Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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INTEGRAL contributions to magnetars and multimessenger astrophysics

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Abstract. The INTEGRAL satellite, in orbit since October 2002, has significantly contributed to the study of magnetars and, thanks to its unique capabilities for the study of transient gamma-ray phenomena, it is now playing an important role in multimessenger astrophysics. The most recent results include the discovery of a peculiar burst from SGR J1935+2154, which gave the first observational evidence for the connection between magnetars and fast radio bursts, and extensive searches for bursting activity in peculiar sources, such as the repeating FRB 20200120E in M81 and the ultra-long period magnetar candidate GLEAMX J162759.5–523504.3.

Keywords. Magnetars, Fast Radio Bursts

1. Introduction

The European Space Agency INTEGRAL satellite, launched in October 2002 and still operational (Kuulkers et al. 2021), is devoted to observations in the hard X-ray / soft γ-ray range with high spectral and angular resolution. Its two main instruments, IBIS and SPI, provide high sensitivity with good imaging and spectroscopic capabilities over a wide field of view ($\sim$900 deg^2) in the range $\sim$20 keV – 10 MeV, and can also detect transient γ-ray signals from every direction in the sky thanks to their active anti-coincidence shields. This is particularly useful because the highly eccentric orbit of INTEGRAL, with a period of 2.7 days, allows uninterrupted observations for 85% of the time (i.e. when the satellite is above the radiation belts) of virtually the whole sky (the fraction of sky occulted by the Earth goes from 0.05% at perigee to 0.4% when the satellite enters/exits the radiation belts). All the data are downlinked in real time and processed with a latency of only a few seconds from the time of their on-board acquisition allowing rapid localization of transient events. These unique properties make INTEGRAL a powerful tool for time-domain and multimessenger astrophysics. A thorough description of the performances for the search of GW counterparts and other transient events can be found in Savchenko et al. (2017). In this short contribution I concentrate on the results obtained for magnetars and fast radio bursts (FRB). See Papitto et al. (2020) and Ferrigno et al. (2021) for more extended accounts.

2. Discovery of persistent hard X-ray emission from magnetars

Magnetars were discovered in hard X-rays, but for many years their detection in this band was limited to the bursts from soft gamma-ray repeaters (SGR). Before the advent of INTEGRAL, their persistent emission was seen only below 10 keV, with very soft spectra suggesting undetectable fluxes at higher energies. The unanticipated discovery of persistent hard X-ray emission from several magnetars with INTEGRAL (Molkov et al.

2004; Mereghetti et al. 2005a; Kuiper et al. 2006; Götz et al. 2006; den Hartog et al. 2008) opened a new window in the study of these objects.

The hard spectral components in magnetars extend up to ∼150–200 keV with power-law spectra (Γ∼0.5-2) and contain an energy similar to, or even larger than, that of the soft X-ray emission. The pulsed flux is generally harder than the unpulsed one, implying an increase of pulsed fraction with energy. Contrary to the soft X-rays, most likely originating from thermal emission from the star surface, hard X-rays are produced by non-thermal magnetospheric particles, with an important contribution from resonant cyclotron scattering (Beloborodov 2013; Baring & Harding 2007).

3. The hard X-ray afterglow of the SGR 1806–20 giant flare

It is well known that magnetars giant flares (GF) consist of two main distinct components: an initial very bright and short (<0.2 s) spike with hard spectrum and a softer pulsed tail lasting a few minutes. Thanks to the sensitivity and uninterrupted coverage provided by the anti-coinicidence shield of the SPI instrument, INTEGRAL could discover a further distinct emission component in the 2004 December 27 GF from SGR 1806–20 (Mereghetti et al. 2005b). With a peak isotropic luminosity of $\sim 10^{47}$ erg s^{-1} and a total energy release of $\sim 10^{46}$ erg (for d=9 kpc), this was the most energetic GF ever seen from a Galactic magnetar.

The light curve obtained with INTEGRAL (Fig. 1, top panel) showed that, after the end of the pulsating tail, the hard X-ray flux above ∼80 keV increased again, reaching a peak ∼700 s after the start of the GF, and returning to the pre-flare background level after ∼4000 s. The time decay of such “afterglow” component was well fit by a power law with $F(t) \propto t^{-0.85}$. The fluence in the 400-4000 s time interval was of the same order of that in the pulsating tail. The power-law time evolution and the hard power law spectrum (Γ ∼1.6, Frederiks et al. 2007) indicate that this long-lasting emission is most likely caused by the interaction of relativistic ejecta with the circumstellar material, similar to the afterglows seen in γ-ray bursts. With standard synchrotron models for γ-ray burst afterglows, it is possible to relate the bulk Lorentz factor of the ejected material, γ_{ej}, to the time t_0 of the afterglow onset. This gives $\gamma_{ej} \sim 15(E/5\times10^{43}\ \mathrm{erg})^{1/8}(n/0.1\ \mathrm{cm}^{-3})^{-1/8}(t_0/100)^{-3/8}$, where n is the ambient density, consistent with a mildly relativistic outflow, as it was also inferred from the analysis of the radio source that appeared after the giant flare (Granot et al. 2006).

4. Bursts from magnetars and fast radio bursts

INTEGRAL also provided data on many short SGR bursts. SGR 1806–20 (Götz et al. 2004, 2006) and 1E 1547.0–5408 (Mereghetti et al. 2009; Savchenko et al. 2010) were oberved during periods of intense bursting activity and, thanks to the high sensitivity of the IBIS instrument, it was possible to study the properties of bursts down to fluences as faint as 2×10^{-8} erg cm^{-2}. Many bursts were localized in real time by the INTEGRAL Burst Alert System (IBAS, Mereghetti et al. 2003), when they occurred in the IBIS field of view.

