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The contribution of AGILE to the knowledge of GRBs and other transients

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AGILE is an Italian Space Agency (ASI) scientific mission with INAF and INFN participation, devoted to high-energy astrophysics. We review here the AGILE contribution to the knowledge of gamma-ray bursts (GRB), but also other bursting events such as Terrestrial gamma-ray flashes (TGF) and Solar flares. We also report the main results on follow-up observations of gravitational wave (GW) events, cosmic neutrinos and fast radio bursts (FRB), obtained thanks to the AGILE efficient and fast real-time analysis system. AGILE real-time searches were performed with dedicated automatic pipelines, using data from all payload instruments: GRID (30 MeV - 30 GeV), MCAL (350 keV - 100 MeV) and the Anticoincidence system (50-200 keV).

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1. The AGILE Mission

AGILE (Astrorivelatore Gamma a Immagini LEggero) is an Italian Space Agency (ASI) scientific mission with with the participation of the Istituto Nazionale di Astrofisica (INAF) and the Istituto Nazionale di Fisica Nucleare (INFN), devoted to high-energy astrophysics [1]. The satellite was launched on April 23, 2007 in an equatorial orbit with initial altitude of about 550 km. The scientific payload is inserted in a small cube of approximate size 60x60x60 cm, containing instruments offering an effective area of about 500 cm^2 at several hundreds MeV, and an unprecedentedly large field of view of about $\sim$ 2.5 sr. The satellite instruments, in nominal status after 16 years of operations, have continuously monitored the sky searching for steady and transient gamma-ray sources. Since November 2009, AGILE has been operating in the so called *spinning* observation mode, with the satellite performing a complete rotation roughly every 7 minutes. In this operation mode, the AGILE gamma-ray imager (GRID) can observe approximately 80% of the sky more than 100 times a day in the energy range 30 MeV – 30 GeV, with a sensitivity to fluxes of the order of 1.5×10^{-6} ph cm^{-2} s^{-1} every 48 hours. The GRID has imaging capabilities of the sky in the gamma-ray energy band. In addition, there is the AGILE 4π non-imaging detector Mini-Calorimeter (MCAL) working in the range $0.350 - 100$ MeV and the Anticoincidence (AC) system in the range $50 - 200$ keV (for a 3D cut of the spacecraft showing its instruments, please see Fig.1). These instruments are routinely employed for the detection of gamma-ray bursts (GRB), Terrestrial gamma-ray flashes (TGF), Solar flares, and they are capable of detecting gamma-ray transients and GRB-like phenomena for timescales ranging from sub-milliseconds to ten-hundreds of seconds. The AGILE Data Center, part of the ASI multi-mission Space Science Data Center (SSDC, previously known as ASDC) is in charge of all the scientific operations: data management, archiving, distribution of AGILE data and scientific software, and user support. An optimized alert system using dedicated analysis pipelines allows the AGILE team to perform the full data reduction and the preliminary quick-look scientific analysis within 30 minutes from the data downlink, for a fast reaction to high-energy transients [2–4].

2. AGILE and GRB

In 2008, AGILE detected GRB 080514B [5], the first GRB with photons of energy above several tens of MeV observed since the time of EGRET/CGRO [6]. AGILE provided definite evidence of extended ~GeV emission for the first time, with the observations of a high-energy component in GRB 080514B lasting more than the keV-MeV component. Prior to AGILE, the existence of a possible longer-lasting high-energy component had only been hypothesized from a few other GRBs observed with EGRET. Thanks to the small dead time of the GRID and the unique simultaneous hard X-ray/gamma-ray capability it was indeed possible to show undoubtedly that the gamma-ray to X-ray flux ratio changes significantly between the prompt and extended emission phase.

The majority of GRBs detected above 100 MeV are long bursts with delayed high-energy emission and typical durations above 2 s [7], possibly associated with stellar explosions of massive stars [8]. Today, the sample of GRBs detected at gamma-ray energies above 100 MeV as seen by the AGILE GRID and Fermi LAT instruments increased to a couple of hundreds, still a small fraction (<5%) of the sample of GRBs detected in the lower energy bands (from X-rays till a few MeV).

