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The *INTEGRAL* view of the pulsating hard X-ray sky: from accreting and transitional millisecond pulsars to rotation-powered pulsars and magnetars

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ABSTRACT

In the last 25 years a new generation of X-ray satellites imparted a significant leap forward in our knowledge of X-ray pulsars. The discovery of accreting and transitional millisecond pulsars proved that disk accretion can spin up a neutron star to a very high rotation speed. The detection of MeV-GeV pulsed emission from a few hundreds of rotation-powered pulsars probed particle acceleration in the outer magnetosphere, or even beyond. Also, a population of two dozens of magnetars has emerged. *INTEGRAL* played a central role to achieve these results by providing instruments with high temporal resolution up to the hard X-ray/soft, γ-ray band and a large field of view imager with good angular resolution to spot hard X-ray transients. In this article we review the main contributions by *INTEGRAL* to our understanding of the pulsating hard X-ray sky, such as the discovery and

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characterization of several accreting and transitional millisecond pulsars, the generation of the first catalog of hard X-ray/soft γ-ray rotation-powered pulsars, the detection of polarization in the hard X-ray emission from the Crab pulsar, and the discovery of persistent hard X-ray emission from several magnetars.

1. Introduction

Since 1967, the pulsar phenomenon has provided the largest share of information we have obtained so far on the properties of neutron stars (henceforth NS; Hewish et al., 1968; Pacini, 1967; Gold, 1968). By now, emission coherently modulated by the NS rotation has been observed at all wavelengths, from the radio to the very high energy domains. A few physical mechanisms can produce pulsations observed at X-ray and soft γ-ray energies covered by *INTEGRAL;* magnetically channeled accretion of matter transferred from a companion star in a binary system, spreading of the thermonuclear burning front over the NS surface resulting from the ignition of accreted matter (so-called type-I X-ray burst oscillations), pulsed emission powered by the rotation of the strong electro-magnetic field anchored to the NS surface and/or the dissipation of such a field in magnetars. Observing pulsars has been crucial to measure fundamental properties of NSs (such as masses, radii, magnetic fields) and understand their evolution (see, e.g., Ghosh, 2007).

In this chapter we review the main results achieved by the *INTEGRAL* mission (Winkler et al., 2003) on accreting and transitional millisecond pulsars, rotation-powered pulsars and magnetars. In this regard, the hard X-ray (20 keV - 1 MeV) imager IBIS/ISGRI (Ubertini et al., 2003; Lebrun et al., 2003) played a major role, as it combined a large field of view (29° × 29° with a fully coded field of 8° × 8°), fine angular resolution (12′ full-width half-maximum) and high temporal resolution (60 µs, Kuiper et al., 2003). The X-ray (3–35 keV) monitor JEM-X (Lund et al., 2003) complemented these properties providing a better angular resolution of 3′ and sensitivity to softer energies, although with a smaller field of view (the fully illuminated part is $\sim 4.8^{\circ} \times 4.8^{\circ}$-wide).

The structure of the article is the following. In Section 2 we review the *INTEGRAL* contribution to the study of accreting millisecond pulsars, Gyr-old and relatively weakly magnetized ($\simeq 10^8 - 10^9$ G) NSs that were spun-up to their current fast spin period (~ ms) by the accretion of matter transferred from a low mass companion star ($\leq M_{\odot}$). These sources also show bursts of soft X-rays caused by the thermonuclear burning of the material accreted on the surface and the *INTEGRAL* results are summarized in Section 2.5. We refer the reader to the article by Sazonov et al. for the results obtained for slower and/or non-pulsating NSs in low-mass X-ray binaries, and to the article by Kretschmar et al. for the case of X-ray pulsars in high-mass X-ray binaries, both in this volume. Section 3 describes the role played by *INTEGRAL* in discovering and characterizing transitional millisecond pulsars, a small sample of sources that are able to alternate between phases of emission as a low-mass X-ray binary and regimes characterized by radio pulsar emission. Studies of pulsars powered by the rotation of their magnetic field, including both slower ($P \sim 0.1 - 10$ s) and strongly magnetized ($B \sim 10^{11} - 10^{13}$ G) *classical* pulsars and recycled millisecond pulsars ($P \sim 1 - 10$ ms; $B \sim 10^8$ G) are presented in Section 4. Finally, *INTEGRAL* observations of NSs powered by the dissipation of their intense ($B \sim 10^{13} - 10^{14}$ G) magnetic field (so-called magnetars) are summarized in Section 5.

2. Accreting millisecond pulsars

Accreting millisecond pulsars (AMSPs in the following) are NSs that transiently accrete the plasma captured from a low-mass companion star ($M_2 \leq M_{\odot}$) via Roche-lobe overflow (Wijnands and van der Klis, 1998; see Patruno and Watts, 2012; Campana and Di Salvo, 2018; Di Salvo and Sanna 2020 for reviews). Their magnetic field ($B_p \simeq 10^8 - 10^9$ G) is strong enough to truncate the disk in-flow before the plasma reaches the surface of the NS. The in-falling matter is then channeled by the magnetic field of the NS to the magnetic polar regions of the NS surface. As long as the magnetic and spin axes are misaligned and the emission beam crosses the line of sight, this produces coherent pulsations mainly observed in the X-ray domain.

The spin periods of AMSPs range between 1.6 and ~ 10 ms. According to the recycling evolutionary model (Bisnovatyi-Kogan and Komberg, 1974; Alpar et al., 1982; Radhakrishnan and Srinivasan, 1982), such an extremely quick rotation is achieved during a prolonged ($\approx 0.1 - 1$ Gyr) X-ray bright phase of accretion of matter lost by a low-mass companion star. The ~ 300 millisecond radio pulsars known to date are then assumed to be the descendants of low mass X-ray binaries (LMXBs in the following). In these systems, a radio pulsar turns on as soon as the pressure of the pulsar wind inhibits the in-fall of matter lost by the companion and accretion ceases (see also Section 3).

So far, AMSPs have been found in binaries hosting either a main sequence star ($M_2 \sim 0.1 - 0.5$ M$_{\odot}$, $P_{orb} \approx$ a few hours), a brown dwarf

Table 1
AMSPs observed by *INTEGRAL*.

Source	P_{spin} (ms)	P_{orb} (hr)	Outburst year	References
INTEGRAL sources				
IGR J00291 + 5934	1.7	2.46	2004, ’15	Shaw et al. (2005); Falanga et al. (2005b); De Falco et al. (2017b)
IGR J17511–3057	4.1	3.47	2009	Falanga et al. (2011)
IGR J17498–2921	2.5	3.84	2011	Falanga et al. (2012)
IGR J17480–2446	90	21.3	2011	Bordas et al. (2010); Ferrigno et al. (2010); Strohmayer and Markwardt (2010); Papitto et al. (2011)
IGR J18245–2452	3.9	11.0	2013	Papitto et al. (2013); Ferrigno et al. (2014); De Falco et al. (2017a)
IGR J17062–6143	6.1	> 0.3	2008	Strohmayer and Keek (2017)
IGR J16597–3704	9.5	0.77	2017	Sanna et al. (2018a)
IGR J17379–3747	2.1	1.88	2018	Sanna et al. (2018b); Strohmayer et al. (2018)
IGR J17591–2342	1.9	8.80	2018	Sanna et al. (2018c)
Other sources				
SAX J1808.4–3658	2.5	2.01	2008, ’15, ’19	Del Santo et al. (2015); Patruno et al. (2017b); Ferrigno et al. (2019)
XTE J1751–305	2.3	0.71	2005, ’07, ’09	Grebenev et al. (2005); Falanga et al. (2007b); Chenevez et al. (2009)
XTE J1807–294	5.3	0.67	2003	Falanga et al. (2005a)
HETE 1900.1–2455	2.7	1.39	2005	Falanga et al. (2007a)
SAX J1748.9–2021	2.3	8.77	2015, ’17	Kuulkers et al. (2015); Li et al. (2018); Di Gesu et al. (2017)
Swift J1749.4–2807	1.9	8.82	2010	Pavan et al. (2010); Chenevez et al. (2010); Ferrigno et al. (2011)
MAXI J0911–655	2.9	0.74	2016	Sanna et al. (2017a); Bozzo et al. (2016); Ducci et al. (2016)

($M_2 \approx 0.05$ M$_\odot$, $P_{orb} \simeq 1-2$ h) or a white dwarf ($M_2 \approx 0.01$ M$_\odot$, $P_{orb} \simeq 40$ min). These binary characteristics are similar to those of millisecond radio pulsars whose signal is irregularly eclipsed by matter ejected by the pulsar wind and engulfing the binary system. These eclipsing radio pulsars are dubbed either black widow ($M_2 \leq 0.05$ M$_\odot$, Fruchter et al., 1988; Draghis et al., 2019) or redback pulsars ($M_2 \simeq 0.1$–1 M$_\odot$, D'Amico et al., 2001; Strader et al., 2019) depending on the mass of the companion star, and are generally considered to share a close evolutionary link with AMSPs (Kluzniak et al., 1988; van den Heuvel and van Paradijs, 1988; Ruderman et al., 1989).

Discovering AMSPs and measuring their spin evolution is crucial to understand what is the maximum spin that can be reached by a NS through accretion. In turn, this indirectly probes whether continuous gravitational-wave spin-down torques are required to limit the accretion driven spin up to the minimum observed period of a millisecond pulsar, ≈ 1.5 ms (Chakrabarty, 2008; Papitto et al., 2014b; Patruno et al., 2017a; Bhattacharyya and Chakrabarty, 2017). The X-ray pulsed emission of AMSPs is emitted close to the surface of a rapidly rotating object that attains a speed of up to $\approx 15\%$ of the speed of light at the equator. General and special relativity effects shape the energy and trajectory of X-ray photons in a way that can be disentangled through X-ray pulse profile fitting. This makes AMSPs among the best candidates to measure simultaneously the mass and radius of a NS and draw constraints on its equation of state (Poutanen and Gierliński, 2003; see also Watts et al., 2016 for a recent review).

