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The role of magnetar transient activity in time-domain and multimessenger astronomy

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Time-domain and multimessenger astronomy (TDAMM) involves the study of transient and time-variable phenomena across various wavelengths and messengers. The Astro2020 Decadal Survey has identified TDAMM as the top priority for NASA in this decade, emphasizing its crucial role in advancing our understanding of the universe and driving new discoveries in astrophysics. The TDAMM community has come together to provide further guidance to funding agencies, aiming to define a clear path toward optimizing scientific returns in this research domain. This encompasses not only astronomy but also fundamental physics, offering insights into properties of gravity, the formation of heavy elements, the equation of state of dense matter, and quantum effects associated with extreme magnetic fields. Magnetars, neutron stars with the strongest magnetic fields in the universe, play a critical role in this context. We aim to underscore the significance of magnetars in TDAMM, highlighting the necessity of ensuring observational continuity, addressing current limitations, and outlining essential requirements to expand our knowledge in this field.

KEYWORDS

magnetars, TDAMM, time-domain, multimessanger, neutron star (NS)

1 Introduction

Over the last 2 decades, magnetars have been the subject of numerous comprehensive review articles. The work by Mereghetti (2008) delved into observational evidence distinguishing a unique class of isolated neutron stars (NSs)—powered by magnetic energy— termed magnetars, which encompass anomalous X-ray pulsars (AXP) and soft gamma repeaters (SGRs) (Mereghetti et al., 2015). Subsequently, in 2015, Mereghetti, along with Pons and Melatos, offered a second review focusing on persistent emission properties, exploring models explaining extreme magnetic field origins, evolutionary pathways, and interconnections with other neutron star classifications (Mereghetti et al., 2015). Additionally, in the same year, Turolla et al. (2015) provided a detailed overview of magnetar origins and evolution, emphasizing the critical role of theoretical modeling in understanding fundamental physics, constrained by both persistent and transient emission observations. Furthermore, the review by Kaspi and Beloborodov (2017) (Kaspi and Beloborodov, 2017) and 4 years later by Esposito, Rea, and Israel (2021)

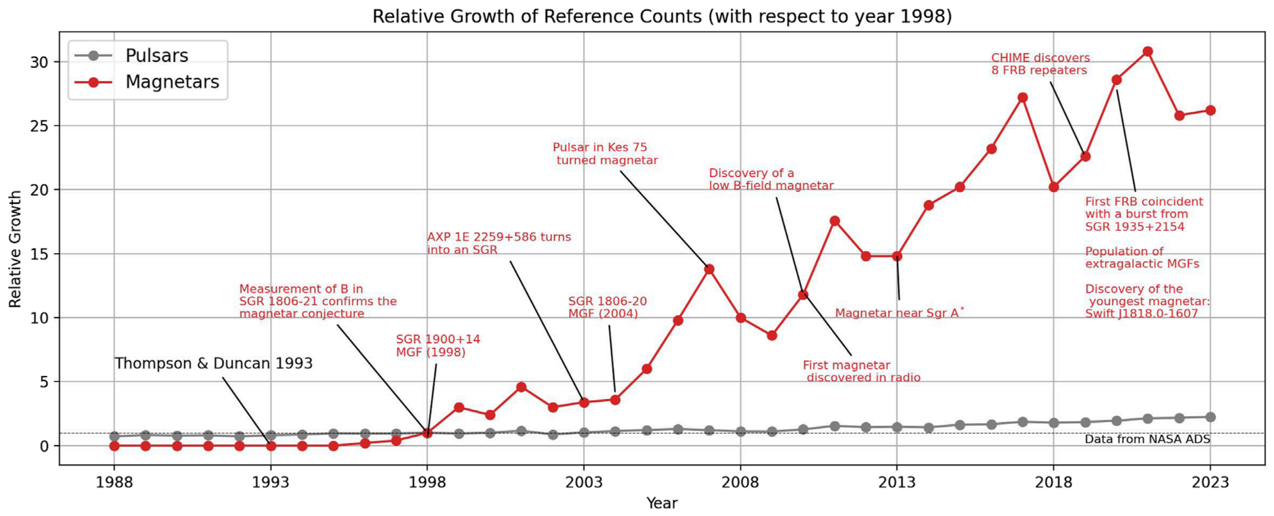

FIGURE 1
Relative increase in peer-reviewed articles mentioning “magnetars” compared to articles mentioning “pulsars” normalized to 1998. In red annotations, we highlight some major events and observations related to magnetars.

(Esposito et al., 2021) updated the discourse on the magnetar population within our Galaxy. These reviews focused on high-energy (X-rays and above) persistent emission characteristics, temporal behavior, and transient activities, collectively enriching our understanding of these enigmatic celestial objects. Recently, Dell’Orso and Stella provided a review focused on newly born millisecond magnetars (Dall’Osso and Stella, 2022).

A clear trend emerging from each of these reviews is that, despite representing only a small fraction of the observed neutron star population, magnetars have been attracting the interest of many scientists from many different areas of astronomy and astrophysics, demonstrated by the relative increase in the number of publications mentioning “magnetars” over the past decades (Figure 1). The sheer number of reviews is the result of continued fundamental discoveries pertaining to the field of magnetars, which shape the understanding of the NS population at large and beyond. The most significant among them is the unification of AXP and SGR under the same name (Duncan, 1998) and progresses with the phenomenology of starquakes (Cheng et al., 1996), the observation of the extremely bright events called giant flares (when a magnetar outshines the Sun for a fraction of a second in hard X-rays) (Hurley et al., 1999; 2005), identification of a population of extragalactic magnetar flares masquerading as short gamma-ray bursts, the observation of new mysterious bright and intermittent galactic long-period radio pulsating sources, and finally the association between magnetars and fast-radio bursts (Mereghetti et al., 2020). Such observational evidence has been catalyzing studies and has increased the interest of a wider and deeper community. Several models predict gravitational wave emission from magnetars at birth and during giant flares, and many theoretical studies suggest that high-energy neutrinos are produced during those events. Furthermore, there are discussions on magnetars being the source of other types of isolated neutron stars, such as central compact objects (CCOs) and X-ray dim isolated neutron stars (XDINs), and transient event ultra-luminous X-ray sources (ULXs), super-luminous supernovae (SLNS), and fast X-ray transients (FXT).

This paper explores the significant role of magnetars in time-domain and multimessenger (TDAMM) astronomy, focusing on their transient activity. The core aspect of this scope highlights the critical role of the high-energy space-based missions that have enabled inference built upon compelling evidence in the past several decades. This study aims to highlight the main characteristics of these missions, while also acknowledging their limitations, thereby proposing viable avenues for enhancing our ability to study these captivating celestial entities. Section 2 provides a brief introduction on the magnetar population, and Section 3 focuses on the fast-transient activity, discussing short bursts, storms, and flares. Section 4 delves into the multimessenger prospects for magnetars, discussing the expectations for the observation of gravitational waves and neutrinos.

2 Magnetars

The question of the conditions necessary to create and power a magnetar underpins the broad interest in these enigmatic celestial objects. To grasp the significance of this question, it is essential to first define a magnetar. Neutron stars are the compact remnants forged in the explosion of massive stars during a supernova event. With a mass typically ranging between about 1.2 and 2 times that of the Sun, the neutron-degenerate matter in NS is squeezed into a sphere that is approximately 10–20 km (6–12 miles) in diameter, reaching supra-nuclear densities in their interior and representing the densest form of matter known in the universe—about fourteen orders of magnitude denser than osmium, the densest element found on Earth. NSs are highly magnetized, which requires a dynamo-like amplification of an original magnetic field from stellar mergers (Schneider et al., 2019), fall-back dynamos (Barrère et al., 2022), or other mechanisms, like inverse cascading of helical and fractionally helical magnetic fields (Brandenburg, 2020). Differential rotation and rotation–convection coupling in the collapsing core of massive stars can also initiate this dynamo effect (Duncan and

Thompson, 1992), which continues in the convective inner structure of the newly formed rapidly rotating NS, and produce strong magnetic fields (Thompson and Duncan, 1993). Magnetars are ultra-magnetized NSs, with recorded (dipolar) magnetic fields of the order of 10^{14-15} G, usually found in isolation (i.e., not in binary systems) and sometimes associated to a nearby supernova remnant. Understanding the type of progenitor star(s) that can generate magnetars is key to understanding their nature and behavior, which ultimately gives access to the physical mechanisms involved in such extreme environments.

Studying the population of magnetars in our Galaxy, both alone and in comparison to the bigger population of isolated NSs, can shed light on their progenitors (Beniamini et al., 2019), and hence the conditions necessary for their formation. The main characteristics of the Galactic magnetar population are illustrated in Figure 2, in comparison to the wider pulsar population (Manchester et al., 2005, ATNF Catalog). Approximately thirty known high-energy emitting magnetars are found in our Galaxy, with the majority located within 1° from the Galactic plane, one in the Large Magellanic Cloud (Cline et al., 1982) and one in the Small Magellanic Cloud (Lamb et al., 2002). They are characterized by a high spin-down rate and slow rotation period, which together with their location in the plane, suggest that active magnetars are typically young, from approximately a hundred years [the youngest known is about 240 years old, discovered in 2020 (Esposito et al., 2020)] to a few tens of thousands of years, as shown in the top-left panel in Figure 2, in comparison with the much older population of pulsars. Except for PSR J1622-4950, which was discovered in radio in 2010 (Levin et al., 2010), all the other known “standard” young magnetars were discovered in the X-ray band, most of them through a first bright transient event. Through the observation and statistical study of the bursting activity of SGR 1806-20 Cheng et al. (1996) found evidence of the hypothesized solid crust on the magnetar surface (see for a similar association with FRBs, Totani and Tsuzuki, 2023). In fact, they found similarities between the magnetar burst energy and waiting time distributions and those for quakes on Earth caused by tectonic movements (Perna and Pons, 2011; Dehman et al., 2020). The discovery of fast radio bursts (FRBs) from galactic magnetars (Bochenek et al., 2020; CHIME/FRB Collaboration et al., 2020) in coincidence with their bursting (Mereghetti et al., 2020; Li et al., 2021) and possibly glitching activity (Younes et al., 2023; Ge et al., 2024) provide crucial information on the physical mechanisms that power these phenomena and the crustal and magnetospheric conditions that can produce FRBs. More recently, radio transient surveys have discovered a population of long-period galactic radio pulsars which are likely older magnetars (Caleb et al., 2022; Hurley-Walker et al., 2022; 2023; Beniamini et al., 2023; Rea et al., 2024). None of these have a high-energy counterpart yet, but given their highly variable nature in the radio and likely magnetar nature along with a possible connection to long-period FRBs (Beniamini et al., 2020), it is plausible that future X-ray and gamma-ray transients could be associated with high-energy monitors with sufficient angular resolution.