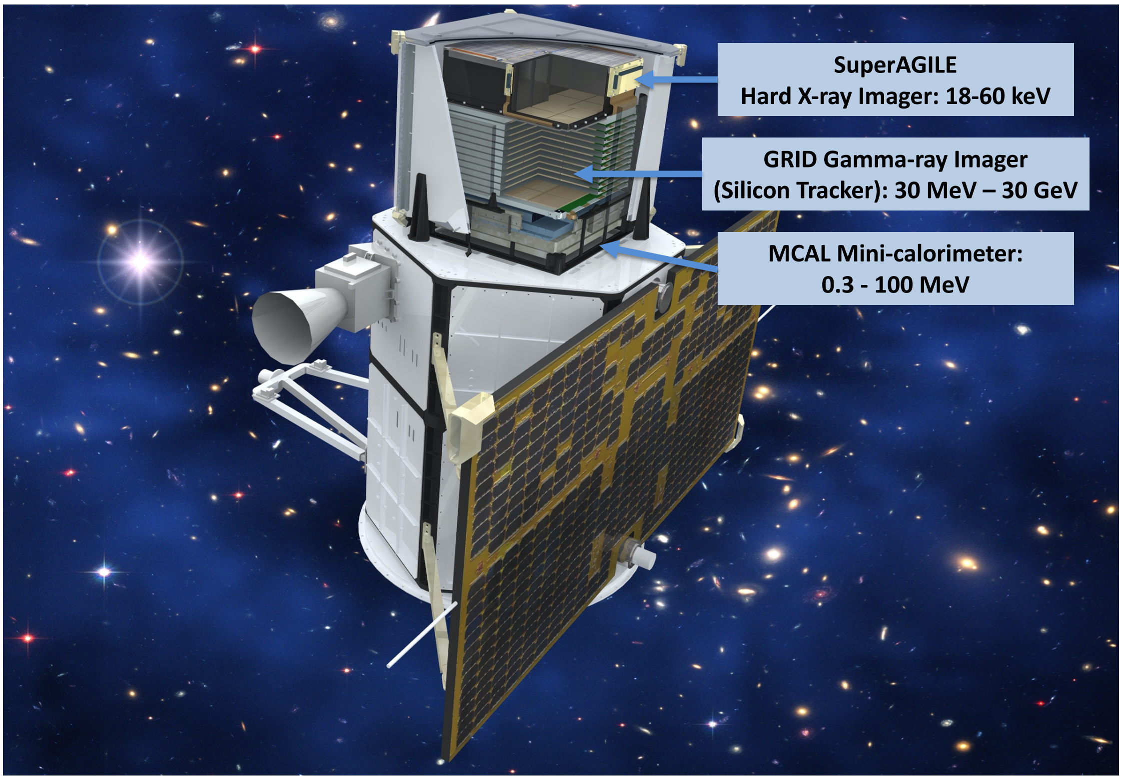

Figure 1: The AGILE satellite and its Payload.

A larger number of GRBs have indeed been detected by non-imaging 4π detector MCAL in the energy range 0.4 – 100 MeV. An updated catalog[1] of more than 500 GRBs detected by MCAL over a period of 13 years, from November 2007 to November 2020, has been recently published in [9].

Short GRBs with durations below 2 s have usually a harder spectrum and are believed to be associated with the coalescence of compact binary systems (two neutron stars or neutron star-black hole system) [10, 11]. A major AGILE contribution to the science of short GRBs was the detection of GRB 090510, promptly published in [12], the first case of a short GRB with delayed gamma-ray emission. The short GRB 090510 light curve, also observed by Fermi [13], is now considered a reference template for potential electromagnetic gamma-ray emission possibly associated to a gravitational wave (GW) event.