2.1. Discovery and follow-up of AMSPs with INTEGRAL

The two dozens of AMSPs discovered so far are all X-ray transients. They undergo a few weeks-long X-ray outbursts and spend most of the time in quiescence, although episodes of X-ray activity lasting up to a few years have also been observed. Recurrence times range from a few months to more than 15 years, for sources which have been observed only once, so far. During outbursts, the mass accretion rate rarely exceeds a few per cent of the Eddington rate ($L_X \approx 10^{36} - 10^{37}$ erg s^{-1}), whereas in quiescence the luminosity is much lower ($L_X \leq 10^{32}$ erg s^{-1}). The discovery of new systems of this class requires instruments with a large field of view and a good sensitivity.

The instruments on-board *INTEGRAL* perfectly satisfy these requirements. They managed to discover the X-ray outbursts of eight sources that were later identified as AMSPs (out of a total of 22; see Table 1, Falanga et al. (2013) and references therein), and to study their X-ray emission from the onset of the outbursts nearly down to the return in quiescence. Since the launch of *INTEGRAL* the large field of view of the IBIS/ISGRI imager has been exploited to monitor regularly the Galactic bulge (Kuulkers et al., 2005; 2007), where most of the transient LMXBs are expected. The highly eccentric long orbit and the special pointing strategy adopted by *INTEGRAL* allowed IBIS/ISGRI to accumulate several thousands of kiloseconds of observations in each monitored region, with a few-hours long uninterrupted coverage, and achieve a hard (20–200 keV) X-ray flux sensitivity as low as a few $\times\ 10^{-11}$ erg cm^{-2} s^{-1} even in crowded regions. For a distance between 5–8 kpc, this limiting sensitivity corresponds to a luminosity of $\approx 10^{35}$ erg s^{-1}, which is usually reached by AMSPs already during the earliest stages of their outbursts, and attained again towards the end of the outbursts before the switch back to quiescence. IBIS/ISGRI observations were also often complemented by data in the soft band covered by JEM-X at similar sensitivity.

These features, complemented by the good angular resolution of the two instruments, proved crucial to discover AMSPs and disentangle

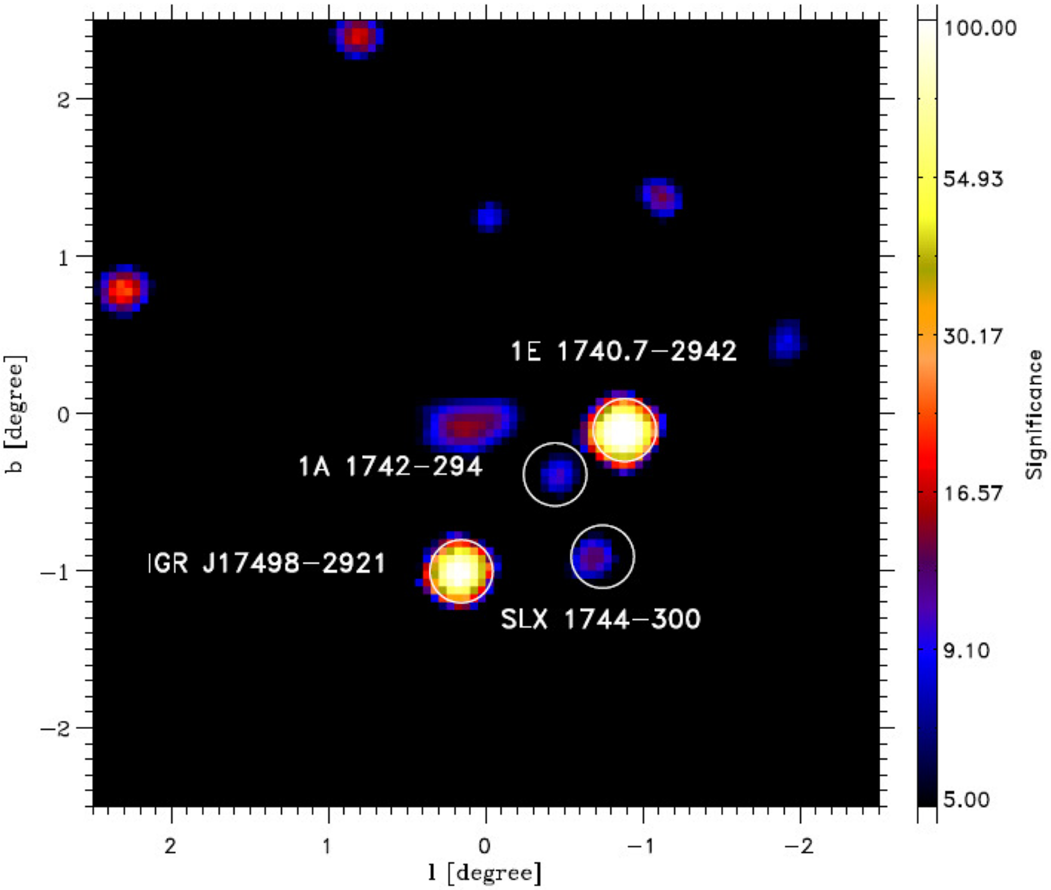

Fig. 1. IBIS/ISGRI 20–100 keV sky image of the field around IGR J17498–2921 obtained during observations performed at the time of the source discovery in 2011, giving an effective exposure of 210 ks. Credit: Falanga et al., A&A, 545, A26 (2012), reproduced with permission © ESO.

their emission from foreground sources (see Fig. 1). These imaging capabilities were particularly important to identify IGR J00291 + 5934, which is located only $\sim 18'$ from the close-by persistent intermediate polar V609 Cas (Falanga et al., 2005b), and IGR J17511–3057, which is located only $\sim 20'$ away from the other AMSP XTE J1751–305 and whose discovery outburst was partly contaminated by a faint activity episode of the latter source (Falanga et al., 2011, see Fig. 2). The good angular resolution of IBIS/ISGRI and JEM-X has also proven fundamental to clearly distinguish the type-I X-ray bursts emitted by the AMSP IGR J17498–2921 from those going off in the nearby bursters SLX 1744–300/299 and 1A 1742–294, located at 0.9° and 0.86°, respectively, from the AMSP (Falanga et al., 2012). In 2010 *INTEGRAL* also discovered the LMXB IGR J17480–2446 in the globular cluster Terzan 5 (Bordas et al., 2010; Ferrigno et al., 2010). The source was subsequently identified as a 90 ms pulsar (Strohmayer and Markwardt, 2010) orbiting a low-mass companion star in a 21 hr orbit (Papitto et al., 2011, see Section 2.5 for details).

INTEGRAL observations have also been extensively carried out to follow up AMSPs first detected by other facilities and which underwent one or multiple outbursts since the beginning of the mission science operations in 2002. In a few cases (e.g. XTE J1751–305, SAX J1748.9–2021, SAX J1808.4–3658), the *INTEGRAL* seasonal pointings toward the Galactic bulge detected the onset of some of the outbursts of AMSPs already discovered. The LMXB nature of Swift J1749.4–2807 was first established during its 2010 outburst announced by *INTEGRAL* (Pavan et al., 2010; Chenevez et al., 2010); the source was later indentified as a 1.9 ms AMSP which showed 1.7 ks-long X-ray eclipses (see, e.g., Ferrigno et al., 2011; Altamirano et al., 2011), making it the first and only eclipsing AMSP discovered so far, with important consequences for the determination of the NS mass and radius (Jonker et al., 2013). The first outburst of MAXI J0911–655, was also observed by *INTEGRAL* (Sanna et al., 2017a; Bozzo et al., 2016; Ducci et al., 2016), which also provided a long term monitoring of the source reporting on the discovery of significant hard X-ray emission more than 450 days after the onset of the event (Victor et al., 2017).

2.2. The X-ray light curves

IBIS/ISGRI and JEM-X provided long term monitoring data with high cadence which have been important to extract light curves of AMSP outbursts and identify the physical mechanisms driving the outburst onset and decay. The observed light curves were generally characterized by a fast rise (a few days) and an exponential decay (up to several weeks) which terminated with a break followed by a linear decay extending down to the limiting observable flux for both IBIS/ISGRI and JEM-X (see Fig. 2). This behaviour has been commonly interpreted in terms of the disk instability model, in which the irradiation of the accretion disk by the central X-ray source plays a key role in the shaping of the light curve profile (King and Ritter, 1998). Modelling of the light-curves observed by the *Rossi X-ray Timing Explorer* (*RXTE*, Bradt et al., 1993) showed that the timescale of the decay and its luminosity at a characteristic time are linked to the outer radius of the accretion disk (Powell et al., 2007). The break observed during the X-ray flux decay at the end of the outburst is thought to be associated with the lowest X-ray luminosity at which the outer disk region can be kept in a hot high-viscosity state by the centrally illuminating source. When the outer disk region enters the cool low-viscosity state, the mass accretion rate onto the compact object is effectively cut-off and the source starts its return to quiescence. The application of this model to the *INTEGRAL* data gave compatible results (Falanga et al., 2005b; 2011; 2012; Ferrigno et al., 2011).

So far, only IGR J00291 + 5934 has shown a double-peaked outburst (Lewis et al., 2010; Hartman et al., 2011), while a few other AMSPs have undergone “re-flares” toward the later stages of the return to quiescence. The mechanism(s) driving these re-brightening episodes is still a matter of debate (see, e.g., Patruno et al., 2016; Bult et al., 2019, and references therein). The typical luminosity at which the re-flares occur is close to the detection limit for both IBIS/ISGRI and JEM-X and thus these events are hardly observable by *INTEGRAL*.