Several magnetars have been discovered in neighboring galaxies: NGC 253 (Sculptor galaxy), M31 (Andromeda galaxy), the M81-M82 group, and M83. Confirmation of pulsating emissions matching typical magnetar rotation periods would validate their identity. Extragalactic magnetars can be observed only during the brightest flares, but an unequivocal association requires the detection of the pulsating emission, typically too fast-fading to be caught in time by sensitive instruments. However, the detection of the brighter short initial spike allows inferring the volumetric intrinsic rates of such phenomena associated with magnetars, providing important clues on their formation channels (Burns et al., 2021). The current population of extragalactic magnetar candidates includes only a handful of objects from nearby galaxies, limiting our constraints on the volumetric intrinsic rates. Such limitation needs more sensitive all-sky soft gamma-ray monitors with the ability to trigger more efficiently on these events.

3 Magnetars in time-domain astronomy

Magnetars show a variety of transient activities observable from soft X-rays up to medium-energy gamma-ray bands and differing in terms of timescales, energetics, and temporal and spectral evolution. Such activity includes outbursts, short bursts, burst storms, and flares, as illustrated in Figure 3.

Apart from the more prolonged outbursts, magnetars are also associated with short bursts of intense radiation, typically lasting only a fraction of a second. These short bursts, often observed in the hard X-ray spectrum, provide valuable insights into the extreme physical conditions prevailing in the vicinity of magnetars. The origins of these short bursts may be linked to the sudden release of magnetic energy or magneto-elastic energy from the crust. Short bursts are quasi-thermal, and broadband soft gamma-ray spectroscopy reveals that they are consistent with trapped fireballs within closed loops at low altitudes in the magnetosphere (van der Horst et al., 2012; Younes et al., 2014).

Magnetars are known for their outbursts, during which the quiescent/persistent X-ray emission increases by as many as three orders of magnitude. Typically these events are characterized by a faster (hours–days) flux rise, followed by a slower (week- to year-long) decay to return eventually to quiescence. Such temporal characteristics enable follow-ups and monitoring by sensitive pointing telescopes, providing accurate flux estimates. Crustal shifts due to magnetic stress are believed to cause magnetar outbursts. Short bursts and flares have been observed during outbursts, as well as isolated in time. Burst storms have been observed to happen at the onset of outbursts.

Magnetar burst storms (or burst forests) refer to periods of heightened and sustained activity, during which a magnetar emits a series of tens to thousands of bursts over a relatively short time frame of minutes to days. These episodes of magnetar burst storms contribute significantly to our understanding of the magnetar’s dynamic behavior. Studying these storms helps decipher the underlying processes that govern the interplay between the decaying intense magnetic field, the internal and external structure of the magnetar, and the radiative processes occurring in high-B-field regime close to the surface of the magnetar.

Magnetar flares represent another facet of their transient activity, characterized by sudden and intense increases in radiation across multiple wavelengths. Such events are characterized by an ms-long bright spike, followed by a dimmer (but still bright) periodic tail decaying in time. These flares are among the most energetic

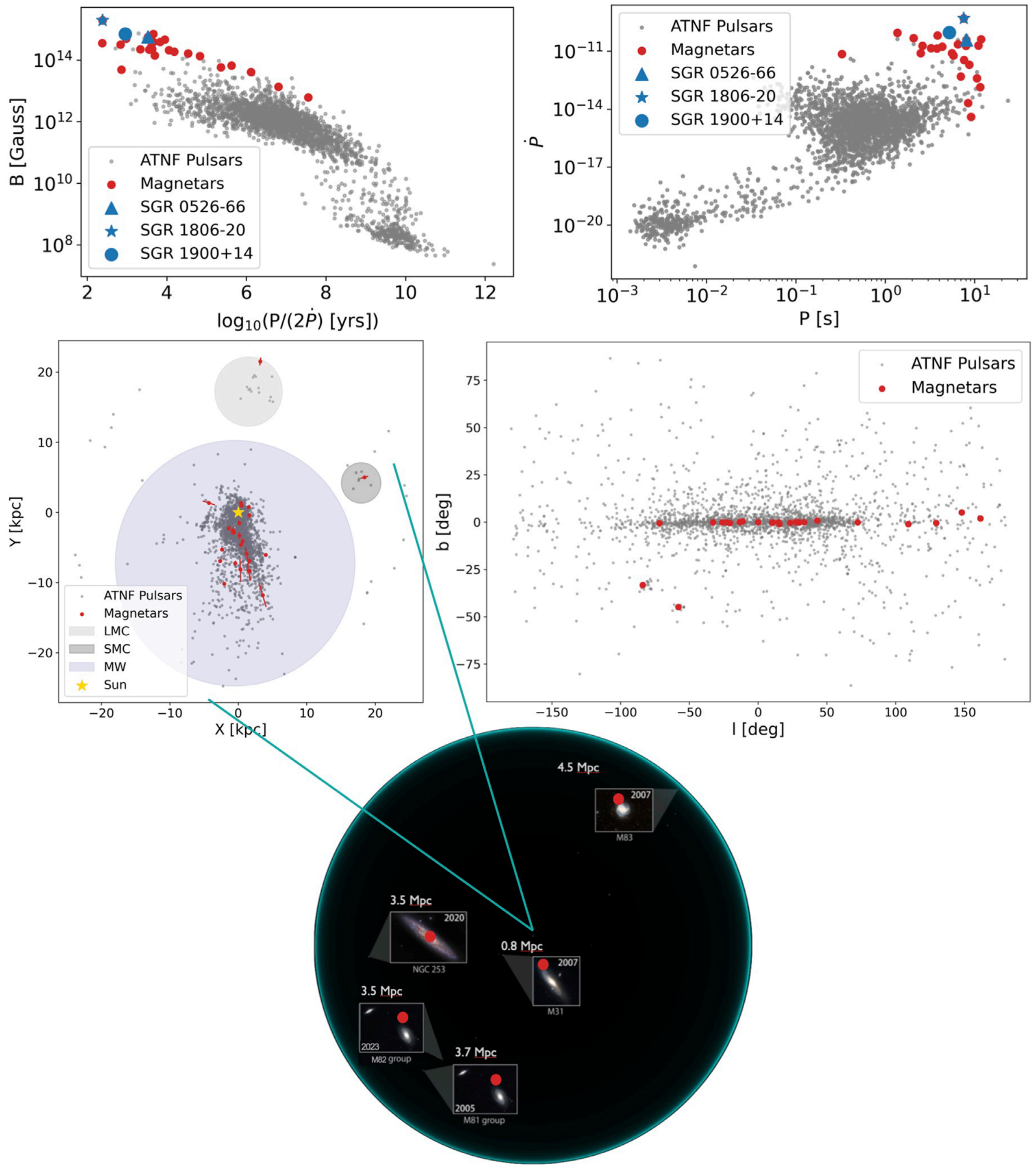

FIGURE 2
Population of galactic high-energy magnetars in red [data from the McGill catalog (Olausen and Kaspi, 2014)], compared to the pulsar population provided by the Australia Telescope National Facility (ATNF) catalog (Manchester et al., 2005) shown in gray. Top left: shows the magnetic field strength as a function of the estimated age; top right: the spin-down rate as a function of the period. Middle: top-Galactic view (left) and Mollweide sky-projection (right) showing the distribution in the Milky Way. Bottom: population of known extragalactic magnetar candidates (Credit: adapted from NASA Goddard press release).

events in the universe, releasing energy on the order of solar flares, but with magnitudes far surpassing those of solar flares Hurley et al. (1999, 2005); Israel et al. (2008). Typically classified in intermediates flares (with $E_{iso} \sim 10^{41} - 10^{43}$ ergs, and giant flares (MGFs) ($E_{iso} \sim 10^{44} - 10^{47}$ ergs), magnetar flares are crucial to enhance our comprehension of the extreme conditions prevailing in