A breakthrough discovery was the first GRB with delayed emission ever detected above 300 GeV, GRB 190114C, as reported by the MAGIC Collaboration [14]. AGILE participated to the multi-frequency observations reported in the companion paper [15], presenting the evolution in time of the GRB 190114C emission across 17 orders of magnitude in energy. Moreover, the prompt and early afterglow emissions of GRB 190114C in the 20 keV–100 MeV energy range as detected by AGILE and Konus-Wind have been presented in [16]. In this AGILE paper a previously unnoticed flux temporal break near T0+100 s was identified, which is incompatible with the commonly

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[1] Interactive SSDC webpage: https://www.ssdc.asi.it/mcal2grbcat/

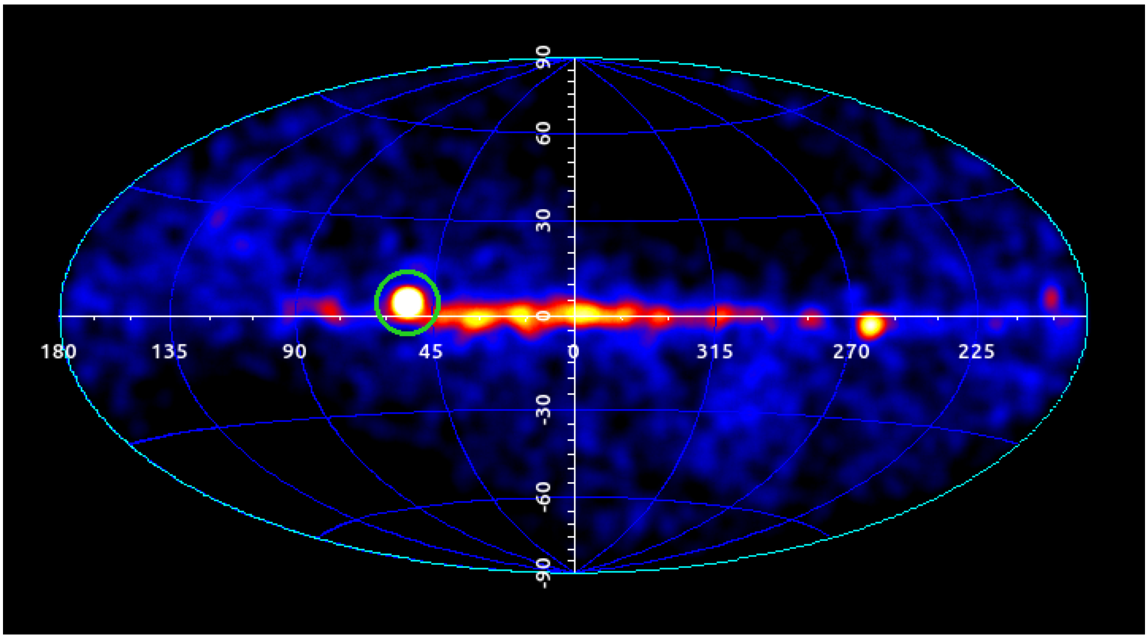

Figure 2: AGILE-GRID all-sky 48h count map above 100 MeV since GRB 221009A trigger time (Galactic coordinates, Aitoff projection). The gamma-ray source associated with GRB 221009A is shown inside the green circle [19].

assumed adiabatic evolution of a fireball in a constant-density medium.

In 2022, the exceptionally energetic "New Year's Burst" GRB 220101A took place more than 12 billion light years away, at the time when the Universe was just about 1.3 billion years old, and its equivalent isotropic energy was the highest ever reconstructed for a GRB up to that time. AGILE results about the GRB 220101A have been published in [17].

This record has since been broken by the recent long-duration gamma-ray burst GRB 221009A, named the "BOAT" (brightest of all time), indeed the brightest and most energetic gamma-ray burst ever recorded, with the first detection of photons above 10 TeV from a GRB reported by LHAASO [18].

In the AGILE field of view, the BOAT clearly outshined all other gamma-ray sources present in the gamma-ray sky, starting from the early GRB phases after the trigger time T0, up to an interval of at least 48 hours after T0, see Fig.2. AGILE data published in [19] suggest a transition between prompt and afterglow emission with a peculiar phase of coexistence of MeV and GeV emissions with very different spectral properties.