A particularly exciting case was that of the 2020 April 28 burst from SGR J1935+2154. This event triggered IBAS (Mereghetti et al. 2020a), which distributed an alert after less than 10 s from the burst, a few hours before the announcement of the independent discovery of the associated radio emission. The properties of this very bright and short radio burst were very similar to those of the FRBs (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020), thus giving a strong support to FRB models involving magnetars (see Zhang (2020) and ref. therein). In hard X-rays this burst was not particularly energetic (E$\sim 10^{39}$ erg for d=4.4 kpc, Mereghetti et al. 2020b), but it was characterized by

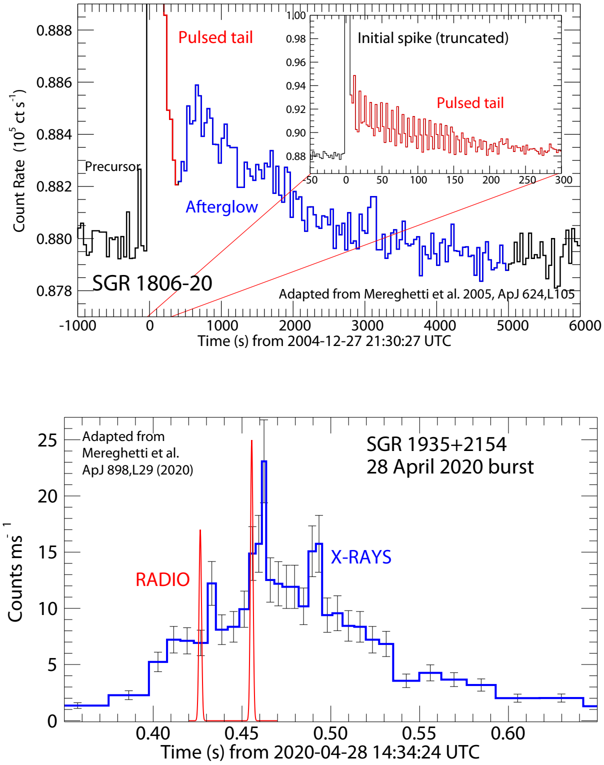

Figure 1. Top: Light curve of the 2004 giant flare from SGR 1806–20. Bottom: Light curve of the 2020 April 28 burst from SGR J1935+2154.

a spectrum peaking at ~70 keV, harder than that of the typical bursts from this and other SGRs. The IBIS light curve (Fig. 1, bottom panel) showed a broad bump, lasting ~0.7 s with superimposed narrow spikes separated by ~29 ms, the same separation of the two pulses seen at 400-800 MHz. It is thus tempting to associate the radio and X-ray pulses to the same phenomenon. Interestingly, the X-ray pulses have a delay of 6.5 ms compared to the radio ones (Mereghetti et al. 2020b).

The discovery of simultaneous bursting emission at radio and high-energies from SGR J1935+2154 gave a renewed impetus to searches for high-energy emission associated to FRBs. INTEGRAL took part in multiwavelength campaigns targeted at repeating FRBs (e.g. Pilia et al. 2020), but the large distances of these extragalactic sources hampers their detection at X/γ-rays and the current limits are not very constraining. The number of relatively close FRBs is now increasing thanks to extensive observations with new radio facilities. The repeating FRB 20200120E has recently been discovered in the M81 galaxy at a distance of only 3.6 Mpc (Bhardwaj et al. 2021). INTEGRAL has repeatedly observed the region of M81, collecting a net exposure time of about 18 Ms. A search for hard X-ray bursts from FRB 20200120E in these archival data gave negative results, but the derived limits are the best currently available in the hard X-ray range for an extragalactic FRB (Mereghetti et al. 2021). Although typical SGR-like bursts with 20–200 keV luminosity below $\sim 10^{45} \left(\frac{10\ ms}{\Delta t}\right)$ erg s^{-1} cannot be excluded (Δt is the burst duration), these limits rule out the emission of intermediate and giant flares from FRB 20200120E. Such events are quite rare in the known Galactic magnetars, but they might occur much more frequently in very young hyper-active magnetars that have been postulated in some FRB models. Note, however, that the location in a globular cluster (Kirsten et al. 2021) also suggests that FRB 20200120E is not a young object, consistently with the INTEGRAL result, and might not be representative of the bulk FRB population.

5. Long period magnetars

Most magnetars have periods in the 1-12 s range, but there are a few peculiar sources showing signs of magnetar-like activity which have significantly longer periods. One of them is the central X-ray source in the RCW 103 supernova remnant, an apparently isolated neutron star with a period of 6.7 hr (De Luca et al. 2006). Another intriguing source recently discovered in the radio band, GLEAMX J162759.5–523504.3, has been reported at this conference. In 2018 January-March it emitted radio pulses, resembling those of magnetars, with a periodicity of 1091 s (Hurley-Walker et al. 2022). INTEGRAL observed its sky location for about 20 Ms from 2003 to 2021, but a search for magnetar-like hard X-ray bursts with the same procedure used for the M81 FRB (Mereghetti et al. 2021), did not reveal any activity from this putative magnetar. For the reported distance of 1.3 kpc, the INTEGRAL limits rule out the emission of bursts with L$\gtrsim 2 \times 10^{38} \left(\frac{10\ ms}{\Delta t}\right)$ erg s^{-1}, well below the typical luminosity of SGR bursts.

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