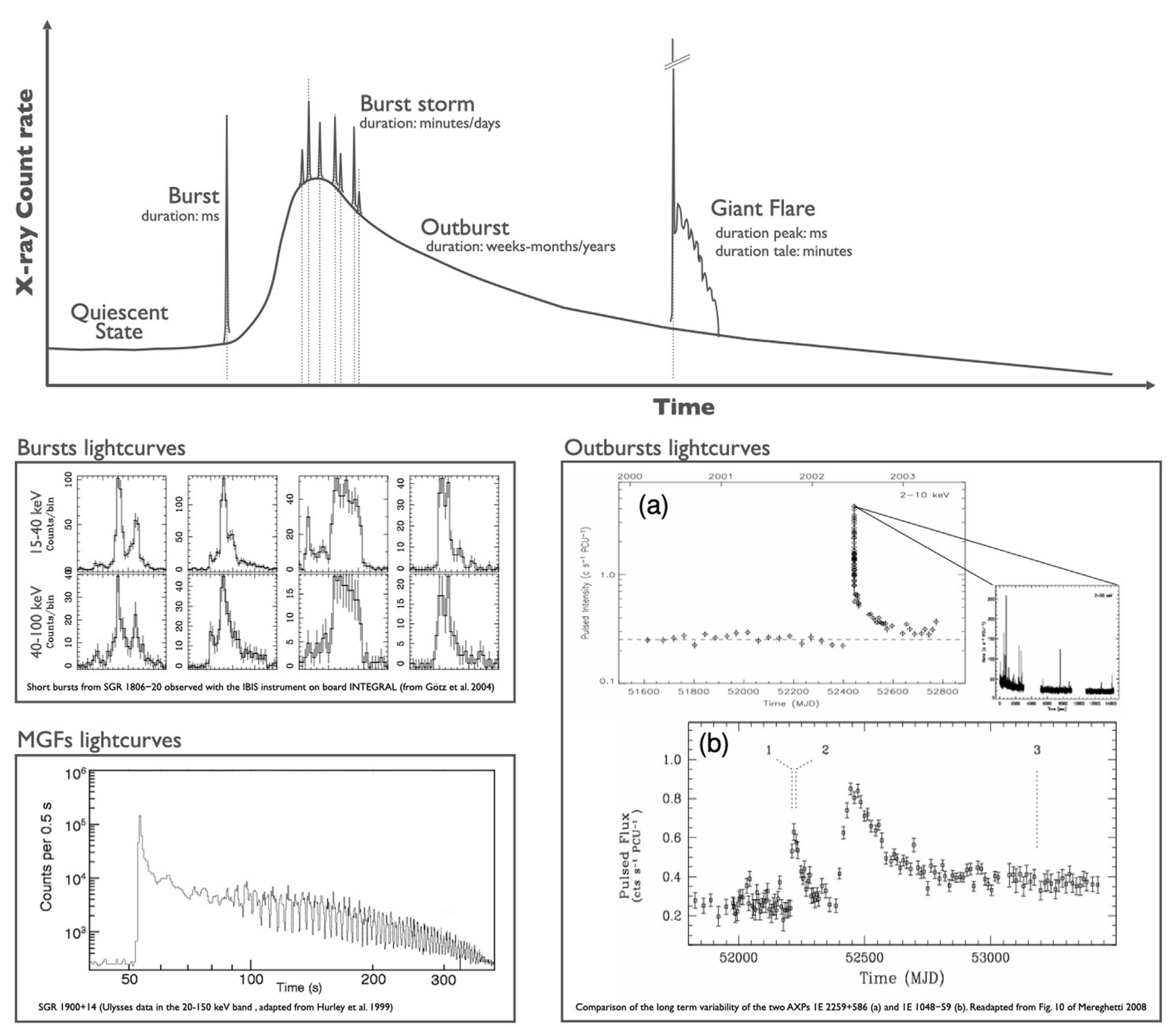

FIGURE 3
Illustration of the topology of transient events from magnetars. The top panel summarizes the different transient activities of magnetars. The panel "Bursts lightcurves" shows examples of short bursts from SGR 1806-20 observed by INTEGRAL-IBIS in 2004 (Götz et al., 2004). The panel "MGFs lightcurves" shows the 1998 MGF from SGR 1900 + 14 as representative of this class of events (Hurley et al., 1999). The panel "Outbursts lightcurves" shows a comparison of the long-term variability of the two AXPs 1E 2259+586 **(A)** and 1E 1048−59 **(B)** (adapted from Figure 10 of Mereghetti et al., 2015).

the vicinity of these celestial bodies and provides valuable data for refining models of magnetar behavior.

High-energy monitors, spectrometers, and fast-repointing instruments have enabled the observation of magnetars' dynamic transient activity since the 1980s. Major contributors including ROSAT (Truemper, 1982), CGRO (Gehrels et al., 1994), RXTE (Swank, 1999), and BeppoSAX (Boella et al., 1997) have been used earlier. Table 1 lists the major high-energy instruments that are currently contributing to monitoring and detection of magnetars' transient activity. High-energy instruments like the GBM on board Fermi, Konus on board WIND, BAT on board Swift, and the ACS on board INTEGRAL offer broad coverage of the soft gamma-ray band, making them valuable for detecting a wide range of transient events, including those from magnetars. Instruments like Chandra, XMM-Newton, NuSTAR, and NICER provide high-angular resolution and are capable of discovering the precise locations of transient events, aiding in follow-up studies and multiwavelength observations; however, except for Swift with minute-scale reaction, the repointing time limits follow-ups to magnetar outbursts and burst storms. Figure 4 is a visual illustration of the available energy, timing, and sky coverage provided by the instruments listed in Table 1.

3.1 Outbursts

Most magnetars display periods of elevated X-ray emissions above their historical minimum level, sometimes by as many as

TABLE 1 Major high-energy instruments currently contributing to magnetar observations. Missions' figures of merit can be found on the NASA's High-Energy Astrophysics Science Archive Research Center (HEASARC). For the time property of INTEGRAL anti-coincidence shield (ACS), we referred to Savchenko et al. (2012).

Mission	FoV	Min. Repoint	Energy (keV)	Time Res.[c]	Launch
Konus-WIND	All-sky	–	20 – 20000	16 ms	1994
Chandra (HRC)	$30' \times 30'$	< 5 days	0.1 – 10	16μs	1999
XMM-Newton (PN)	$27.5' \times 27.5'$	< 24 hours	0.2 – 12	30 μs	1999
INTEGRAL (ACS)	All-sky	–	> 80	50 ms	2002
Swift BAT	15%	–	15 – 350	100 μs	2004
Swift XRT	$23.6' \times 23.6'$	Minutes	0.3 – 10	1.7 ms	2004
Fermi GBM	70% of sky	–	8 – 40000	2.6 μs	2008
Fermi LAT	25% of sky	–	$(0.1 - 800) \times 10^6$	10 ms	2008
MAXI (gas cam.)	$1.5° \times 160°$	–	2 – 30	50 μs	2008
NuSTAR	$10'$[a]	< 24 hours	3 – 79	2 μs	2012
NICER	$5'$[b]	< 4 hours	0.2 – 12	100 ns	2017

[a] FoV (50% resp.) at 10 keV.
[b] Non-imaging.
[c] This is the highest temporal resolution reached in any mode of any instrument on-board.

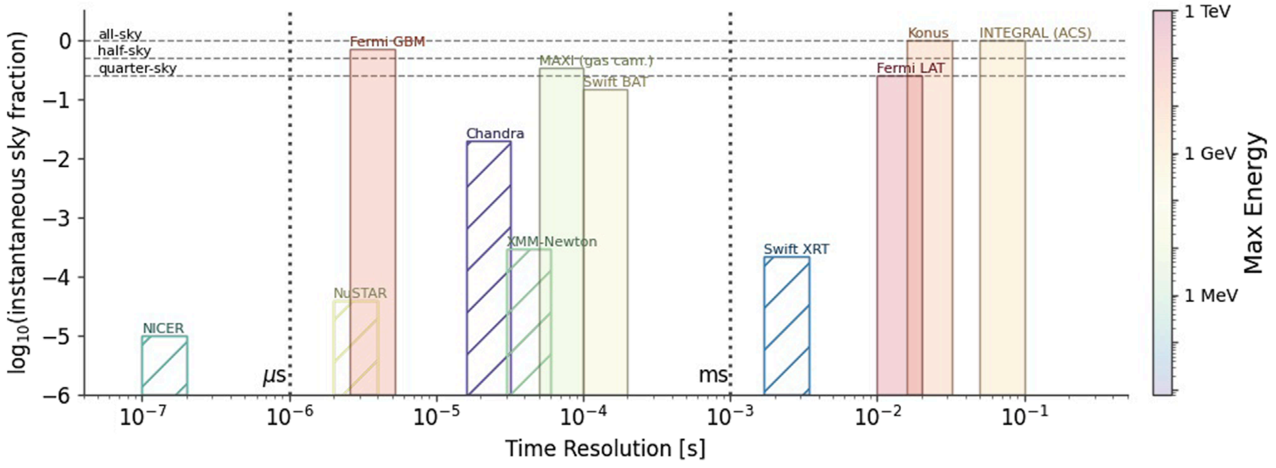

FIGURE 4
Active high-energy missions available for magnetar transient activity observations. On the *y*-axis, we show the sky coverage, monitors are marked with filled rectangles, while pointing telescopes are marked with hatched rectangles. On the *x*-axis, we report the time resolution of the different instruments. The colors mark the upper end of the energy range covered by the instruments.

three orders of magnitude in luminosity (Coti Zelati et al., 2018), i.e., magnetar outbursts. These epochs, which are typically observed concurrently to the onset of bursting activity (see below), are defined by extreme spectral–temporal variability to the soft and hard X-ray emissions in the form of harder spectra, pulse profile and fraction variation, timing noise, and glitches (Gavriil et al., 2004; Woods et al., 2007; Rea et al., 2009; Dib and Kaspi, 2014; Hu et al., 2020; Younes et al., 2022). At radio wavelengths, six confirmed magnetars have shown transient *radio pulsed emission*, appearing around outburst epochs (Camilo et al. (2006); Lower et al. (2020b), or, in a few occasions, disappearing (Lower et al., 2023). For a few magnetars, the infrared to optical emissions have also been observed to vary (Tam et al., 2004). These outburst epochs last from months to years during which the multiwavelength properties usually return back to their pre-outburst states (Coti Zelati et al. (2018).

Magnetar outbursts are generally attributed to crustal shifts (e.g., due to stresses on the surface from internal B-field restructuring and perhaps decay), imparting a twist onto an external magnetic field loop [see (Turolla et al., 2015) and references therein]. The surface heating arises due to either energy deposition in the crust, e.g., from Hall wave avalanches (Thompson and Duncan, 1996; Beloborodov and Li, 2016), or bombardment of the surface by accelerated particles in a twisted external B-field (Beloborodov, 2009). Both models predict the formation of surface hotspots, which could explain the altered pulse shape and amplitude during magnetar outbursts as well as the harder spectra and increased X-ray power. Although in both cases the outburst is initiated by an elastic failure of the crust (Dehman et al., 2020), their evolution is dictated by different regions of the NS. For the external model, as the twisted fields "unwind," magnetic energy is released in the form of radiation, typically leading to the shrinkage and cooling of the hotspot (Beloborodov, 2009), whereas if the heating is purely internal, the outburst decay is determined by crustal cooling scenarios heavily dependent on the micro- (e.g., crust impurity) and macro-physics [depth and total energy deposited in the crust (Brown and Cumming, 2009; Pons et al., 2009)].

