

Before speculating on the nature of the ultimate origin of FRB 180916, it is useful to discuss the energetics. At this moment, we obtained upper limits to the high-energy emission in 4 different energy bands from X-rays to  $\gamma$ -rays and for different time intervals and integrations. We focus in this paper to observations during the 5-day FRB-active intervals.

*X-ray flux upper limits in the energy range 1-10 keV* (for typical integrations of  $10^3$  s) as obtained by *Swift* observations. The typical 1-2 ks UL is  $F_{X,UL} \sim 3 \times 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to an isotropic-equivalent X-ray luminosity  $L_{X,UL} \sim 8 \times 10^{41}$  erg s $^{-1}$ . Summing the 7 *Swift* observations of Table 5 we find an integrated UL  $F_{X,UL} \sim 5 \times 10^{-14}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to an isotropic X-ray luminosity  $L_{X,UL} \sim 1.5 \times 10^{41}$  erg s $^{-1}$ .

*Hard X-ray upper limits in the range 18-60 keV* were obtained by Super-*AGILE* during periods of favorable exposure in the time interval of this campaign. Summing up the observations, the UL is  $1.8 \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$ .

*MeV fluence upper limits in the range 0.4-1 MeV* (at the millisecond level up to seconds) obtained by *AGILE/MCAL* simultaneous with the FRBs of Table 1 marked with "YES" in the MCAL column. Typical fluence UL in the sub- and millisecond range of integrations are  $F_{MeV,UL} \sim 10^{-8}$  erg cm $^{-2}$  corresponding to an isotropic MeV energy UL  $E_{MeV,UL} \sim 2 \times 10^{46}$  erg.

*GeV flux upper limits in the range 100 MeV – 10 GeV* (for integrations of hours/days/months) obtained by the *AGILE/GRID* during active intervals of FRB 180916. The typical 5-day flux UL is  $F_{\gamma,UL} \sim 10^{-10}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to an isotropic-equivalent  $\gamma$ -ray luminosity  $L_{\gamma,UL} \sim 3 \times 10^{44}$  erg s $^{-1}$ . A more stringent limit is obtained by summing all GRID exposures of the FRB 180916 field over the interval 2007-2019: we find an integrated flux UL  $F_{\gamma,UL,ave} \sim 8 \times 10^{-13}$  erg cm $^{-2}$  s $^{-1}$ , corresponding to an isotropic long-term averaged  $\gamma$ -ray luminosity  $L_{\gamma,UL,ave} \sim 2 \times 10^{42}$  erg s $^{-1}$ .

#### 4.1. *The magnetized neutron star hypothesis*

Neutron stars of the magnetar-type are natural candidates for a class of FRBs and should be considered for FRB 180916 (for a recent review on magnetars, see [Kaspi & Beloborodov 2017](#)). Magnetic instabilities or sudden magnetospheric particle acceleration phenomena can lead to short radio bursts. The action by an "external driver" in a binary system can provide intruding particles and/or e.m. fields that may lead to instabilities. The magnetic fields associated with magnetars (of the order of  $B_m \sim 10^{14} - 10^{16}$  G) lead to maximal energies  $E_m \sim R_m^3 B_m^2 / 6 \simeq (2 \times 10^{49} \text{ erg}) R_{m,6}^3 B_{m,16}^2$ , with  $B_{m,16}$  the magnetar inner magnetic field in units of  $10^{16}$  G and where we assumed a magnetospheric radius of the magnetar  $R_{m,6} = R_m / (10^6 \text{ cm})$ . A fraction of the total magnetic energy can therefore be dissipated by instabilities on timescales related to plasma relaxation. The ambipolar diffusion (dissipation) timescale of the inner magnetar field has been estimated to be  $\tau_d \sim 10^{11}$  s ([Thompson & Duncan 1996](#)) and leads to an average dissipated luminosity

$$L_m \sim E_m / \tau_d \sim (10^{38} \text{ erg s}^{-1}) R_{m,6}^3 B_{m,16}^2 \tau_{d,11}^{-1} \quad (1)$$

where  $\tau_{d,11}$  is the dissipation time in units of  $10^{11}$  s. Larger/smaller values of  $\tau_d^{-1}$  (e.g.; [Beloborodov 2017](#)) and/or of  $B_{m,16}^2$  imply larger/smaller average luminosities. The luminosity  $L_m$  of Eq. 1 provides a reference value for interpreting our X-ray and  $\gamma$ -ray observations of FRB 180916.

We see that if an instability mechanism is occasionally triggered in the magnetar system, in order to be detected in our observations we require that the object emits within a millisecond in the radio band an energy 10-1000 times larger than that deduced by the average luminosity  $L_m$ . This is a demanding but not impossible requirement for a highly magnetized system subject to sudden relaxation (e.g., the case of the soft  $\gamma$ -ray repeater SGR 1806-20; [Palmer et al. 2005](#)).