2.3. The hard X-ray spectra of AMSPs

The spectra of AMSPs in outburst measured by *INTEGRAL* are typically hard and dominated by a power law $dN/dE \propto E^{-\Gamma}$, with photon index $\Gamma \sim 2$, extending up to 100 keV or beyond (Poutanen, 2006). Most likely, these hard X-ray photons originate from the accretion columns above the polar caps, where electrons energized by the shock between the in-falling plasma and the NS surface up-scatter the surface soft photons to higher energies (Gierliński et al., 2002; Gierliński and Poutanen, 2005). In most cases, the combined IBIS/ISGRI + JEM-X spectra could be well fit with a thermal Comptonization model compps (Poutanen and Svensson, 1996) in the slab geometry assumed for the accretion columns (Falanga et al., 2005b; 2011; 2012; 2005a; 2007a; Ferrigno et al., 2011). The main model parameters are the Thomson optical depth $\tau_T \sim 1 - 3$ across the slab, the electron temperature $kT_e \sim 25 - 50$ keV, the temperature $kT_{bb} \sim 0.3 - 1.0$ keV of the soft-seed blackbody photons (assumed to be injected from the bottom of the slab), and the emission area $A_{bb} \sim 20$ km^2. Fig. 3 shows a typical broad-band AMSP spectrum observed during the decay of an outburst, fitted with a compps model. The spectrum observed during an outburst of the transitional millisecond pulsars IGR J18245–2452 is instead significantly harder, with a photon index $\Gamma \sim 1.3$ and seed photons coming from a larger region and characterized by a lower temperature (De Falco et al., 2017a, see Section 3.1). *INTEGRAL* observations of Aql X-1, which has been detected as an AMSP only for a couple of minutes (Casella et al., 2008), also caught the source in a state characterized by a very hard spectrum extending up to 150 keV (Rodriguez et al., 2006).

The spectra of several *INTEGRAL*-detected AMSPs have been also observed by using combined *INTEGRAL* and (quasi-)simultaneous *XMM-Newton* (Jansen et al., 2001) and *NuSTAR* (Harrison et al., 2013) observations. Although they have been clearly found to be dominated by hard power-law components, typically ascribed to the Comptonization of seed thermal photons in agreement with previous *INTEGRAL* results, the extension into the soft X-ray regime frequently revealed the presence of a additional thermal components originating from hot spots on the NS surface or from the inner disk boundary. In addition, a broad iron line produced by the reflection of the X-ray photons onto the inner

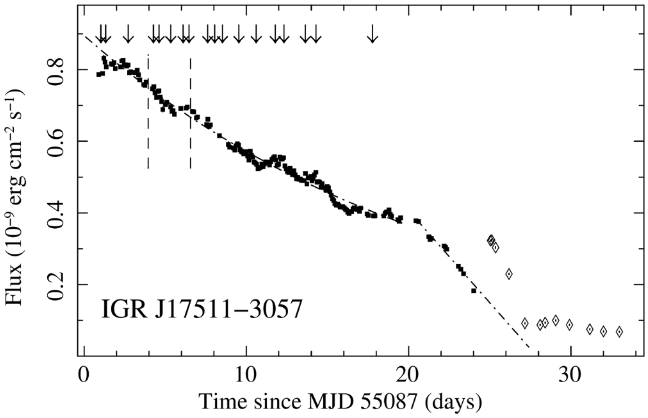

Fig. 2. The light curve of the outburst of IGR J17511–3057 observed in 2009. The typical exponential decay profile is clearly visible, with a break occurring about 20 days after the onset of the event. The light curve is obtained from the *RXTE*/PCA (2 - 20 keV) data, with the vertical dashed lines indicating the interval of the *INTEGRAL* observations. The arrows mark the times of the detected X-ray bursts. The diamonds refer to the observations in which both IGR J17511–3057 and XTE J1751–305 were active and the instruments on-board *RXTE* were unable to separate the contribution of the two sources. Credit: Falanga et al., A&A, 529, A68 (2011), reproduced with permission © ESO.

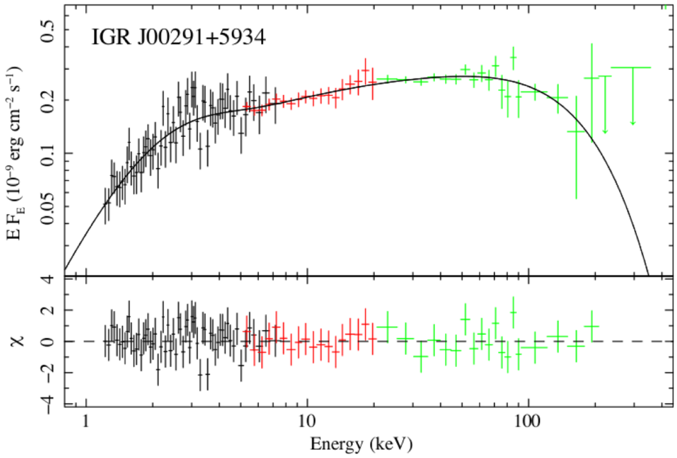

Fig. 3. The unfolded broad-band spectrum of the AMSP IGR J00291 + 5934 measured by JEM-X (red points) and IBIS/ISGRI (green points) during an outburst exhibited in 2015. *Swift*/XRT data were also used for the analysis and are shown as black points. The best fit is obtained with the COMPPS model (solid black line), resulting in a plasma temperature of $kT \sim 50$ keV. The bottom panel shows the residuals from the best fit. Credit: De Falco et al., A&A, 599, A88 (2017), reproduced with permission © ESO (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

regions of the accretion disk surrounding the compact object was sometimes also observed (Papitto et al., 2009; Cackett et al., 2009; Sanna et al., 2017b; 2018c; Di Salvo et al., 2019). In at least one case, high spectral resolution observations carried out with the gratings onboard *Chandra* were able also to detect outflows from the outer regions of the accretion disk (Nowak et al., 2019), and to provide hints of an expanding hot corona with high outflow velocities also in the case of IGR J00291 + 0034 (Paizis et al., 2005).

Little spectral variability, if any, has been generally observed during the course of an outburst. SAX J1748.9–2021 in the globular cluster NGC 6440 clearly made an exception. It has been observed to switch between hard and soft spectra (Patruno et al., 2009) such as occurs in the so-called “Atoll” sources (Hasinger and van der Klis, 1989). The combined extensive monitoring performed with IBIS/ISGRI and JEM-X during the source outburst in 2015 was able to efficiently catch one of these spectral state changes (Li et al., 2018; see Fig. 4); a dramatic transition from a hard to a soft state state occurred over roughly half a day, about ten days after the onset of the outburst. In that outburst the source reached a peak luminosity of about 5×10^{37} erg s^{-1}, a value higher than usually observed from AMSPs. After the state change, the spectrum observed with *XMM-Newton* appeared to be very soft with a Comptonization electron temperature around 2 keV (Pintore et al., 2016). The (quasi) simultaneous spectrum observed with *INTEGRAL* also revealed the presence of a hard power-law component with a photon index of 2.3. Similar hard tails are often observed in Z-sources

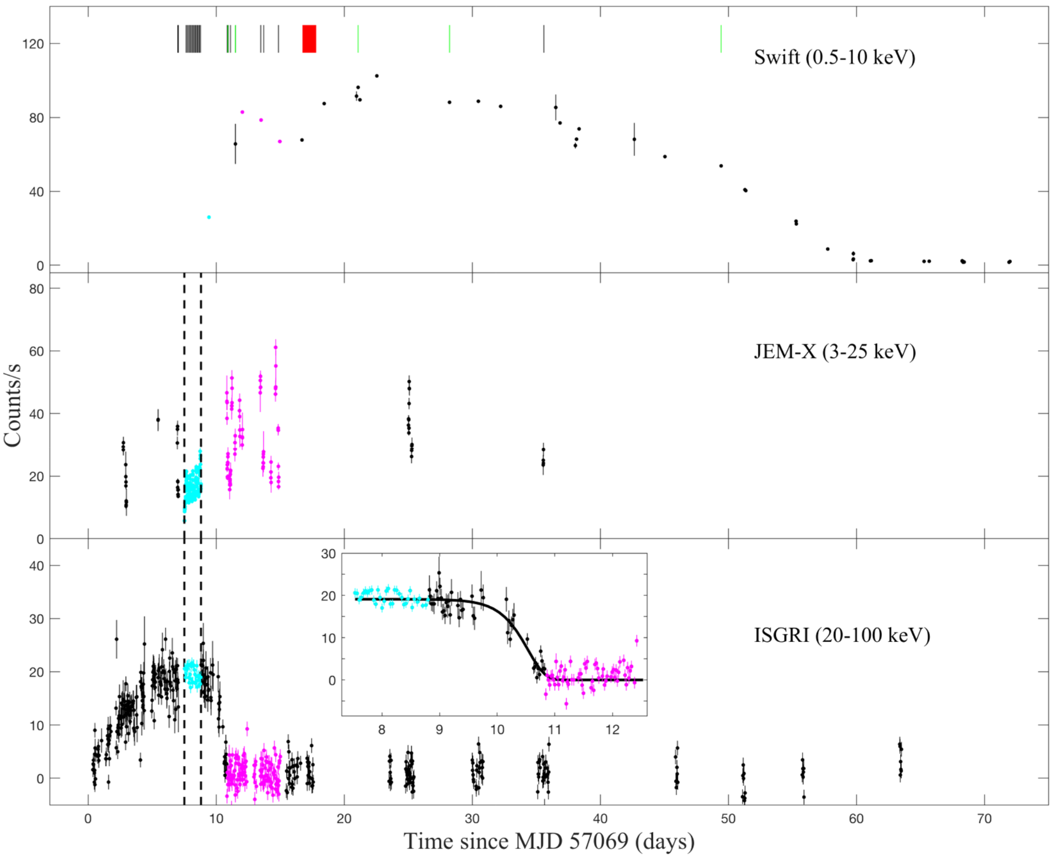

Fig. 4. The light curve from the 2015 outburst of the AMSP SAX J1748.9–2021. The top panel shows data collected with *Swift*/XRT, while the two panels below report the JEM-X and IBIS/ISGRI data. The spectral transition from hard (light blue) to soft (magneta) state is clearly visible in the *INTEGRAL* data (see the inset of the bottom panel). The figure also shows the time of a dedicated 100 ks-long *INTEGRAL* ToO observation (marked with vertical dashed lines) and all the thermonuclear bursts recorded during the outburst with *INTEGRAL, Swift*, and *XMM-Newton* (black, green, and red vertical lines, respectively). Credit: Li et al., A&A, 620, A114 (2018), reproduced with permission © ESO (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