3. AGILE and GW

The first GW event ever detected by the LIGO detectors was GW150914 [20], the first breakthrough discovery of a binary black hole (BH) merger occurred at time T0 = 09:50:45 UTC on September 14, 2015. The AGILE Team was not part of the multifrequency follow-up collaboration with the LIGO-VIRGO team at the time of the GW150914 detection, but an extensive search through AGILE data for a high-energy counterpart to GW150914 was performed retroactively as soon as the event was made public on February 11, 2016 [21]. Even though BH - BH binaries are not anticipated to emit detectable electromagnetic (e.m.) radiation, nevertheless such radiation can be emitted before, during, and after coalescence, depending on the physical conditions of the system [22]. It is then of great interest to explore this possibility and search for e.m. counterparts of such GW events. No e.m. counterpart was detected by any observatory. The AGILE GRID missed the coverage of the prompt event in its field of view, but could determine important upper limits (UL) immediately before and after the event. AGILE observations have been significant in providing the fastest response to the event with optimal gamma-ray sensitivity above 100 MeV, with gamma-ray UL close to 10^{-8} erg cm^{-2} s^{-1} in the range 50 MeV–10 GeV obtained in the interval 250–350 s after T0.

The current LIGO-Virgo-KAGRA (LVK)[2] O4 observing run started on May 24, 2023. Indeed, the first 2023 GW event (S230518h) was published on May 18, 2023 [23], prior to the official start of O4, during the last days of the so-called engineering run of the LIGO detectors. The LVK GW event S230518h has been identified as a significant GW compact binary merger candidate with high probability (86%) to be composed by a Neutron Star-Black Hole (NSBH) merger, which has a higher probability to have an electromagnetic counterpart. AGILE results from the fast follow-up of GW S230518h were published in [24], reporting the AGILE MCAL flux upper limits in the 0.4 – 1 MeV energy range, for 1 s integration time from the GW trigger time (T0), at different celestial positions within the accessible Localization Region (LR). The detection of a short pulse in the same energy band with S/N $\sim$ 5.7 at T0+10.77 s was also reported by AGILE in the soft energy band E<1.4 MeV.

In the famous case of GW170817[25, 26], the first (and up to now the only) GW event connected to a NS-NS merger for which an electromagnetical counterpart, GRB170817A, was ever observed (2017 Nobel Prize in Physics), there was no AGILE detection due to Earth occultation at trigger time T0. However, the AGILE GRID was first gamma-ray instrument with exposure above 100 MeV on the localization region starting at ~T0 + 930 s, providing significant upper limits in the early phases and important constraints to exclude a highly magnetized magnetar for the remnant of GW170817- GRB170817 [27].

In general, AGILE follow-up observations provided among the most significant upper limits above 100 MeV on all significant GW events detected up to now. Preliminary results from the current O4 run of the LVK Collaboration show no confirmed e.m. counterparts observed to date.

4. AGILE and FRB

Fast Radio Bursts (FRB) are millisecond radio pulses originating from powerful sources of unknown origin at extragalactic distances [28]. AGILE data provide important constraints on the prompt (millisecond and hundreds of millisecond timescales) emission in the sub-MeV/MeV range,

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[2] LIGO (Laser Interferometer Gravitational-Wave Observatory), Virgo (Virgo Gravitational Wave Interferometer), and KAGRA (Kamioka Gravitational Wave Detector) are the currently operating advanced gravitational wave detector network.

and on the study of the persistent long timescale gamma-ray emission above 30 MeV from repeating FRBs [29–32].

A breakthrough in FRB science happened in 2020, with the AGILE detection of an X-ray burst from the galactic magnetar SGR 1935+2154 [33], an important finding that supports magnetar models and sheds light on the understanding of the physical mechanism of FRBs.

5. AGILE: TGF and Solar Flares

AGILE provided unexpected and unique contributions also to the physics of Terrestrial Gamma-ray Flashes (TGF) and Solar Flares. Here we report the references and links to the most recent AGILE updates in these fields:

- The 3rd AGILE TGF Catalog: it was originally composed of two companion papers [34, 35]. The online version of the 3rd AGILE TGF Catalog at SSDC[3], initially including events detected by the MCAL during the period March 2015 - September 2018, has been recently updated to include all events up to December 31, 2021, bringing the total number of events to 5344, 599 of which are associated with lightning sferics. The interactive webpage also gives access to the available TGF light curves and counts lists, providing supplementary material to the published papers.