FRB 180916 might be then a magnetar occasionally subject to sudden instabilities that dissipate in a millisecond what normally would have been emitted on longer timescales of order of seconds/minutes/hours. Eq. 1 provides a reference luminosity for optical/X-ray/ $\gamma$ -ray emission that should dissipate most of the instability energy. The expected average high-energy flux at the FRB

180916 distance is expected to be

$$F \simeq 4 \times 10^{-17} \xi b^{-1} R_{m,6}^3 B_{m,16}^2 \tau_{d,11}^{-1} \text{ erg cm}^{-2} \text{ s}^{-1}, \quad (2)$$

where  $\xi$  is the conversion factor from magnetic to radiated energies, and  $b$  a beaming factor. In order to be detectable in the optical/X-ray/ $\gamma$ -ray band we need enhancements with respect to the average dissipated luminosity  $L_m$  by factors of  $10^3 - 10^4$ . These requirement is certainly demanding, but not impossible to satisfy in a highly unstable system.

Our upper limits therefore constrain the high-energy dissipation related to the active periods of FRB 180916. These considerations based on isotropic emission can be modified to account for beaming effects. If beaming plays a role in the FRB phenomenon, our energy constraints can be made even lower, and approach hour/day luminosities of the order of those of Eq. 1.

We conclude that a magnetar with extreme properties in terms of its magnetic field or dissipation process might power the FRB 180916 radio bursts and be detectable in the X-ray range by current instruments.

#### 4.2. *The black hole hypothesis*

A black hole interacting with a gaseous/plasma environment in a binary system should be considered and cannot be discarded based on our data. In order to power the required detectable luminosities the mass of the BH has to be in the range from above solar to hundreds or more of solar masses. The radio and high-energy luminosities to be produced by the BH is most likely accretion-powered and values larger than that of Eq. 1 can be obtained for limited time intervals.

Following (Marcote et al. 2020), we remark that the radio position of FRB 180916 is positionally coincident with a remarkable "cusp" of star formation in its host galaxy. If this is not a coincidence, the apparent cusp can actually be a "wake" of stars caused by the presence of a BH of a mass sufficiently large to influence an otherwise ordered flow. Therefore, in principle the BH mass can be of order of thousands solar masses or more for the presence of an intermediate mass BH or the remnant of a galactic nucleus as a consequence of a galaxy merging.

The BH hypothesis cannot at the moment be discarded, especially if we consider the energetics of the bulk of FRBs that requires energies and luminosities emitted in the radio (and presumably at higher energies) substantially larger than those of FRB 180916 (e.g., [Cordes & Chatterjee 2019](#)).

## 5. CONCLUSIONS

*AGILE* and *Swift* joint observations of FRB 180916 set important constraints on the energetics of the source by providing the best upper limits on the X-ray and  $\gamma$ -ray emissions.

We focused in this paper on the 5-day time intervals during which FRB 180916 is more active in producing radio bursts according to C20. A multi-frequency campaign of FRB 180916 involved radio (SRT, Northern Cross), X-ray (*Swift*) and  $\gamma$ -ray (*AGILE*) observations starting on Feb. 3, 2020 and ending on Feb. 8, 2020. In addition, we retrieved and studied *AGILE* data for several source active cycles during the time interval Aug. 25, 2019 – Mar. 28, 2020. We also checked all 35 known radio bursts from FRB 180916 searching for any quasi-simultaneous transient detected by *AGILE*.

Our best upper limits can be used in the context of a magnetar-like object dissipating its magnetic energy in a timescale  $\tau_d$ . If  $B_m$  is the equivalent strength of the magnetic field that corresponds to the dissipated portion of the magnetic energy, our constraints translates into the relation (assuming  $\xi b^{-1} \sim 1$ )

$$R_{m,6}^3 B_{m,16}^2 \tau_{d,8}^{-1} \lesssim 1, \quad (3)$$

where  $\tau_{d,8}$  is in units of  $10^8$  s. Eq. 3 shows that magnetic dissipation (relaxation) timescales of the order of our X-ray and  $\gamma$ -ray observations ( $10^3 - 10^5$  s) are incompatible with the presence of a very strong magnetic field of order of  $10^{16}$  G. On the other hand, the very impulsive nature of the FRB phenomenon implying millisecond timescales is indicative of short durations for particle energization and radio emission. Our MeV upper limits obtained at millisecond timescales interpreted in terms of isotropic emission are close to the peak energy detected in the MeV range from SGR 1806-20 ( $2 \times 10^{46}$  erg emitted in about 200 ms). After an impulsive phase leading to the radio bursts, the system may "relax" on a longer timescales with associated X-ray and possibly  $\gamma$ -ray emission. Eq.3 is then an important (and best so far) constraint in the context of a magnetar model for FRB 180916.

The search for high-energy counterparts of FRB sources continues, and more data on FRB 180916 and other FRBs are necessary. Considering the variability in the interaction between a companion star and a compact object near periastron as observed in X-ray binaries, a systematic monitoring of FRB 180916 is necessary. *AGILE* will then continue to monitor and search for high-energy emissions from FRB 180916, our so-far unique periodic-repeating FRB.

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