Hence, given the abovementioned, multiwavelength follow-up studies of magnetar outbursts have distinctly revealed their highly dynamic nature; physics of plastic deformation of the crust, characteristics of the twisted B-field loops (twist magnitude, loop locale, and total volume), pair-production and particle acceleration required for the coherent radio emission, and the interconnection between all of these elements.

The high-energy properties of magnetar outbursts have been extensively studied with RXTE, XMM-Newton, Chandra, Swift/XRT, NuSTAR, and most recently NICER. Yet the most consequential results have come from the long-term monitoring previously afforded by RXTE (Dib and Kaspi, 2014) and currently conducted with XRT (Archibald et al., 2013; 2020) and NICER (Lower et al., 2020a; Younes et al., 2020b). Apart from the obvious benefit of such observational campaigns, i.e., the measurement of the period and period-derivative, and hence of the fundamental properties of the sources (magnetic dipole field strength, spin-down age, and spin-down power), continuous long-term monitoring of several bright magnetars from 1998 to 2012 revealed the common detection of some timing anomalies, mainly in the form of large spin-up (or on one occasion spin-down) glitches, at the onset of outbursts likely implying an internal trigger mechanism to these events (Archibald et al., 2013; Dib and Kaspi, 2014). Moreover, these monitoring campaigns revealed the delayed, erratic variability in the spin-down torque of these sources months to years after outburst onset, providing clues to the dynamics of the untwisting magnetospheric B-field lines (Woods et al., 2007; Younes et al., 2017; Archibald et al., 2020). Most recently, NICER (with the added benefit of the large effective area, relatively low background, and ease of repointing), through almost daily observations of the magnetar SGR 1830–0645, was able to resolve, for the first time, pulse peak migration which simplified the triple-peaked pulse profile at outburst onset to a single peak in 37 days (Younes et al., 2022). These results provide the strongest evidence yet for plastic motion of the crust, long theorized to drive magnetar outbursts. Finally, for the same reasons, NICER has been able to time fainter magnetars, especially around periods of strong X-ray and radio bursting activity. Target of opportunity campaigns have been particularly revealing. A very recent example is provided by the FRB-emitting magnetar SGR 1935 + 2154, for which a double glitch event within 9 h was detected, bracketing the largest spin-down rate ever observed from an NS along with an FRB (Hu et al., 2024; Younes et al., 2023). This discovery has implications for the rate of superfluid material in a magnetar, outflowing plasma-loaded wind, production mechanism of FRBs in magnetars, and possibly gravitational wave emission.

Long-term monitoring of magnetars in X-rays (in tandem with radio and infrared campaigns) is unquestionably fruitful. In this regard, continued operation of Swift and, especially, NICER is essential, and similarly, the operation of a satellite with a similar type of capabilities, such as Strobe-X, in the future (Ray et al., 2019).

3.2 Short bursts and burst storms

Short bursts are one of the most unique and defining properties of the magnetar population. These sub-second, bright hard X-ray flashes, capable of reaching luminosities of about 10^{42} erg s^{-1} (Figure 5), are easily identifiable by a suite of past and present large field-of-view hard X-ray monitors. They have played a crucial role in the inception of the soft gamma repeater class (Atteia et al., 1987; Kouveliotou et al., 1987; Laros et al., 1987) and cementing the anomalous X-ray pulsar (AXP) class as part of the same underlying population (Kaspi et al., 2003): NSs with activity driven by the extreme magnetic field strength (Duncan and Thompson, 1992; Paczynski, 1992). Magnetar short bursts can occur in isolation when one or few events are observed over the course of days, or, for the most active magnetars (which tend to be the youngest, Perna and Pons, 2011), during burst storms/forests when hundreds to thousands are emitted over the course of minutes to hours (Collazzi et al., 2015).

Due to the dimness of most magnetars during their quiescent state, the large absorbing column in their direction (being at low galactic latitudes), and the lack of adequate large field-of-view X-ray instruments[1], magnetars are rarely discovered through their persistent X-ray emission. This is plainly demonstrated through the discovery space of new magnetars in the last 20 years, which is fully dominated by the detection of short bursts, primarily with the Swift Burst Alert Telescope (BAT). The BAT is sensitive to short magnetar bursts and able to localize them to within few arcminutes. The rapid follow-up with the Swift X-ray telescope (XRT) confirms the activity through the detection of the (at the time) bright X-ray counterpart and provides arcsecond localization. Follow-up X-ray observations with the adequate time-resolution (which currently happens primarily with NICER) detects the pulse period of the source and its derivative, thus confirming the magnetar nature of the source (see, e.g., Ray et al., 2019, among numerous ATels of this kind). In summary, during its 20-year operation, the Swift telescope has enabled the discovery of more than double of the confirmed magnetar population in the galaxy and identified numerous new outbursts from the already known ones (Kaspi and Beloborodov,

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[1] eROSITA might detect few magnetars at the end of its full-sky survey, yet these will likely be marked as candidates as many might not be bright enough for pulsation detection.

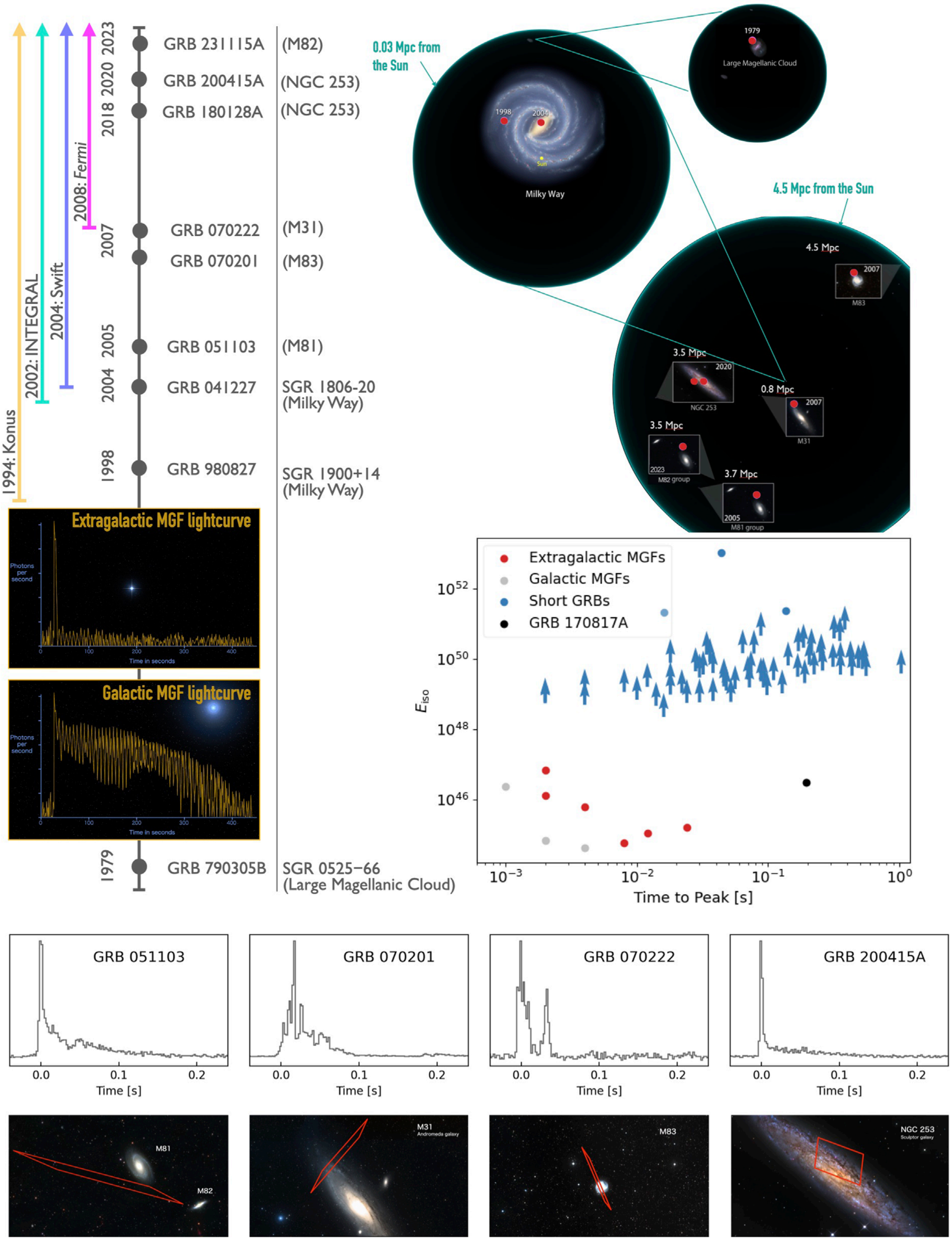

FIGURE 5
Illustration summarizing the current known population of MGFs and MGF candidates. The plot of the intrinsic energetic as a function of the rise time is the updated version of the plot presented in Ref. Negro and Burns (2023) with the addition of two more recent extragalactic identified events (see the text for more details). We also report the light curves and the IPN localizations for four of the MGF candidates identified in Burns et al. (2021). (Credit images: adapted from NASA Goddard).