(see e.g. the *INTEGRAL* spectrum of Sco X-1, Di Salvo et al. (2006); Revnivtsev et al. (2014)) and atoll sources in the soft state (see e.g. the IBIS/ISGRI spectrum of GX 13+1 (Paizis et al., 2006), and the *XMM-Newton/INTEGRAL* spectrum of GX 3+1 (Pintore et al., 2015) and are interpreted in terms of Comptonization of photons off electrons with a non-thermal distribution of velocity. This non-thermal component may be related to high energy electrons injected in the Comptonization region by a (failed?) jet or powered by magnetic reconnections close to the accretion disk. During the outburst occurred in October 2017, SAX J1748.9–2021 showed instead a *standard* outburst X-ray luminosity of 3×10^{36} erg s^{-1} and a more common hard spectrum (photon index $\Gamma \sim 1.6 - 1.7$, and electron temperature of 20 keV, Pintore et al., 2018). This demonstrates the importance of a high-energy monitor such as *INTEGRAL* for addressing the spectral state of these sources and individuate peculiar ones.

2.4. *The hard X-ray pulse profiles*

AMSPs are relatively faint X-ray transients and the amplitude of their pulsations is ≤ 10 per cent, (Patruno and Watts, 2012). For this reason, usually X-ray pulsations could not be discovered independently by *INTEGRAL* without a previous detection by a large area focusing or collimated instruments, as those on-board *RXTE, XMM-Newton*, and more recently *NuSTAR* and *The Neutron Star Interior Composition Explorer Mission* (*NICER*, Arzoumanian et al., 2014). Only during the 2015 outburst of IGR J00291+5934, did *INTEGRAL* data statistics reach a sufficient level to measure the pulsar ephemeris directly from the IBIS/ISGRI event files (Kuiper et al., 2015), obtaining parameters compatible with those derived by *RXTE*. Once the spin and orbital parameters of an AMSP were provided, the *INTEGRAL* data could be folded to increase the signal-to-noise ratio and carry out a pulse timing analysis in a very broad energy range, covering up to a few hundreds of keV. In this way, IBIS/ISGRI detected X-ray pulsations up to 150 keV from IGR J00291+5934 (Falanga et al., 2005b), IGR J17511–3057 (Falanga et al., 2011), IGR J17498–2921 (Falanga et al., 2012), and IGR J18245–2452 (De Falco et al., 2017a), while an accurate analysis of the data has not been published yet for recently discovered IGR AMSPs, such as IGR J16597–3704, IGR J17379–3747, IGR J17591–342 and IGR J17062–6143 (Kuiper et al., in prep.). The measurements obtained by IBIS/ISGRI permitted to perform an analysis of the pulsed fractions in a hard ($>$ 20 keV) X-ray domain previously poorly covered by other instruments. Different trends were observed from source to source. IGR J17511–3057, IGR J17498–2921 and IGR J18245–2452 showed a constant, or slightly decreasing pulsed fraction above 10 keV, compatible with the results obtained by *RXTE* for SAX J1808.4–3658 and XTE J1751–305 (see left panels of Fig. 5 labelled as (b) and (c); see Falanga and Titarchuk, 2007 and references therein). A decrease of the pulsed fraction at high energies has been explained in the context of the two pulsed components assumed to originate from the hot-spot on the NS surface and from the accretion column above the poles (Gierliński et al., 2002; Gierliński and Poutanen, 2005, see Section 2.3). The soft blackbody radiation from the hot-spots is more beamed along the axis than the hard photons produced by Compton up-scattering in the accretion columns, naturally accounting for the lower pulsed fraction observed at higher energies (Poutanen and Gierliński, 2003). On the other hand, a clear increase of the pulsed fraction with energy above $\sim$ 50 keV was observed from IGR J00291+5934 (see left panel labelled as (a) in Fig. 5). Embedding of the accretion columns in a Compton cloud was proposed to explain this (Falanga and Titarchuk, 2007). In fact, the electron cross section and the resulting Compton optical depth decrease at high energies, allowing a larger fraction of the pulsed harder X-rays to reach the observer un-scattered. Note that a trend of increasing pulsed fraction with energy, albeit already at softer X-rays, was observed by other missions (e.g., *RXTE, XMM-Newton* and *NuSTAR*) also from SAX J1748.9–2021 (Patruno et al., 2009; Sanna et al., 2016), Swift J1756.9–2508 (Patruno et al., 2010; Sanna et al., 2018d) and, to a lesser extent, Swift J1749.4–2807 (Ferrigno et al., 2011).

INTEGRAL crucially contributed also to reveal the complex dependence of time lags of pulsed photons with energy (see right panel of Fig. 5, taken from Falanga and Titarchuk (2007)). The measured soft

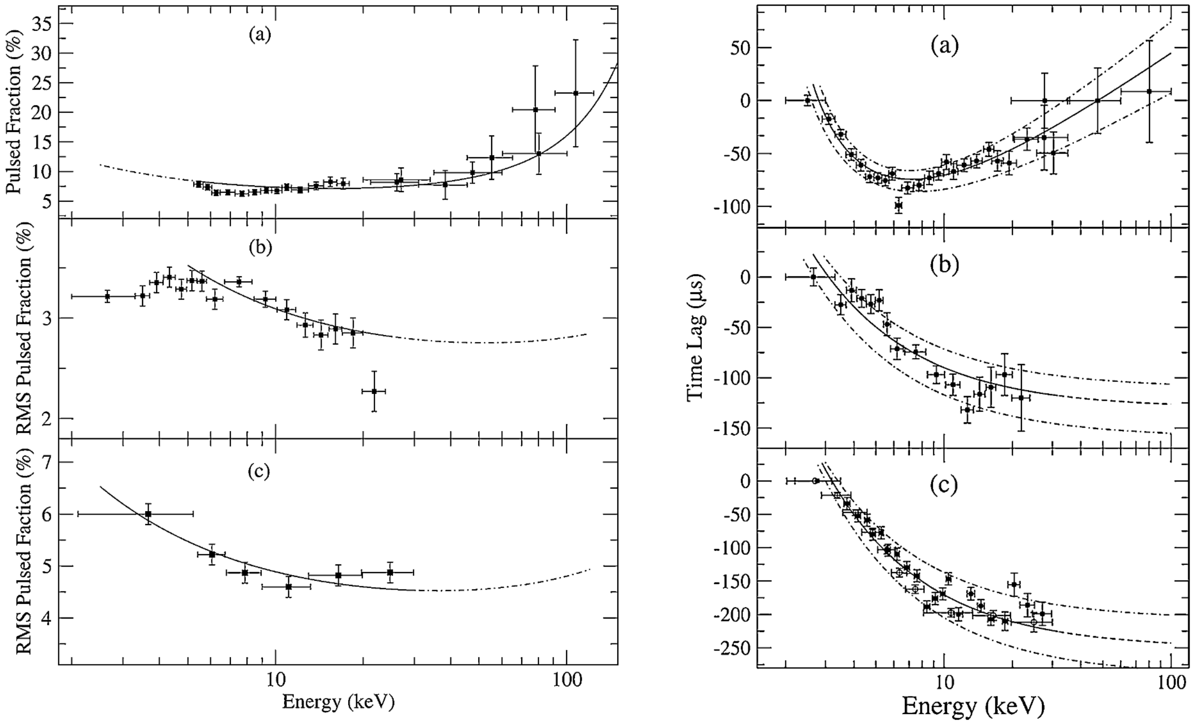

Fig. 5. The pulsed fraction (panel (a), left) and the time lags of the hard pulse (panel (a), right) measured during the 2005 outburst of the AMSP IGR J00291+5934 using data from the *RXTE*/PCA, *RXTE*/HEXTE, *INTEGRAL*/JEM-X, and *INTEGRAL* IBIS/ISGRI. Panel (b) and (c) show the same quantities for SAX J1808.4–3658 and XTE J1751–305, as measured by *RXTE*. (Credit: Falanga & Titarchuk, ApJ, 661, 2 (2007), reproduced with permission of the AAS).

lags mean that the low-energy pulses are delayed relative to the pulses seen at higher energies. Below ~ 10 keV, the soft photons generally lag the hard photons, although the opposite behavior was observed during an outburst of the transitional millisecond pulsar IGR J18245–2452 (see Section 3.1). The observed soft phase/time lags were explained either in terms of down-scattering of hard photons emitted in the accretion columns by the colder surrounding plasma (Falanga and Titarchuk, 2007; Cui et al., 1998; Titarchuk et al., 2002) or by the broader emission pattern of hard photons Comptonized in the accretion columns with respect to soft photons emitted from the NS hot spots, which make harder photons to be seen before the softer ones as the NS rotates (Poutanen and Gierliński, 2003; Gierliński and Poutanen, 2005; Ibragimov and Poutanen, 2009). Above an energy of 6 keV, the dependence of the lags observed from IGR J00291 + 5934 reverses, and the harder photons (~ 100 keV) arrive later than the softer (~ 10-20 keV) ones. In the Comptonization scenario this is explained by the fact that higher energy photons were up-scattered more times and took longer to reach the observer (see, e.g., Falanga et al., 2012; Falanga and Titarchuk, 2007; Falanga et al., 2011, and references therein).