- The First AGILE Solar Flare Catalog: the first catalog of solar flares detected by the AGILE onboard Anti-Coincidence system in the 80-200 keV energy range, from May 1st, 2007 to August 31st, 2022, has been published in [36]. In more than 15 years, AGILE detected a total sample of more than 500 minute-lasting X-ray transients, compatible with a solar origin. All detected events have been cross-related with the official GOES, RHESSI and Fermi GBM. Of these there are more than 1400 new "AGILE-only" events constituting a new dataset of solar flares detected in the hard X-ray energy band. Also for this solar flare catalog, an interactive SSDC web page gives access to supplementary material[4].

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References

[1] M. Tavani, G. Barbiellini, A. Argan et al., The AGILE mission. Astron. Astrophys. 502, 995 (2009). https://doi.org/10.1051/0004-6361/200810527

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[3] https://www.ssdc.asi.it/mcal3tgfcat/

[4] https://www.ssdc.asi.it/agilesolarcat/

[2] C. Pittori, The AGILE data center and its legacy. Rendiconti Lincei. Scienze Fisiche e Naturali 2019, 543 30, 217–223, arXiv:astro-ph.IM/1911.12314, https://doi.org/10.1007/s12210-019-00857-x.

[3] A. Bulgarelli et al., The AGILE Alert System for Gamma-Ray Transients. ApJ 2014, 781, 19, arXiv:astro-ph.IM/1401.3573, https://doi.org/10.1088/0004-637X/781/1/19.

[4] N. Parmiggiani et al., The AGILE real-time analysis software system to detect short-transient events in the multi-messenger era. Astronomy and Computing 2023, 44, 100726. https://doi.org/10.1016/j.ascom.2023.100726.

[5] A. Giuliani et al., AGILE detection of delayed gamma-ray emission from GRB 080514B. A&A 2008, 491, L25–L28, arXiv:astro-ph/0809.1230. https://doi.org/10.1051/0004-6361:200810737.

[6] G. Kanbach et al., The project EGRET (energetic gamma-ray experiment telescope) on NASA's Gamma-Ray Observatory GRO. SSRv 520, 1989, 49, 69-84. https://doi.org/10.1007/BF00173744.

[7] C. Kouveliotou et al., Astrophysical Journal Letters v.413, p.L101. https://doi.org/10.1086/186969

[8] J. S. Bloom et al., The Astrophysical Journal, Volume 572, Issue 1, pp. L45-L49. https://doi.org/10.1086/341551

[9] A. Ursi et al., The Second AGILE MCAL Gamma-Ray Burst Catalog: 13 yr of Observations, 2022 ApJ 925 152. https://doi.org/10.3847/1538-4357/ac3df7

[10] P. D'Avanzo, Short gamma-ray bursts: A review, Journal of High Energy Astrophysics, Volume 7, p. 73-80. 10.1016/j.jheap.2015.07.002

[11] B. P. Abbott et al., Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, 2017 ApJL 848 L13. https://doi.org/10.3847/2041-8213/aa920c

[12] A. Giuliani et al., AGILE Detection of Delayed Gamma-ray Emission From the Short Gamma-Ray Burst GRB 090510. ApJL 2010, 708, L84–L88, arXiv:astro-ph.HE/0908.1908. https://doi.org/10.1088/2041-8205/708/2/L84.

[13] M. Ackermann et al., Fermi Observations of GRB 090510: A Short-Hard Gamma-ray Burst with an Additional, Hard Power-law Component from 10 keV to GeV Energies. ApJ 2010, 716, 1178–1190, arXiv:astro-ph.HE/1005.2141. https://doi.org/10.1088/0004-637X/716/2/7611178.