2017; Esposito et al., 2021). The most significant among those discoveries is the identification of other classes of NSs as capable of showing magnetar-like activity, most noticeably high-B radio-pulsar (Archibald et al., 2016; Göğüş et al., 2016), CCOs Rea et al. (2016), and low-field magnetar Rea et al. (2010), as well as the discovery of a canonical magnetar with a bright X-ray wind nebula (Younes et al., 2016), a property typically attributable to rotation-powered pulsars (Kargaltsev et al., 2015). These discoveries have enabled a more comprehensive understanding of what constitutes a magnetar, observationally, and theoretically, the latter through magneto-thermal evolutionary studies of poloidal and toroidal/crustal fields in NSs (Pons et al., 2009; Viganò et al., 2013; Gourgouliatos et al., 2016; De Grandis et al., 2020; Igoshev et al., 2021; Dehman et al., 2023b; a).

Magnetar short bursts are also crucial for understanding the enigmatic FRBs (Section 4.3). Following the detection of a short X-ray burst coincident with an FRB-like radio emission from the magnetar SGR 1935 + 2154 (Bochenek et al., 2020; CHIME/FRB Collaboration et al., 2020; Mereghetti et al., 2020; Tavani et al., 2021; Li et al., 2021; Ridnaia et al., 2021), studies on the comparison of the spectral and temporal properties of the FRB-associated X-ray short burst to those without an FRB counterpart (which constitutes the overwhelming majority of short X-ray bursts) have shed light on the unusually hard spectrum of the X-ray burst that accompanies the FRB (Mereghetti et al., 2020; Younes et al., 2021). This likely pointed to an active region in the vicinity of the open-field line zone which permits the release of bright radio waves away from the presumably dense environment of the closed magnetosphere (Younes et al., 2021). Moreover, population-wide comparison of extragalactic FRBs and magnetar short bursts, such as duration, rate, and waiting time distribution, have shed some light on the origin of extragalactic FRBs (Cruces et al., 2021; Wei et al., 2021). Yet these have not been able to confirm what fraction of magnetar short bursts is indeed magnetars. This is partly due to our poor knowledge of the magnetar population in the Galaxy, and their activity cycle. Moreover, the detection of FRB 20200120E from a globular cluster in the nearby galaxy M 81 Bhardwaj et al. (2021) challenges the notion that most, if not all, FRBs have a magnetar central engine, unless these magnetars were formed through unconventional channels, e.g., accretion-induced collapse or the merger of two white dwarfs. X-ray observations of this FRB 20200120E with current X-ray instruments ruled out coincident short bursts that are at the high end of the burst fluence distribution ($L_X \gtrsim 10^{42}$ erg s$-^1$) and approaching the luminosities of intermediate flares (Pearlman et al., 2023).

Several advances in the magnetar field could be achieved with modest effort and investment. For instance, we currently lack a comprehensive, preferentially live, catalog of magnetar short bursts; an essential first step to understanding the activity rate and cycle of the population as a function of, e.g., spin-down age and magnetic field strengths. This could inform population studies of FRBs and comparison to the magnetar population. Ensuring the continued operation of Swift (or a new Swift-like instrument) is crucial for continued discovery of new magnetars and other exotic sources that exhibit magnetar-like activity. For instance, the low-magnetic field magnetar, SGR 0418 + 5729, bears a striking resemblance to XDINs during quiescence (Haberl, 2007). None of the latter sources (known as the magnificent seven) have shown magnetar-like activity, yet this could be due to their larger ages, implying a lower rate of activity than that of canonical magnetars. If XDINs are confirmed to be magnetars, this would have significant consequences on the number density of magnetars in the Milky Way and their formation rate, providing clues for the birth process of magnetars (Beniamini et al., 2019). New large FOV hard X-ray monitors that are capable of providing arcminute localization, preferentially equipped with sensitive follow-up X-ray instruments, e.g., NICER-like effective area, are key for continued scientific success in our understanding of the magnetar bursting and outburst phenomena. Additionally, next-generation X-ray instruments, such as HEX-P, AXIS, or Strobe-X, should be able to reach weaker short bursts in the nearby universe, further constraining the magnetar nature of nearby FRBs, including FRB 20200120E (Alford et al., 2024).

3.3 Magnetar giant flare spikes

In the 1970s, the debate on the origin of gamma-ray bursts (GRBs) was an outstanding question in astrophysics. Key pieces of information were that GRBs were not associated to known sources, none had been shown to repeat, and that their light curves had spiky but random behavior. The arrival of GRB 790305B was the first GRB localized to a known position (a supernova remnant in the Large Magellanic Cloud), was followed by a weaker GRB from the same position, and an incredibly bright spike was observed, followed by a periodic, exponentially decaying tail (Mazets et al., 1979). The tail period is approximately 8 s, complemented by a weaker interpulse occurring at a phase of 0.5 (Mazets et al., 1979; Cline et al., 1980). The rapid rise time of less than 0.25 ms was the fastest ever seen (Cline et al., 1980). This was the first Magnetar Giant Flare (MGF) seen and the first signal from a magnetar identified. Since then, two more flares have been identified from magnetars in the Milky Way (Hurley et al., 1999; Palmer et al., 2005). All three show similar characteristics, with tails lasting for hundreds of seconds. Due to their extreme luminosities, the spikes of these three giant flares saturated all viewing detectors.

MGFs are the most luminous transients created by magnetars. The crust of the magnetar may store significant elastic energy, which is released when the crust, stressed and powered by the internal magnetic field energy density, deeply and widely fractures (Lander et al., 2015). Magnetic reconnection may occur in the magnetosphere, releasing a bright spike where the plasma blows off on open field lines, followed by a periodic tail caused by the emission form a plasma fireball magnetically trapped on the rotating surface of the magnetar (Duncan and Thompson, 1992; Paczynski, 1992).

By building and characterizing a larger population of MGFs, it will be possible to place better constraints on their intrinsic rates, energetics distribution, and maximal energy release. The rates are of key importance to understand the possibility of detection via GWs during future observing runs (Abbott et al., 2019; Macquet et al., 2021) and the possibility that intermediate or giant flares may produce cosmological FRBs (Popov et al., 2018; Bochenek et al., 2020). The rates are key to understanding the formation channels and the fraction of magnetars that emit giant flares, allowing us to understand the processes which produce the most powerful magnets in the cosmos. The rates and energetics distribution will determine if the giant flares are the extreme events of the same underlying population which produces SGR short bursts, or if they are fundamentally distinct. The maximal energy release can be related to the maximal surface magnetic field of magnetars.

Furthermore, a sample of events allows for testing of theories on the physical mechanisms that power the prompt spikes. However, galactic events saturate any reasonable GRB monitor, precluding spectral and temporal properties of the spikes at the brightest intervals. This saturation has prevented the study of whether giant flares only occur with single pulses or if they show the same internal pulse variability observed in typical and intermediate SGR short bursts.

Galactic events likely only occur every few decades. In order to substantially increase the sample size during our lifetimes, we must recover and study extragalactic events. These are also key events to study the spectral and temporal properties as they are often sufficiently far to avoid significant saturation effects on GRB monitors. Given the exceptionally high peak luminosities of their initial spikes, instruments with high sensitivity, such as the *Fermi* Gamma-ray Burst Monitor (Meegan et al., 2009) or the Swift Burst Alert Telescope [BAT: Barthelmy et al., 2005)], can detect MGF emissions from magnetars located in galaxies possibly up to distances of 25, Mpc (Burns et al., 2021). However, the periodic tail "smoking gun" signature is not yet recoverable far beyond the Milky Way. Even with more sensitive detectors which can see the tails to the local group, the majority of events they detect will be seen only via their initial spikes.

Thus, identification of extragalactic giant flares requires reasonably precise localizations and comparison with nearby galaxy catalogs. Six candidate events at differing degree of significance events have now been found: GRB 070201 from M31, GRB 051103 and 231115A from M82, GRB 070222 from M83, and GRB 180128A and GRB 200415A from NGC 253 (Frederiks et al., 2007; Ofek, 2007; Mazets et al., 2008; Ofek et al., 2008; Hurley et al., 2010; Burns et al., 2021; Roberts et al., 2021; Svinkin et al., 2021; Trigg et al., 2023). This spatial alignment method and expectation of extragalactic MGFs masquerading as cosmological short GRBs date back decades (Hurley et al., 2005). Only GRB 051103 and GRB 070201 were identified prior to 2020. Population analyses considering localizations of all short GRBs by Swift and the InterPlanetary Network (IPN) against galaxy catalogs failed to identify additional candidates. The discovery of GRB 200415A led to the development of an improved search method, weighting possible host galaxies by star formation rate and distance based on the brightness of the GRB, which identified GRB 070222 in archival data (Burns et al., 2021). Additionally applying selections to short GRBs including the rise time and duration, both preferentially shorter for MGFs, identified GRB 180128A (Trigg et al., 2023). Recently, INTEGRAL detected, localized to few arc minutes—which is orders of magnitude better than the second best-localized MGF—enabling rapid follow-up observations, and promptly identified GRB 231115A as an MGF (Mereghetti et al., 2023; Yin et al., 2023), which is the first giant flare with rapid follow-up observations. Further analysis of this event is ongoing. It is important to notice how, in this case, even in the absence of a pulsating tail, it was possible to unambiguously identify the origin of the event as an MGF, thanks to the precise localization. A well-constrained association to a nearby galaxy, in fact, allows for accurate estimation of distances and hence intrinsic energetics of the burst, effectively excluding other typically more energetic progenitors.

Constructing a population of MGFs is key for several reasons. Study of galactic and extragalactic MGFs allows for more precise measures on rates and intrinsic energetic functions (Burns et al., 2021), which indicate if these giant flares are the extreme end of the SGR short burst distribution or fully distinct. These measures are also key to understanding if MGFs can power FRBs. The study of individual events provides precise temporal and spatial information for deep multimessenger searches. Recovery of the MGF signal, individually or stochastically (Macquet et al., 2021; Kouvatsos et al., 2022), allows measure of the f-mode frequency, giving an insight into the structure of NSs and their equation of state (Kunjipurayil et al., 2022). The study of extragalactic MGFs allows for careful (unsaturated) study of their temporal and spectral evolution, providing insights into their physical origin (Trigg et al., 2023). Lastly, identifying extragalactic MGFs is the easiest, possibly only way to study magnetars beyond the Magellanic Clouds.