2.5. Thermonuclear type-I X-ray bursts

The *INTEGRAL* observing strategy generally implies a few-day long observations toward a pre-defined region of the sky. The *INTEGRAL* monitoring programs aimed at the Galactic bulge, as well as dedicated observational campaigns devoted to specific sources, often offered nearly uninterrupted light curves of all sources in the field and covering a significantly larger fraction of the outbursts of AMSPs with respect to other telescopes. These light curves were particularly useful to search for thermonuclear type-I X-ray bursts and accurately constrain their recurrence time as a function of the mass accretion rate ($\dot{m}$) inferred from the observed non-burst X-ray flux (Lewin et al., 1993). Fig. 6 shows an example of a particularly intense burst observed by *INTEGRAL* from the AMSP HETE J1900.1–2455 (Falanga et al., 2007a), during which the double peaked profile in the IBIS/ISGRI data proved that a photospheric radius expansion took place (see, e.g., Galloway and Keek, 2017, for a recent review). On the other hand, the light curves of most of the thermonuclear bursts shown by the AMSPs observed by *INTEGRAL* were characterized by a fast rise and an exponential decay lasting a few tens of seconds. Such short burst profiles indicate that the ignition most likely occured in presence of hydrogen-poor material, suggesting that either the accreted material is hydrogen-deficient or that the CNO abundances in AMSPs was slightly higher than the solar value (see, e.g., De Falco et al., 2017b; Falanga et al., 2011; 2012; De Falco et al., 2017a; Falanga et al., 2007a; Li et al., 2018; Ferrigno et al., 2011). In the case of IGR J17511–3057, this suggestion could be strengthened by the fact that the variation of the burst recurrence time as a function of $\dot{m}$ (see Fig. 7) was found to be much shorter than that predicted in case of helium-ignition models (Falanga et al., 2011).

Among the many thermonuclear bursts observed by *INTEGRAL* from the more than a hundred of bursting sources known (see, e.g., Chelovekov et al., 2017, for a recent catalogue of the bursts observed by JEM-X), it is worth mentioning here the peculiar case of IGR J17480–2446. This source is located in the Globular Cluster Terzan 5 and underwent so far a single bright detectable outburst in 2010 (Bordas et al., 2010) which displayed a number of remarkable unique features. First of all, pulsations were clearly detected at a spin period of about 91 ms, making this a unique source linking AMSPs and slower spinning pulsars in LMXBs (Strohmayer and Markwardt, 2010; Papitto et al., 2011; 2012; Testa et al., 2012). Evolutionary calculations suggested that this binary system might have formed through a close encounter between the NS and its companion within the globular cluster, and that the compact object is only a mildly recycled pulsar as accretion did not begin earlier than a few 10^7 yr ago (Patruno et al., 2012). Furthermore, the source showed several hundreds of thermonuclear bursts along the outburst. The recurrence time markedly decreased during the rising part of the outburst (Motta et al., 2011; Linares et al., 2012; see Fig. 8). Close to the outburst peak the frequency of the bursts became so high and their peak flux so close to the level of the persistent emission that they could no longer be identified by visual inspection in the source light curve (Motta et al., 2011; Altamirano et al., 2012; see Fig. 8), but rather emerged as mHz quasi periodic oscillations in the Fourier power density spectrum (Revnivtsev et al., 2001). A careful analysis of the spectral softening of the emission during the burst decay proved unequivocally that they had all a thermonuclear origin (Motta et al., 2011; Linares et al., 2011; Chakraborty et al., 2011). Although a decrease of the recurrence time with increasing mass accretion rate had been theoretically anticipated (Heger et al., 2007), this was the first time that it was observed in an LMXB in such great detail. This made IGR J17480–2446 a unique laboratory to test thermonuclear burning models. All the thermonuclear bursts also displayed burst oscillations at a frequency within a few per cent of the spin rotation of the NS, proving for the first time that millisecond rotational velocities are not required to produce these kind of timing features and ruling out models based on this assumption (Cavecchi et al., 2011). IGR J17480–2446 also displayed a clear evidence of a fast-moving disk wind with ejection velocity up to ~ 3000 km s^{-1}, a rare feature in NSs hosted in LMXB and much more common in systems harboring accreting BHs (Miller et al., 2011). In addition, the source endured an extremely high level of crustal heating during the outburst, which did not seem to have cooled completely even 5.5 years since the end of the outburst (Degenaar et al., 2011; 2013; Ootes et al., 2019).

Peculiar burst properties have also been observed from SAX J1748.9–2021. The burst recurrence time drastically decreased from ≈ 2 to ≈ 1 hr as the source underwent an abrupt hard-to-soft state spectral transition (Li et al., 2018, see Fig. 4). The relation between the burst recurrence time and the mass accretion rate indicated that in both

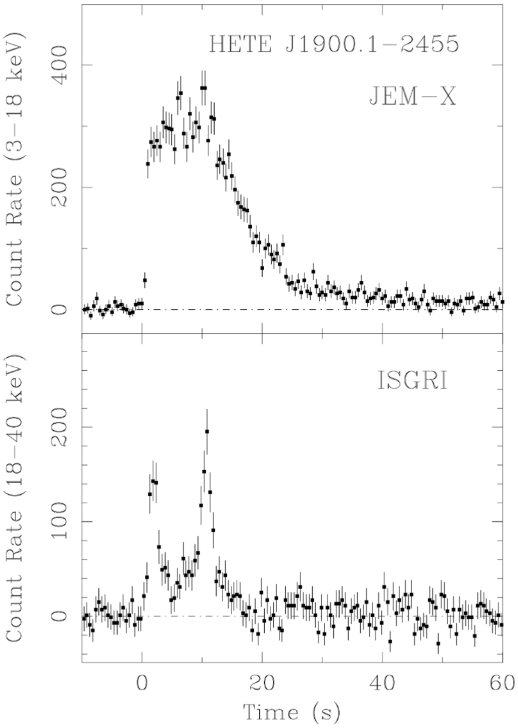

Fig. 6. An intense type-I X-ray burst observed by JEM-X and IBIS/ISGRI from the AMSP HETE J1900.1–2455 during its outburst in 2005. The upper panel shows the JEM-X light curve (3–18 keV), while the lower panel shows the IBIS/ISGRI light curve (18–40 keV). The double peaked IBIS/ISGRI light curves clearly show the presence of a photospheric radius expansion. Credit: Falanga et al., A&A, 464, 1069-1074 (2007), reproduced with permission © ESO.

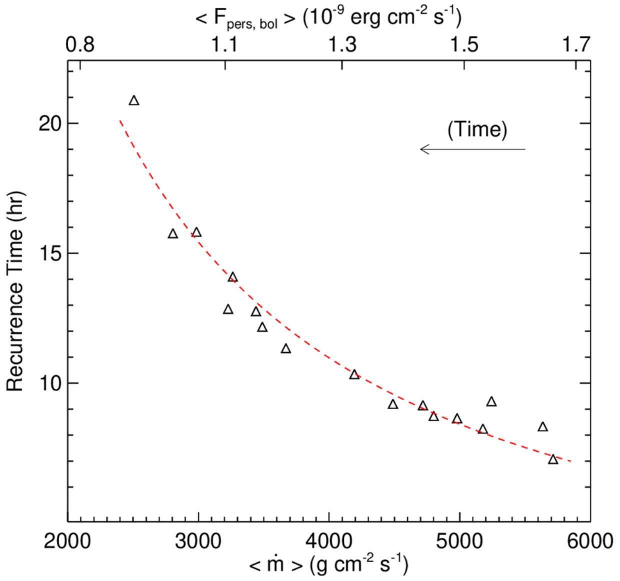

Fig. 7. An example of the study of the burst recurrence time in the AMSP IGR J17511–3057 during its 2010 outburst. Triangles in the figure represent the observed burst recurrence times shown as a function of the mass accretion rate per unit area. By using a fit to the data with a power-law model, the recurrence time is found to increase with time roughly as $\langle F_{\rm pers,bol}\rangle^{-1.1}$ Credit: Falanga et al., A&A, 529, A68 (2011), reproduced with permission © ESO.

states the bursts were consistent with being produced by a mixture of H and He.

INTEGRAL observations of thermonuclear type-I X-ray bursts from LMXBs also played an important role in the study of the properties of the X-ray coronae from the effect of the burst emission on the surrounding accretion flow (see Degenaar et al., 2018 and references therein). Stacking of 123 bursts observed by *INTEGRAL* from the persistent LMXB 4U 1728–34 revealed a deficit of hard 40–80 keV photons compared to the persistent emission due to the enhanced corona cooling caused by the soft burst photons (Kajava et al., 2017); such a deficit had not been detected before by *RXTE* (Ji et al., 2014), possibly due to the different response and background contamination. The reader is referred to the article by Sazonov et al. in this volume for more details on bursts of LMXBs.