[14] MAGIC Collaboration. Teraelectronvolt emission from the gamma-ray burst GRB 190114C. Nature 575, 455–458 (2019). https://doi.org/10.1038/s41586-019-1750-x

[15] MAGIC Collaboration et al., Observation of inverse Compton emission from a long gamma-ray ray burst. Nature 575, 459–463 (2019). https://doi.org/10.1038/s41586-019-1754-6

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[16] A. Ursi et al., AGILE and Konus-Wind Observations of GRB 190114C: The Remarkable Prompt and Early Afterglow Phases. ApJ 2020, 904, 133. https://doi.org/10.3847/1538-4357/abc2d4

[17] A. Ursi et al., AGILE Observations of GRB 220101A: A 'New Year's Burst' with an Exceptionally Huge Energy Release, ApJ 933, 2022. https://doi.org/10.3847/1538-4357/ac746c

[18] Huang Y., Hu S., Chen S. et al., The LHAASO Experiment, 2022 GCN 32677 https://gcn.nasa.gov/circulars/32677

[19] M. Tavani et al., AGILE Gamma-Ray Detection of the Exceptional GRB 221009A, 2023 ApJL 956 L23. https://doi.org/10.3847/2041-8213/acfaff

[20] B. P. Abbott et al., (LIGO Scientific Collaboration and Virgo Collaboration), Physical Review Letters, Volume 116, Issue 6, id.061102 (2016)

[21] M. Tavani et al. Astrophysical Journal Letters, Volume 825, Issue 1, article id. L4, 9 pp. (2016).

[22] L. Barack et al., Black holes, gravitational waves and fundamental physics: a roadmap, Classical and Quantum Gravity, Volume 36, Issue 14, article id. 143001 (2019).

[23] LIGO/Virgo/KAGRA Collaboration, LIGO/Virgo/KAGRA S230518h: Identification of a GW compact binary merger candidate, GCN #33813 (2023), https://gcn.nasa.gov/circulars/33813

[24] F. Verrecchia et al., GCN #33826 (2023), https://gcn.nasa.gov/circulars/33826

[25] B.P. Abbott, R. Abbott, T.D. Abbott et al., Multi-messenger observations of a binary neutron star merger. Astrophys. J. Lett. 848, L12 (2017). https://doi.org/10.3847/2041-8213/aa91c9

[26] B.P. Abbott, R. Abbott, T.D. Abbott et al., Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. Astrophys. J. Lett. 848, L13 (2017). https://doi.org/10.3847/2041-8213/aa920c

[27] F. Verrecchia et al., AGILE Observations of the Gravitational-wave Source GW170817: Constraining Gamma-Ray Emission from an NS–NS Coalescence, ApJL 850, 2017. https://doi.org/10.3847/2041-8213/aa965d

[28] D. R. Lorimer et al., A Bright Millisecond Radio Burst of Extragalactic Origin, 2007, Sci, 318, 777

[29] C. Casentini et al., AGILE Observations of Two Repeating Fast Radio Bursts with Low Intrinsic Dispersion Measures. ApJL 2020, 890, L32 arXiv:astro-ph.HE/1911.10189. https://doi.org/10.3847/2041-8213/ab720a.

[30] M. Tavani et al., Gamma-Ray and X-Ray Observations of the Periodic-repeater FRB 180916 during Active Phases. ApJL 2020, 893, L42, arXiv:astro- 807 ph.HE/2004.03676. https://doi.org/10.3847/2041-8213/ab86b1.

[31] M. Pilia, et al., The Lowest-frequency Fast Radio Bursts: Sardinia Radio Telescope Detection of the Periodic FRB 180916 at 328 MHz. ApJL 2020, 896, L40, arXiv:astro-ph.HE/2003.12748. https://doi.org/10.3847/2041-8213/ab96c0.

[32] F. Verrecchia et al., AGILE Observations of Fast Radio Bursts. ApJ 2021, 915, 102, arXiv:astro-ph.HE/2105.00685. https://doi.org/10.3847/15 813 38-4357/abfda7.

[33] M. Tavani et al., An x-ray burst from a magnetar enlightening the mechanism of fast radio bursts. Nat. Astron. 5, 401 (2021). https://doi.org/10.1038/s41550-020-01276-x

[34] A. Lindanger et al. (Paper I), Journal of Geophys. Res.: Atmosph, 125, e2019JD031985 (2020). DOI: 10.1029/2019JD031985.

[35] C. Maiorana et al. (Paper II), Journal of Geophys. Res.: Atmosph, 125, e2019JD031986 (2020). DOI: 10.1029/2019JD031986.

[36] A. Ursi et al., ApJS 267 (2023), arXiv:2305.14957, DOI: 10.3847/1538-4365/acd4b6.