All of these scientific results support the need for continuous, sensitive, all-sky monitoring of the gamma-ray sky. Reasonable localization accuracy is necessary to enable follow-up searches across and beyond the electromagnetic spectrum. The possible harder spectrum of brighter bursts may be key to driving sensitivity at higher energies than typical GRB monitors. Coverage of gamma-rays above the MeV regime is needed to search for more GeV flares, similar to the one found after GRB 200415A (Ajello et al., 2021), which may inform or reject the bow-shock origin proposed in Ajello et al. (2021).

3.4 Pulsating MGF tail from extragalactic magnetars

The initial spike of the three confirmed MGFs was closely followed by a bright ($L_X \approx 10^{43}$ erg s$-^1$) thermally emitting ($kT \approx$ 10 keV) tail, declining quasi-exponentially below the sensitivity of large field-of-view hard X-ray monitors in approximately 300 s). The rotational motion of the NS induces periodic modulation to this tail at the star spin period, providing the smoking-gun evidence for the magnetar central engine of these extreme events.

These tails are thought to be generated due to the magnetosphere of the NS trapping a fraction of the energy released by the initial burst (likely when magnetic pressure overcomes the radiation pressure as emission from the initial spike abates). This trapped fireball of photon-pair plasma is optically thick and slowly releases energy from its surface as it cools and shrinks in size (essentially evaporating Thompson and Duncan, 1996). Observationally, the tail spectra in the 1–100 keV range are dominated by a thermal component with observed temperatures on the order of tens of keV, which decreases with time. A non-thermal component is also present, most prominently at early times and dominating the emission at higher energies ($\gtrsim$ 100 keV, Boggs et al., 2007).

The spectra of the time-integrated tails of the three MGF tails were compatible with a dominant blackbody component (kT of tens keV) and a subdominant power-law only emerging above 30–40 keV (Figure 4 of Hurley et al., 2005). The intrinsic total radiative energy of the three observed MGF tails hovers at approximately a few 10^{44} erg (Mereghetti, 2008), despite the fact that the energy from their initial spikes varies by two orders of magnitude. This raises the intriguing question of whether MGF tails are standard candles. The current statistics of the available observations limits our capability to provide a meaningful answer. However, the relevance of this realization has important implications for both cosmology (providing a tool for more accurate distance measurements) and the measurement of the, largely unknown, magnetic Eddington limit (Turolla et al., 2015). Additionally, quasi-periodic oscillations (QPOs) at several differing frequencies have been discovered in the tail emission of the galactic MGFs of SGR 1900 + 14 and SGR 1806–20 (Israel et al., 2005; Strohmayer and Watts, 2005). If interpreted as oscillation modes in the NS crusts, these QPOs could be utilized to place limits on the dense matter equation of state, complementing other major efforts such as light curve modeling of millisecond pulsars by NICER (Miller et al., 2019; Riley et al., 2019) and the waveform modeling of the gravitational wave signal from double NS mergers (Abbott et al., 2017). Thus, expanding our ability to detect MGF tails beyond our galaxy and immediate neighborhood will substantially increase the sample size of these events, in turn providing crucial data to test these tails as an independent cosmological probe and infer the Eddington limit of highly magnetized NSs.

To this end, we simulate the possible detection of MGF tails with currently operating X-ray satellites, scaled to the extragalactic distance of 3.5 Mpc (e.g., the distance of the star-forming galaxies M82 and NGC 253). We assume an event like the 1998 MGF from SGR 1900+14 as presented in Feroci et al. (2001), in which the spectrum is modeled as a blackbody, with temperature decreasing over time. We use the effective areas of the instruments as presented in the left panel of Figure 6. The right panel of Figure 6 displays the number of expected signal counts as a function of a hypothetical repointing time starting at 60 s and integrating over the duration of the tail (300 s). In this time window, for most pointed X-ray telescopes, the expected background counts is on the order of a few (not included in our simple calculations, as detailed simulations are reserved for an upcoming publication). At 3.5 Mpc, all instruments are capable of detecting the tail assuming a relatively fast repointing, e.g., that of XRT aboard Swift. A NuSTAR or NICER-like instrument, under the same circumstances, could detect the tail up to approximately 35 Mpc. With an MeV-sensitive mission which could detect MGF spikes up to these distances and beyond, an X-ray follow-up instrument with the above capabilities could provide smoking-gun evidence for a population-size sample of MGF, paving the way for a major leap toward the understanding of these phenomena. On the other hand, a large field-of-view X-ray instrument such as eROSITA (Predehl et al., 2021) or one equipped with a sensitive lobster eye optic, such as Einstein Probe (Yuan et al., 2022), might be able to detect MGF tails independently and provide an estimate of "orphan" MGF tails where the spike emission is beamed away from the observer.

3.5 Polarization of magnetars' bursts and flares

X-ray polarization of magnetars traces the magnetic field geometry as well as the shape, dimension, and physical state of the surface emitting region and exotic effects of quantum electrodynamics (QED) that are expected to take place in the presence of extreme magnetic fields like those of magnetars. Despite the significant recent observational advancements made with the NASA's IXPE mission (Weisskopf et al., 2022), the highly degenerate parameters space prevents from definitive conclusions on QED effects (Taverna et al., 2022; Zane et al., 2023). IXPE results, which focus primarily on persistent emission, highlight the need for further theoretical effort and advancements in numerical simulations to build more accurate models. Furthermore, the impossibility in decoupling QED effects on polarization from geometrical polarization expected when the emitting region is a small patch on the magnetar's surface suggests the need for extending the range of measured polarization below 1 keV. Probing the polarization from the cooler X-ray radiation emitted from a wider portion of the surface is expected to be a better probe of QED effects. In this context, the further advancement of technologies like the ones developed for the Rocket Experiment Demonstration of a Soft X-ray Polarimeter (REDSoX) (Marshall et al., 2023), recently approved by the NASA, will be critical in this endeavor.

Extant models of magnetar burst polarizations are sparse (Taverna and Turolla, 2017) and are currently in development Wadiasingh et al. (2023). The combination of different outgoing photon angles sampled by the observer on a magnetic loop, however, is expected to reduce the time-averaged polarization of the bursts to approximately 30 – 60%. Polarization of bursts is also expected to be energy-, viewing-, and magnetic-geometry-dependent, with possible influences of gravitational lensing by the magnetar. Any actual observational constraints on burst polarization, combined with measured broadband spectra of high-energy monitors, can greatly inform the factors influencing burst polarization, such as magnetar viewing geometry, size of the active flux tube, and rotational spin phase of the burst. This, in turn, combined with other high-energy observations, can elucidate the active region and physics of the magnetar crust. As magnetar bursts are sporadic and unpredictable, catching a bright burst serendipitously in pointed observations is unlikely, unless a burst storm is ongoing, in which case, assessment of the polarization could be limited by counts statistics for individual short bursts or pile-up in case of extremely bright events. This can be observed with current instruments (such as IXPE) through the delayed X-ray emission from the very bright bursts scattered off dust layers along the line of sight. Such observations would be effective in the approximation that the dust scattering-induced polarization is negligible (*sim*10^{-}5 modulation), which is valid for small (arcminutes) scattering angles (see Appendix B.2 of Negro et al., 2023). A fast-pointing soft X-ray polarimeter or a sensitive monitor with polarization capability would greatly widen our observational portfolio, allowing for more modeling and better understanding of the processes involved in galactic magnetar burst activity.

In the context of MGFs, polarization observations would provide key information about the structure of the magnetar magnetosphere. Taverna and Turolla (2017) modeled the spectral and polarization properties of the 1–100 keV radiation emitted during the MGF tails, invoking a simplified "trapped-fireball" model, in which the electron–positron pair plasma is injected into the magnetosphere and remains trapped within the closed lines of the strong magnetic field. The linear polarization predicted by this model is very high (greater than 80% between 1 and 100 keV). Taverna and Turolla

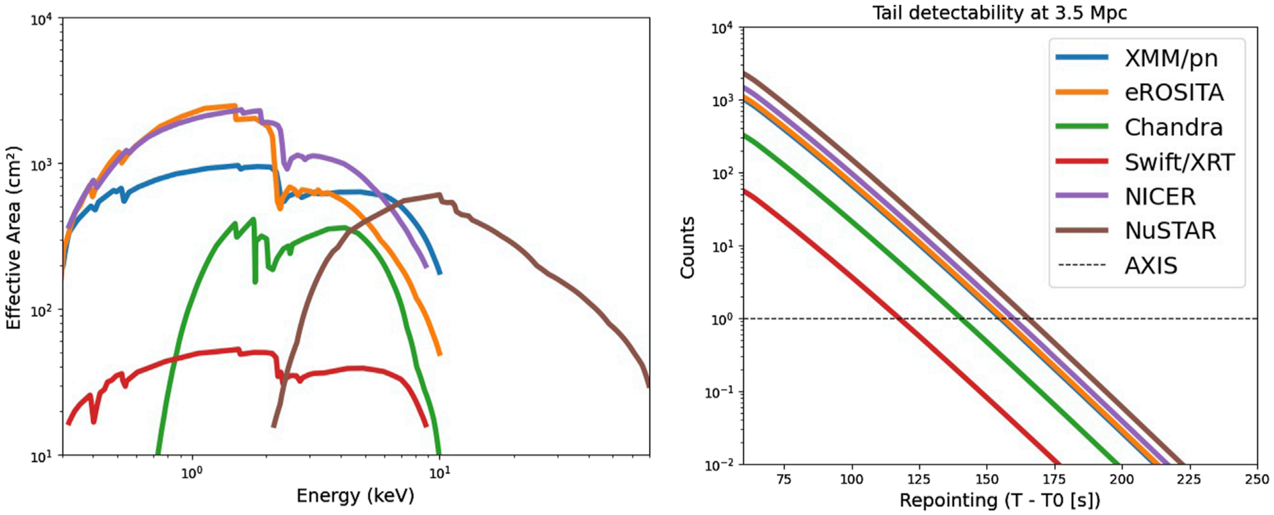

FIGURE 6
Right: Expected number of counts for time-integrated observation of an MGF tail as it would appear at a distance of 3.5 Mpc (e.g., NGC 243) as a function of repointing time after the initial MGF spike. We assume an MGF tail similar to the one observed in 1998 from SGR 1900 + 14 Feroci et al. (2001), scaled to 3.5 Mpc. Left: effective areas of different instruments considered are shown for comparison.