3. Transitional millisecond pulsars

According to the classical recycling picture (Bisnovatyi-Kogan and Komberg, 1974; Alpar et al., 1982; Radhakrishnan and Srinivasan, 1982), the switch on of a millisecond radio pulsar powered by the rotation of its magnetic field should occur only after the Gyr-long mass accretion phase in a LMXB has ceased and the pulsar wind pressure becomes dominant. However, the possibility that a source could swing between a radio pulsar behaviour and a LMXB regime also over much shorter timescales (days to weeks) had been proposed already a few years before AMSPs were actually discovered (Stella et al., 1994; Campana et al., 1998; Burderi et al., 2001). When the X-ray luminosity of a transient LMXB drops below 10^{32} erg s^{-1} at the end of an outburst, the magnetospheric radius of a $\sim 10^8$ G NS spinning at a period of a few milliseconds expands beyond the light cylinder radius of the pulsar, $r_{LC} = 71.6(P_s/1.5\ \text{ms})$ km, where P_s is the pulsar spin period. A radio pulsar powered by the rotation of its magnetic field could then eject the residual disk matter and power the emission of the binary in quiescence. The discovery that AMSPs were weakly magnetized X-ray transients which dropped to an X-ray luminosity of $10^{31} - 10^{32}$ erg s^{-1} during quiescence (see Section 2.2) was compatible with such a picture (Campana et al., 2002). Furthermore, the optical luminosity of quiescent AMSPs turned out to be too large to be compatible with reprocessing of such a faint X-ray emission, suggesting it was instead due to reprocessing of the more powerful spin-down energy (Burderi et al., 2003). The rate at which AMSPs spin down during quiescence (Hartman et al., 2008) and the fast and complex orbital evolution (Hartman et al., 2008; di Salvo et al., 2008) were also very similar to those observed from the so-called redback millisecond radio pulsars (Strader et al., 2019; Roberts, 2013). However, deep searches for radio pulsations from AMSPs in quiescence were not successful, even when conducted at high radio frequencies (5 and 8 GHz) at which free-free absorption is less important (Patruno et al., 2017b; Burgay et al., 2003; Iacolina et al., 2010).

The quest for sources switching back and forth between a radio pulsar and an accretion powered phase finally succeded when the radio pulsar PSR J1023 + 0038 showed indications of a past accretion disk activity (Archibald et al., 2009), and eventually with the discovery of IGR J18245–2452, an AMSP that is detected as a radio pulsar during quiescence (Papitto et al., 2013). Dubbed *transitional* millisecond pulsars (see Campana and Di Salvo, 2018 and Papitto and de Martino, 2020, for reviews), these sources are crucial to investigate how the interaction between the NS magnetosphere and the disk in-flow determines the pulsar emission regime. *INTEGRAL* played a crucial role in the recent discovery of this class mainly thanks to its all-sky monitoring capabilities. On one hand it detected the onset of the outburst of IGR J18245–2452 (Eckert et al., 2013); on the other, its catalogue included steady and relatively faint hard sources which were later identified as candidate transitional millisecond pulsars through multi-wavelength follow-up observations (Strader et al., 2016; Coti Zelati et al., 2019).

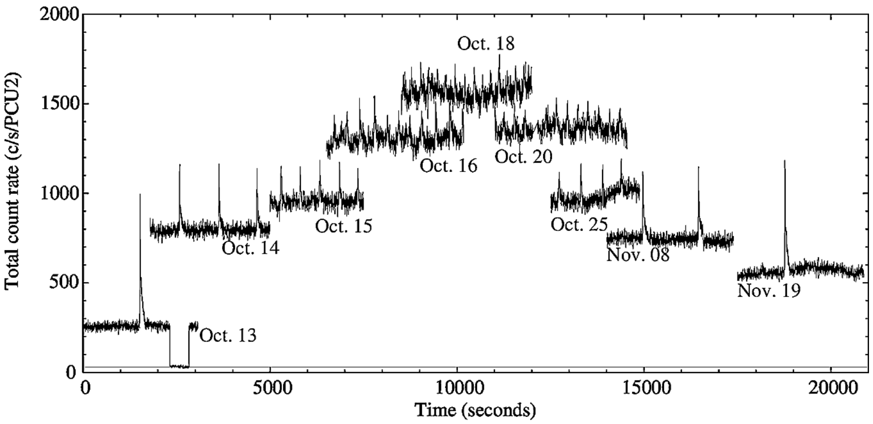

Fig. 8. The evolution of the thermonuclear burst frequency in IGR J17480–2446 during the course of its 2010 outburst. Data were obtained from *RXTE* and the x-axis shows the time at different phases of the outburst, which evolution of the persistent emission is represented in the y-axis in units of count-rate recorded by the PCU2 on-board *RXTE*. Times have been shifted arbitrarily for display purposes. Credit: Linares et al., ApJ, 748, 2 (2012). reproduced with permission of the AAS.

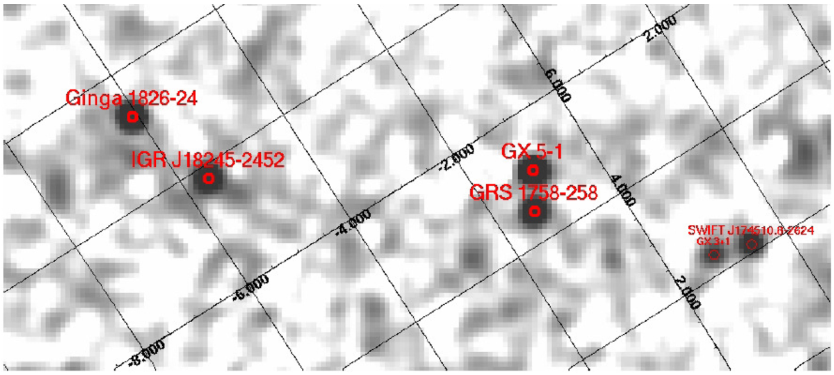

Fig. 9. Mosaic of the IBIS/ISGRI field around IGR J18245–2452 at the time of its discovery in 2013. Credit: Papitto et al., Nature, 501, 517 (2013), Supplementary Information.

3.1. *Swinging between accretion and rotation-powered states, IGR J18245 − 2452*

In 2013, IBIS/ISGRI discovered the transient IGR J18245–2452 in the globular cluster M28 (Eckert et al., 2013, see Fig. 9). The luminosity observed from the transient (3×10^{36} erg s^{-1} at a distance of 5.5 kpc) suggested that it was powered by mass accretion in a binary system. Subsequent observations of type-I X-ray bursts both by *INTEGRAL* (De Falco et al., 2017a) and *Swift* (Papitto et al., 2013) identified the compact object in the binary as a NS. Finally, a coherent X-ray periodicity at the 3.9 ms spin period of the NS was detected thanks to high-time resolution *XMM-Newton* observations; the spin and orbital parameters of this newly-discovered AMSP were the same as those of a radio pulsar detected a few years before when the X-ray source was in quiescence, so unveiling the transitional nature of the system (Papitto et al., 2013).

IBIS/ISGRI and JEM-X observations measured the properties of this transitional pulsar in the accretion phase and allowed to put it in the context of AMSPs (De Falco et al., 2017a). The observed spectral energy distribution (see Fig. 10) was dominated by a power law component with a photon index of $\Gamma = 1.32(1)$ and a cut-off energy of 122^{+21}_{-16} keV. Interpreted in terms of Comptonization of soft photons radiated from the NS hot spots, the spectral energy distribution measured from IGR J18245–2452 was the hardest among AMSPs. X-ray pulsations were detected by IBIS/ISGRI up to 60 keV, with a pulsed fraction of $\sim 10\%$, compatible with the values detected at low energies (see the top panel of Fig. 11). The high energy pulses of IGR J18245–2452 lagged behind the pulses detected at soft X-rays by up to 150 μs (see the middle panel of Fig. 11). This was normally not observed in other AMSPs (see Section 2.4) and was ascribed to a peculiar energy dependence of the emission pattern of the hot spots on the NS surface (De Falco et al., 2017a). Type-I X-ray bursts observed by *INTEGRAL* and *Swift* were all powered by ignition of Helium.

3.2. *X-ray sub-luminous transitional millisecond pulsars*

The month-long outburst observed in 2013 from IGR J18245–2452 has been the only bright accretion event observed from a transitional millisecond pulsar so far. Other transitional millisecond pulsars, such as PSR J1023 + 0038 (Archibald et al., 2009) and XSS J12270–4859 (Bassa et al., 2014), have persisted for years in an accretion disk state characterized by a much fainter X-ray luminosity ($L_X \simeq 5 \times 10^{33}$ erg s^{-1}), variable among two roughly constant levels (dubbed *high* and *low* modes) and frequent flares (de Martino et al., 2010; Linares, 2014; Patruno et al., 2014; Bogdanov et al., 2015). This peculiar accretion disk state was also characterized by a variable, bright continuous radio emission (Deller et al., 2015; Bogdanov et al., 2018) and by an unexpected γ-ray ($\sim$ GeV) emission with a power roughly comparable to that observed in the X-ray band (Stappers et al., 2014; Torres et al., 2017). X-ray pulsations were detected only in the *high* mode (Archibald et al., 2015; Papitto et al., 2015), simultaneously to unexpectedly bright optical pulses (Ambrosino et al., 2017; Papitto et al., 2019).