(2017) adopted a similar model to predict the linear polarization from MGF tails, assuming a more realistic temperature distribution in the fireball, but integrating over wider energy ranges, finding a lower polarization degree, as high as 30% (1–30 keV) and 10% (30–100 keV) depending on the viewing angle with respect to the magnetic axis of the magnetar.

Such discrepancy in different predictions highlights how polarization measurements of MGF tails could help constrain the trapped-fireball model and potentially drive new theories to explain magnetar flares. Such observations are not possible in the soft X-ray band as IXPE could not repoint fast enough to catch the emission, while at higher energies, at which the future missions COSI and POLAR 2 will operate, theoretical predictions are lacking. COSI—the COmpton Spectrometer and Imager (Tomsick et al., 2023)— scheduled to launch in 2027, will be sensitive to soft gamma rays between 200 keV and 5 MeV and will have polarization capabilities for assessing galactic MGF tails. A dedicated study on the ability of the COSI to detect extragalactic MGFs is needed.

4 Magnetars in multimessenger astronomy

4.1 Gravitational waves from magnetar bursts and flares

Gravitational waves (GWs) from magnetars can be generated through various astrophysical processes that involve rapid changes in the mass distribution or extreme deformations of these highly magnetized NSs. The intense magnetic fields associated with magnetars significantly influence their dynamics and can give rise to GW emissions. This happens when the intense magnetic fields of magnetars undergo instabilities, causing dramatic reconfigurations. The associated GW waveforms depend on the specifics of the starquake, and the characteristic frequencies are unknown. MGFs excite two different types of oscillations, the fundamental (of f-mode), which radiate GWs, and the shear modes or torsional modes, that manifest themselves with observable QPOs. The f-mode is thought to be excited when the magnetar's internal magnetic field rearranges itself, while QPOs are other oscillation modes most likely excited due to seismic vibrations and are longer-lived than the f-mode. QPOs have been detected in the tail emission of all three nearby MGFs (Israel et al., 2005; Strohmayer and Watts, 2005; Strohmayer and Watts, 2006; Watts and Strohmayer, 2006), and, interestingly, QPOs in short repeated bursts from SGR J1550-5418 were also reported in 2014 by Huppenkothen et al. (2014). In general, however, the frequencies detected are disparate and the vibration modes are difficult to identify, given the numerous stellar parameters involved (magnetic field, mass, radius, composition, etc...) and the rarity of these events.

While GWs are generally anticipated to accompany energetic bursts, this expectation is especially pronounced and accessible in the case of MGFs, representing the most intense starquakes in magnetars. This expectation is predicated upon the assumption that mass redistribution can yield a GW luminosity that is a sizable fraction of the total radiative luminosity of $10^{45} - 10^{47}$erg/sec in the initial spike. Such GW luminosities are readily accessible to LVK for magnetars in the Milky Way and in nearby galaxies. Despite these expectations, the detection of GWs from MGFs remains elusive, with none having been observed to date (see The LIGO Scientific Collaboration et al., 2022, for the search in the previous LIGO-VIRGO-KAGRA observing run). In 2004, in occasion of the MGF from SGR 1806–20 (Palmer et al., 2005), the early LIGO interferometers reported only upper limits (Abbott et al., 2007) on a possible GW emission. The Gamma-ray Transient Network Science Analysis Group (Burns et al., 2023) pointed out that the current GW detector network is about two orders of magnitude more sensitive than the first generation detector network, and another factor of 100 is expected within the next 20 years of upgrades. Such improvement from the GW front can lead the first detection of GWs from magnetars in Milky Way and beyond. In this context, the presence of wide field-of-view high-energy monitors with a fast turnaround is imperative to promptly detect electromagnetic counterparts. Such observations would constrain the total energy that can be radiated via GW, as well as the ratio between electromagnetic energy vs. GW energy during magnetar flares, providing major advances in our understanding of magnetars (and NSs in general), constraining the models of matter structure and behaviors in such extreme environments.

GWs are also likely produced during the birth of the magnetar. Section 3.3 described the relevance of observing a second MGF from the same magnetar, in terms of being the first source of repeating GRBs. However, another implication of repeating MGFs, as pointed out by Stella et al. (2005), is the requirement of a magnetic field above 10^{16} G of newly born magnetars. Such extreme internal field necessarily deforms the NS; if its moment of inertia has axes not aligned with the rotational axis, it would generate a week-long strong gravitational wave signal. The frequency of such a GW signal is dictated by the fast rotation period of the newly born magnetar. Stella et al. (2005) predicted the detection of such a GW signal by Advance LIGO-class detectors up to the distance of the Virgo Cluster (~ 2000 galaxies), where magnetars are expected to form at a rate of more than one magnetar per year. GW detections of newborn magnetars (Lander and Jones, 2020) have so far not been forthcoming.

Models predicting gravitational wave signals from magnetars (see Ciolfi and Rezzolla, 2012; Dall'Osso and Stella, 2022, and references therein) face considerable uncertainty due to our limited understanding of their internal magnetic field configurations and matter equations of state. This uncertainty spans from optimistic to pessimistic expectations. Further investigation into magnetars' transient activity holds promise in elucidating the underlying physics, potentially improving prediction reliability.

4.2 Neutrinos from magnetars

During the initial phases of a magnetar flare or burst, the intense release of energy can heat the NS's crust and interior. Subsequent cooling processes, involving neutrino emission, become prominent. Neutrinos, being weakly interacting particles, can escape the dense magnetar environment and carry away significant amounts of energy. We can distinguish between high-energy neutrinos, of GeV–TeV energy, detectable by instruments like the IceCube Observatory (IceCube Collaboration et al., 2006), and MeV neutrinos, like the ones produced in stellar processes and supernovae explosions, detectable by instruments like Super-Kamiokande (Walter, 2008). Both classes of neutrinos, when detected in coincidence with the electromagnetic counterpart, are a crucial aspect of multimessenger astronomy—which, in a sense, can be dated back to the detection of MeV neutrinos from SN 1987A (Blanco et al., 1987). In the context of magnetar bursts and flares, models have been developed to predict the emission of high-energy neutrinos, the detection of which would provide important information about the flaring mechanism, as well as the crustal composition. In general, the production of neutrinos requires the presence of hadronic or photo-hadronic interactions. In MGFs, the neutrino fluxes depend on the baryon load, which is not well-constrained, due to uncertainties on the relative importance of thermal and non-thermal components (Ioka et al., 2005). Hence, detection of neutrinos from magnetars would be extremely insightful to understand their composition.

One can build the expectation of the high-energy neutrino yield knowing the expected photon flux of the outflow. This was done in Guépin and Kotera (2017), where they computed the minimum photon flux necessary for neutrino detection by IceCube, as well as the maximum neutrino energy expected, for a number of different sources of outflows (including magnetar bursts and flares). The study is generalized in terms of the intrinsic bolometric luminosity, the Lorentz factor, and the time variability of the emission. Figure 7 highlights the results for magnetars' transient activity. This study shows how neutrino detection is limited to only very nearby bright events, i.e., MGFs with a maximum luminosity distance of ~0.39 Mpc (minimum photon flux of $10^4 - 10^6$ ph $\mathrm{cm}{-}^2\mathrm{s}{-}^1$ to have a neutrino detected in IceCube). The procedure followed by Guépin and Kotera (2017) is somewhat simplistic and assumes high hadronic yield and maximally efficient proton acceleration associated with relativistic outflows. This might be attained for MGFs, but it is unlikely for short bursts. Models predict relativistic outflows in the tails of MGFs (van Putten et al., 2016) as a necessary ingredient to reproduce the observed pulse fraction, offering therefore prospects for high-energy neutrino emission during the tail-phase of MGFs if proton acceleration is tenable. As pointed out by Ioka et al. (2005), if TeV neutrinos are detected, one would also expect detectable EeV cosmic rays and possibly TeV gamma-ray emission in coincidence. No claim of such detection has been made so far.

Ghadimi and Santander (2023) searched for high-energy neutrinos from galactic magnetars, performing a time-integrated search over 14 years of data collected by the IceCube Observatory (Aartsen et al., 2017). The results point out that a next-generation upgrade of the neutrino detector with improved sensitivity is in order, as the current IceCube capabilities are ~ two orders of magnitude above the needed sensitivity to detect a stacked signal from all known magnetars. The creation of a magnetar burst catalog would be beneficial for targeted time-dependent neutrino searches anticipated in Ghadimi and Santander (2023) as future studies.

4.3 Link to fast radio bursts

FRBs are extragalactic flashes of radio emission of millisecond duration of isotropic-equivalent energies $10^{36} - 10^{41}$ erg, first[2] reported by Lorimer et al. (2007). Only recently (since about 2014) has their true astrophysical nature been accepted, over instrumental backgrounds or artifacts (Spitler et al., 2014). FRBs have now become a major interest of study and industry in radio astronomy

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[2] Although possibly much earlier by Linscott and Erkes (1980).

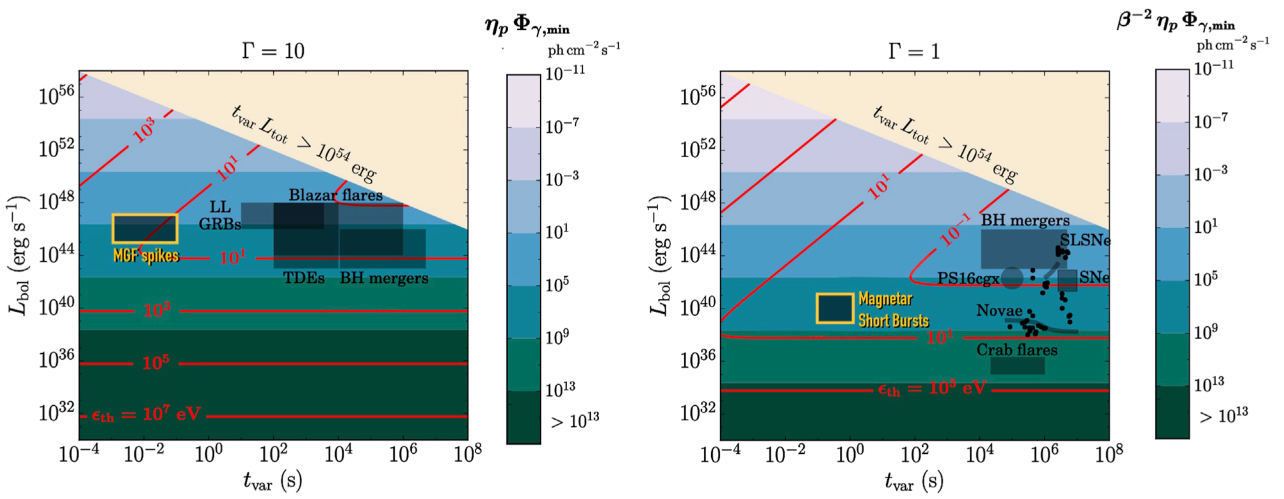

FIGURE 7
Adapted from Guépin and Kotera (2017) (Figure 1). The two plots illustrate the minimum photon flux needed to detect neutrinos in IceCube detectors for different Lorentz factors. Highlighted with yellow boxes are the magnetars' transients considered, short bursts, and MGF spikes.

(Caleb and Keane, 2021), with propagation effects particularly useful in cosmological probes (Zhou et al., 2014; Li et al., 2018) such as the baryon fraction of the intergalactic medium (Macquart et al., 2020). They are also, currently, an important topic in time-domain astronomy. Many future facilities prominently feature FRBs or radio transients more broadly, as one of their key science topics. Yet, as given below, there is an intimate association between magnetars and their soft gamma-rays short bursts.

Magnetars were initially proposed as the engines of the 2001 Lorimer burst among many models, although in the form of giant flares producing FRBs (Popov and Postnov, 2010; 2013). Yet various non-magnetar and exotic models were also proposed Platts et al. (2019). As the first repeating FRB was discovered (Spitler et al., 2016), giant flares from "hyperactive" magnetars became a popular model (Beloborodov, 2017; Metzger et al., 2019) over cataclysmic events. However, statistics of waiting times and power-law distributions of fluence in repeating FRBs suggested much more similarity with magnetar short bursts (Wadiasingh and Timokhin, 2019). Yet, as of 2019, no FRBs were seen from many thousands of short bursts recorded from known magnetars in our local universe. Moreover, radio limits on the SGR 1806-20 giant flare in 2004 ruled out any contemporaneous bright radio flashes (Tendulkar et al., 2016); thus, it appears that giant flares do not necessarily produce FRBs. As suggested by Wadiasingh and Timokhin (2019); Wadiasingh et al. (2020), special conditions (e.g., charge starvation and pair cascades in the magnetosphere) must be satisfied such that not all short bursts produce radio emission (yet all FRBs would be associated with short bursts, as the FRB occurs in the beginning "clean" stage of the fireball created in short bursts). As FRBs result from coherent emission processes, and short bursts are incoherent, the energy contained in FRBs is generally expected to be a small fraction of the total energy observed in the quasi-thermal short bursts. The same conditions thought to be conducive to the production of FRBs (i.e., explosive pair production demanded by large coherent electric fields) likely are also suitable for proton acceleration and the production of high-energy neutrinos at low altitudes in the magnetar magnetosphere (Herpay et al., 2008).

The situation was clarified dramatically in April 2020, when SGR 1935 + 2154 underwent a burst storm, emitting thousands of short bursts in the hard X-rays (Younes et al., 2020a; Palmer, 2020). In the waning hours of this storm, CHIME/FRB (CHIME/FRB Collaboration et al., 2020) and STARE2 (Bochenek et al., 2020) observed a bright radio flash consistent with an FRB from SGR 1935 + 2154. The radio burst was bright enough (energy ~10^{36} erg isotropic equivalent) if placed at a cosmological distance to be similar to weaker extragalactic FRBs. Thus, at least a fraction of FRBs originate from magnetars. The burst featured a bright (10^{40} erg) and prompt hard X-ray short burst counterpart detected by INTEGRAL, HXMT-Insight, and Konus Wind (Mereghetti et al., 2020; Li et al., 2021; Ridnaia et al., 2021) (although not by Fermi-GBM and Swift-BAT due to Earth occultation). The HXMT-Insight light curve of the FRB-associated burst featured a $30-40$ Hz quasi-periodic oscillation (Li et al., 2022), consistent with a low-order crustal torsional eigenmode of an NS, bolstering the case that FRBs are related to magnetar crustal dynamics and how that is transmitted to the magnetosphere (Wadiasingh and Chirenti, 2020). Moreover, the radio led features in the short burst counterpart by a few milliseconds, suggesting a magnetospheric origin to this radio burst, and perhaps all FRBs (Ge et al., 2023; Giri et al., 2023). More recent statistical "aftershock" analyses of extragalactic FRBs and SGR 1935 + 2154 have revealed similarities to each other and to earthquake dynamics (but not solar flare catalogs) (Totani and Tsuzuki, 2023; Tsuzuki et al., 2024), suggesting that the crustal dynamics on magnetars are key to understanding FRBs.

Radio activity in SGR 1935 + 2154 is also connected with torque and potentially interior dynamics of the magnetar. In October 2020, SGR 1935 + 2154 became radio-active again, exhibiting bright radio bursts (Kirsten et al., 2021) as well as a prolonged episode of pulsar-like pulsed radio emission (Zhu et al., 2023). This is suggestive of conditions which are conducive to both phenomena and a magnetospheric origin of FRBs. For this episode, X-ray timing revealed a jump in the period of the magnetar Younes et al. (2023) i.e., a spin-down glitch, consistent with a baryon loaded wind extracting angular momentum from the star. More recently, Hu et al. (2024) have reported X-ray timing revealing two spin-up glitches separated by ~9 hours bracketing FRB-like radio bursts (Dong and Chime/Frb Collaboration, 2022; Maan et al., 2022) during an epoch of waning burst rate but high spin-down in October 2022. This result suggests a high superfluid fraction of the magnetar, with burst activity possibly triggering the first spin-up glitch. The glitch, in turn, possibly triggered the baryonic wind and magnetospheric conditions conducive for radio bursts.

There are many open questions concerning FRBs and the putative magnetar connection: Why do only a small fraction of magnetar short bursts result in an FRB-like emission? Why are some extragalactic FRB sources much more prolific FRB producers than galactic magnetars? What is the origin of long-timescale periodic activity windows in extragalactic FRBs (Rajwade et al., 2020; Chime/Frb Collaboration et al., 2020), and is this related to the recently reported galactic long-period magnetar candidates (Caleb et al., 2022; Hurley-Walker et al., 2022; 2023; Beniamini et al., 2023)? Can magnetars involved in NS mergers produce radio bursts (Cooper et al., 2023)? To answer these questions, further study of local magnetars and extragalactic magnetar signals correlated in time and sky location in multiple messengers will likely be crucial.

5 Summary and conclusion

We conclude by underscoring the critical role of continuous monitoring and real-time detection and alert capabilities in advancing our understanding of magnetars, as well as other transient events in the high-energy astrophysical landscape.

Long-term monitoring campaigns of magnetar outbursts, particularly in X-rays alongside radio and infrared observations, have yielded invaluable insights into the behavior of magnetars. Swift and NICER have played pivotal roles in this regard, with their continued operation being paramount for future discoveries. Sensitive, continuous monitoring of the high-energy sky plays a crucial role in detecting bursts and flares from magnetars, both alone and in concert with FRB monitoring, and possibly future GW and neutrino observations. Increased sensitivity of all-sky monitors could reveal MGF tail emission of extragalactic events, providing the unambiguous signature for a magnetar origin. At the same time, improved localizations could unambiguously exclude a cosmological origin of the detected gamma-ray burst (Mereghetti et al., 2023). Precise localizations may also allow for determination of repeat giant flares from individual magnetars in other galaxies, a question which has not been resolved directly in 50 years of monitoring the Milky Way. Capturing orphan MGF tail detection, where the spike emission is directed away from the observer, also requires ultra-fast repointing instruments or large field-of-view X-ray instruments equipped with sensitive optics. High-energy polarimetry offers a unique window into the physical processes driving magnetar transients, shedding light on magnetic field configurations, emission mechanisms, and the nature of the emitting sources. The recent non-selection of LEAP—A LargE Area burst Polarimeter—by NASA represents a missed opportunity to gather new insights from fast-transient polarization in the 50–500 keV energy range. In general, a wide-field polarimeter with sensitivity down to tens of keV would greatly contribute to enhancing our understanding of magnetar dynamics through the observations of nearby extragalactic MGFs and galactic intermediate flares.

The aging status of current instruments, including Konus, Swift, and Fermi, coupled with the decommissioning of AGILE and the impending decommissioning of INTEGRAL, underscores the urgency of advancements in technology and development of new missions to ensure uninterrupted coverage and enhanced capabilities for detecting fast transients. As technology evolves, there is optimism for improved sensitivity, localization, and monitoring capabilities, paving the way for further discoveries in the dynamic field of high-energy astrophysics.

Author contributions

MN: conceptualization, project administration, writing–original draft, and writing–review and editing. GY: writing–original draft and writing–review and editing. ZW: writing–original draft and writing–review and editing. EB: writing–original draft and writing–review and editing. AT: writing–original draft and writing–review and editing. MB: writing–original draft and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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