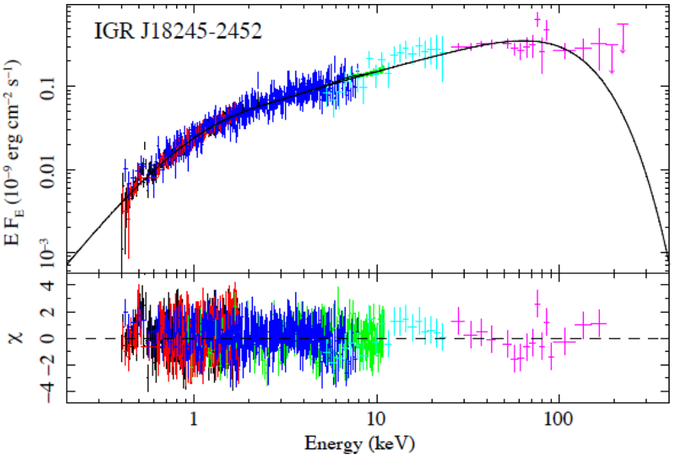

Fig. 10. The unfolded absorbed broad-band spectrum of IGR J18245–2452 observed during the 2013 X-ray outburst, fitted with a Comptonization COMPPS model (black line). Data points from *XMM-Newton*/RGS (red and black points, 0.4–1.8 keV), *XMM-Newton*/EPIC-pn (green points, 0.9–11 keV), *Swift*/XRT (blue points, 0.4–8 keV), *INTEGRAL*/JEM-X (light blue points, 5–25 keV) and *INTEGRAL* IBIS/ISGRI (magenta points, 22–250 keV) were included. The bottom panel shows residuals with respect to the best fit model. Credit: De Falco et al., A&A, 603, A17 (2017), reproduced with permission © ESO (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

The ability of IBIS/ISGRI in detecting faint, quasi persistent hard X-ray sources was crucial to identify such transitional pulsars in this enigmatic state. The case of XSS J12270–4859 is illustrative. A program of optical spectroscopy of unidentified *INTEGRAL* sources showed the presence in its spectrum of broad, double-peaked emission lines originating from an accretion disk (Masetti et al., 2006). While such a spectrum hinted at a cataclysmic variable, the presence of a γ-ray counterpart detected by the *Fermi*/LAT instrument suggested an atypical low-mass X-ray binary instead (de Martino et al., 2010; Hill et al., 2011; de Martino et al., 2013). The IBIS/ISGRI spectrum was described by a power law with a hard photon index ($\Gamma = 1.3$) extending up to 100 keV without a detectable cut-off (de Martino et al., 2010). The continuous detection by IBIS/ISGRI showed that the source could persist in such a state for at least a decade, possibly powered by a millisecond pulsar that ejects disk mass through the propeller effect (Papitto et al., 2014a; Papitto and Torres, 2015) or accreting material at a very low rate (D'Angelo and Spruit, 2012; Bozzo et al., 2018). The

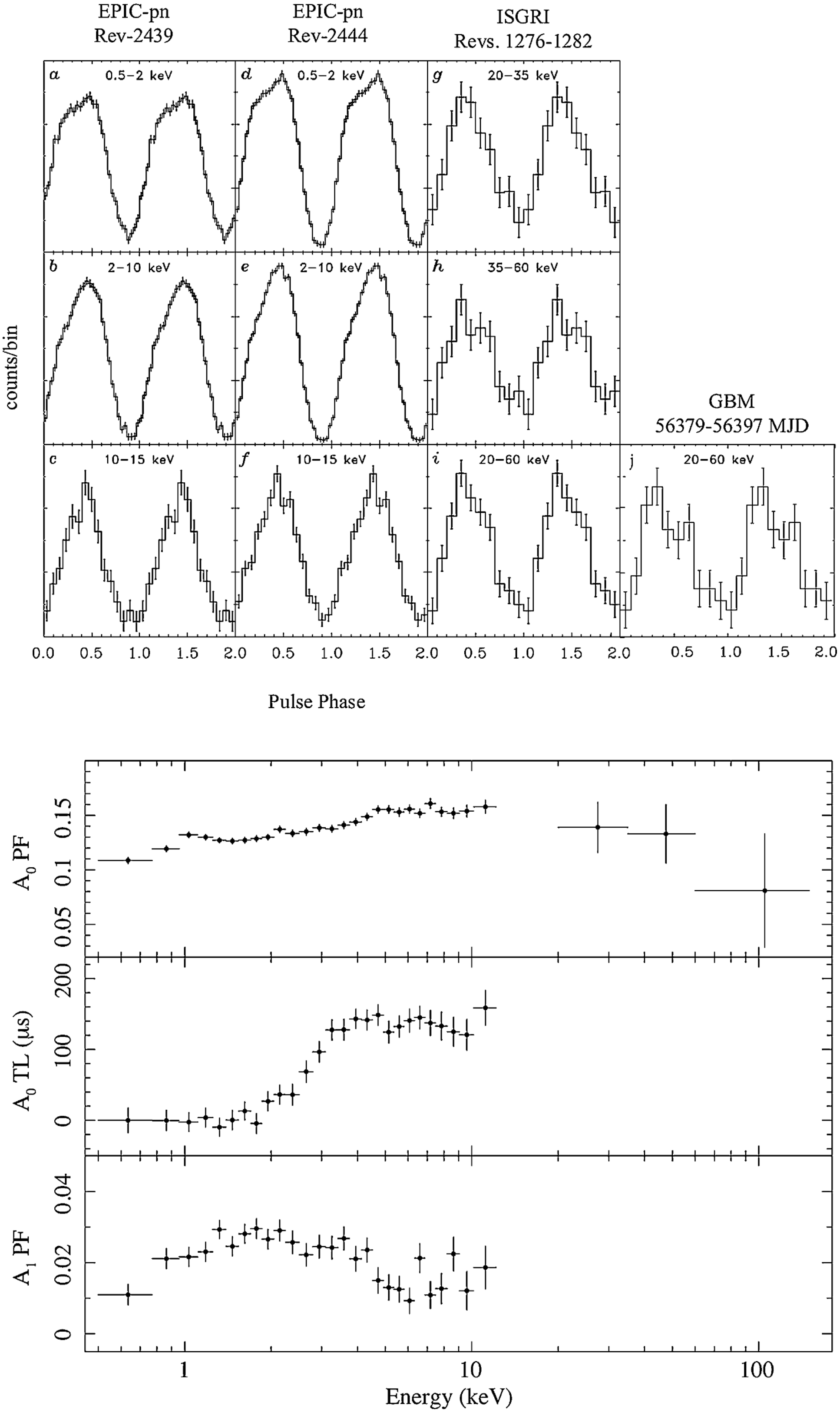

Fig. 11. Top panel: pulse profiles of IGR J18245–2452 observed by *XMM-Newton*/EPIC-pn (panels a)-f), *INTEGRAL* IBIS/ISGRI (panels g)-i) and *Fermi*/GBM (panel j); bottom panel, from top to bottom: pulsed fraction of the first harmonic, hard phase/time lags, and pulsed fraction of the second harmonic. Credit: De Falco et al., A&A, 603, A17 (2017), reproduced with permission © ESO.

transitional nature of the source was eventually demonstrated when its disk disappeared (Bassa et al., 2014) and it switched on as a radio pulsar (Roy et al., 2015).

Cross referencing the *INTEGRAL* IBIS/ISGRI catalogue with that of the Large Area Telescope (LAT; 20 MeV - 300 GeV) aboard the *Fermi Gamma-ray Space Telescope* (The Fermi-LAT collaboration, 2019) turned

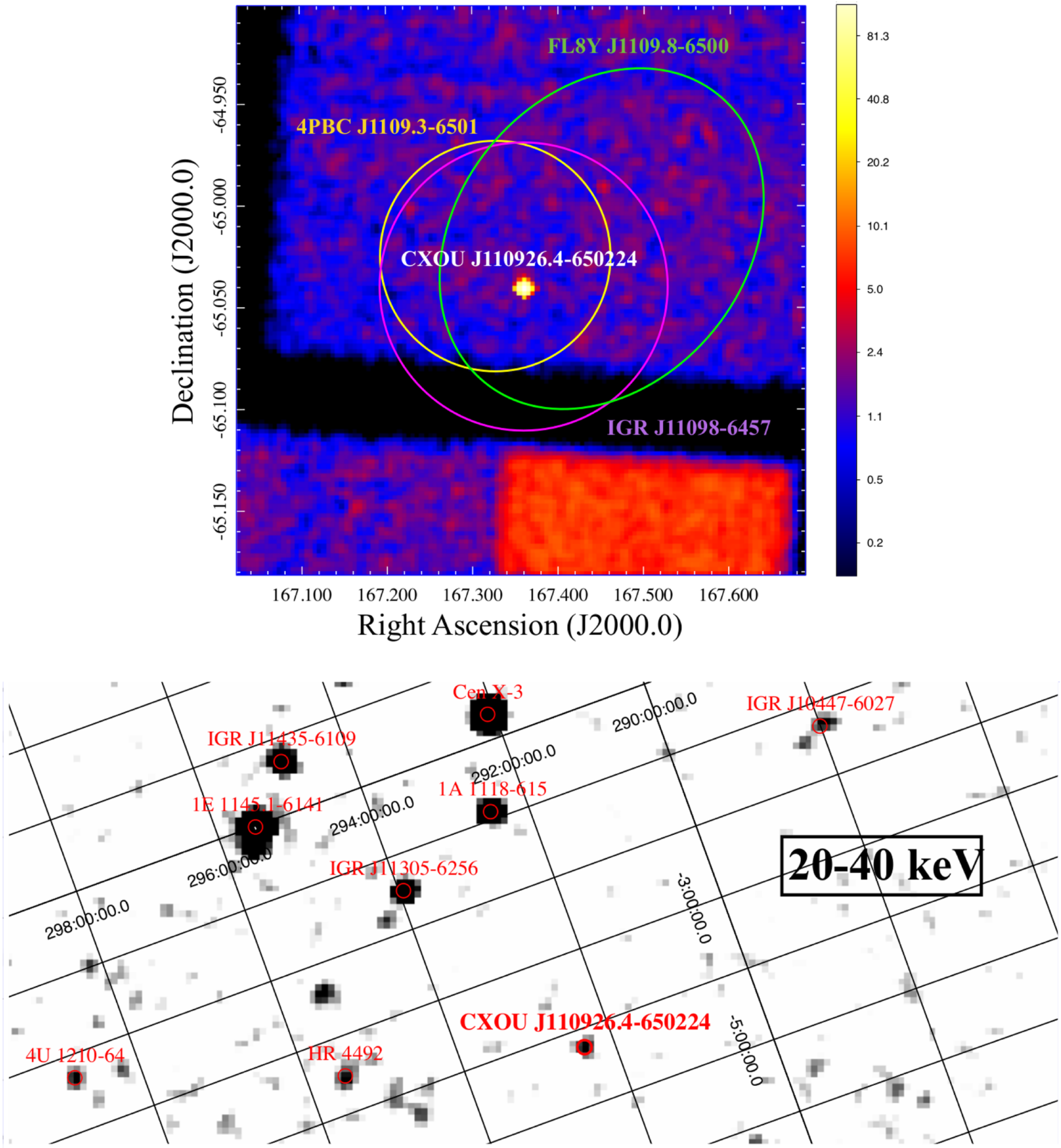

Fig. 12. **Top** panel: *Chandra*/ACIS-I 0.3 - 8 keV image of the field around CXOU J110926.4–650224 with the error circles of the counterparts from *INTEGRAL* (IGR J11098–6457, 20–40 keV, magenta line) *Swift*/BAT (4PBC J1109.3–6501, 15–150 keV, yellow line) and *Fermi*/LAT (FL8Y J1109.8–6500, 100 MeV - 300 GeV, green line) catalogues. **Bottom** panel: *INTEGRAL* IBIS/ISGRI 20–40 keV mosaic image of the field around IGR J11098–6457. Credit: Coti Zelati et al., A&A, 622, A211 (2019), reproduced with permission © ESO (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

out to be one of the most effective techniques to identify strong candidate transitional millisecond pulsars in such a faint and peculiar accretion disk state (see Fig. 12), and allowed the identification of the candidates IGR J04288–6702 (Strader et al., 2016) and IGR J11098–6457 (Coti Zelati et al., 2019). Follow-up observations of these two sources at optical and soft X-ray energies hinted at similar time variability properties as those observed from the other known transitional millisecond pulsars. However, their transitional nature is yet to be firmly established, waiting for a switch to the radio pulsar state hopefully in the near future.

4. Rotation-powered pulsars

Before the launch of *INTEGRAL*, highly magnetized ($B \simeq 10^{11} - 10^{12}$ G) rotation-powered pulsars were already known to emit steadily from radio frequencies up to high-energy γ-rays. The Compton Gamma-Ray Observatory (*CGRO*) had increased the number of detected high-energy ($E \geq 100$ MeV) γ-ray pulsars to a total of eight (see Thompson et al., 1997 for a review). However, the timing signatures and spectral shapes in the energy band from ∼ 20 keV to ∼ 5 MeV (or higher): were only measured for three pulsars the Crab pulsar (PSR B0531 + 21), PSR B1509–58 and the Vela pulsar (PSR B0833–45). This very small sample exhibited very different characteristics. The Crab and Vela pulsars showed double-peaked pulse profiles, while PSR B1509–58 showed a broad single pulse. The latter had a spectral shape peaking in luminosity at MeV energies, vastly different from that of the Crab (Kuiper et al. (1999)). The Vela pulsar was only marginally detected at hard X-ray/soft γ-ray energies but appeared to be the strongest pulsar at GeV energies, where it reached maximum luminosity with a spectral shape completely different from both the Crab and PSR B1509-

58 (Hermsen et al., 1994).

The high-energy non-thermal emission from highly magnetized rotating NSs was believed to originate from particle acceleration along the open magnetic field lines in the pulsar magnetosphere. The different competing models could be grouped in two categories, the so-called Polar Cap (PC) models and Outer Gap (OG) models. In the PC scenario charged particles (mainly $e^{+}e^{-}$) are accelerated along the open field lines in the vicinity of the magnetic poles. Subsequent cascade processes (starting with curvature radiation or inverse Compton scattering) give rise to the emergent high-energy spectrum (e.g. Daugherty and Harding, 1994). In the OG scenario the acceleration of charged particles and production of high-energy radiation takes place in charge depleted gaps between the null-charge surface and the light cylinder above the last closed field lines (e.g. Cheng et al., 1986a; Cheng et al., 1986b). It was also predicted that due to their quick rotation, millisecond pulsars should be fairly strong high-energy γ-ray emitters (Srinivasan, 1990).

With the launch in June 2008 of *Fermi*, the LAT produced groundbreaking results at high-energy γ-rays. The number of detected γ-ray pulsars increased from eight to ∼ 250 (status in 2019), including 90 millisecond pulsars (MSPs). These numbers can be compared to the seven pulsars securely detected above 100 MeV with the Energetic Gamma Ray Experiment Telescope (EGRET) aboard CGRO and the single recycled MSP J0218 + 4232, likely detected above 100 MeV (Kuiper et al., 2000). The number of γ-ray sources totals more than 5000 in the fourth *Fermi* catalog (The Fermi-LAT collaboration, 2019), including 239 identified pulsars and many candidate rotation-powered pulsars. These results stimulated also major developments in theoretical modelling of the high-energy emissions in pulsar magnetospheres. The new emission characteristics, e.g. spectral turnover at GeV energies, pulse morphologies, favoured OG models over PC models (Harding et al., 2005) and Slot Gap models (Dyks and Rudak, 2003; Muslimov and Harding, 2004). However, recent global particle-in-cell simulations of pulsar magnetospheres reveal that most particle acceleration occurs in and near the current sheet beyond the light cylinder and the separatrices (Chen and Beloborodov, 2014; Mochol and Petri, 2015; Cerutti et al., 2016; Philippov and Spitkovsky, 2018; Brambilla et al., 2018; Kalapotharakos et al., 2018).

INTEGRAL promised for the first time fine imaging and accurate localization of hard-X-ray/γ-ray sources, with good timing and good sensitivity over the broad energy range from 3 keV to ∼ 10 MeV. However, the predictions on the expected results for rotation-powered pulsars over this energy window were very uncertain. They relied on uncertain interpolations performed on a handful of radio pulsars between the spectra of pulsed emission measured at higher γ-ray energies and at soft X-ray energies, or on extrapolations of the spectra measured only at lower X-ray energies. As expected, the strong Crab pulsar emission could be used as a calibration source, and studied in more detail at hard X-rays. However, the next-in-flux known hard X-ray pulsar, PSR B1509–58, whose hard X-ray emission had been studied earlier using the instruments aboard *CGRO* (Kuiper et al., 1999) and the Italian/Dutch mission *BeppoSAX* (Cusumano et al., 2001), was already a factor 30–50 times weaker than the Crab in the 20–100 keV band. The Vela pulsar was even fainter, with a hard X-ray luminosity ∼ a thousand times lower than the Crab. Using data from the *RXTE*, hard X-ray timing and spectral properties had been also reported for the Crab-like pulsar in the Large Magellenic Cloud (LMC), PSR B0540–69 (de Plaa et al., 2003), which turned out to be ∼ 250 times weaker than that of the Crab in the hard X-ray domain. For the recycled rotation-powered pulsars, the MSPs, the prospects for detections with *INTEGRAL* were even smaller. Three MSPs, PSR B1821–24, PSR J0218 + 4232, and PSR B1937 + 21, had been reported to emit non-thermal emission at X-ray energies with very hard spectra with power-law indices $\Gamma \sim 1.1$. X-ray pulsations were detected up to 20 keV for PSR B1821–24 (Rots et al., 1998) and PSR J0218 + 4232 (Kuiper et al., 2004b), and up to 25 keV for PSR B1937 + 21 (Cusumano et al., 2003). However, the reported fluxes were even more than three orders of magnitude weaker than that of the Crab at 20 keV.

Given the expected low *INTEGRAL* count rates of the weak pulsed emission, it is no surprise that in the first decade of the *INTEGRAL* mission most analyses did not address the pulsed emission but exploited the imaging capabilities in the analyses of the total emission from pulsars and their Pulsar Wind Nebulae (PWNe). Only later, first detections at hard X-rays have been reported and the total spectra (pulsar + PWN) discussed. The detection of emission up to 200 keV from PSR B1509–58 in SNR MSH 15–52 (Sturner et al., 2004) was followed by the presentation of the spatial and spectral properties of just the unpulsed emission in the 20–200 keV band (Forot et al., 2006). PSR B0540–69 / SNR 0540–693 in the LMC was first detected up to 100 keV (Götz et al., 2006a), later up to 200 keV, while significant pulsations with a high duty cycle were visible up to 100 keV (Slowikowska et al., 2007). For PSR J1617–5055 near RCW 103 (18–60 keV; Landi et al., 2007) and later PSR J1811–1925 in G11.2–0.3 (up to ∼ 200 keV; Dean et al., 2008b) the total spectra could be discussed for the first time. In addition, with *INTEGRAL* IBIS/ISGRI PSR J0537–6910 was detected in the 20–60 keV band in a very deep survey of the LMC region (Grebenev et al., 2013).

The above summary indicates that very long *INTEGRAL* exposures were required to increase the sample of pulsars for which pulsed emission could be detected at hard X-rays. Similar to the case of AMSPs (see Section 2.4), the low pulsed-count rates in the *INTEGRAL* window required timing analyses to rely on pulsar ephemerides determined in radio monitoring observations, or in the X-ray band below ∼ 10 keV where instruments such as the PCA aboard RXTE were sufficiently sensitive to allow for measurements of pulsar ephemerides. The latter was required when the pulsars were not detected in the radio band. Once these timing solutions were determined at lower energies, phase folding of the event arrival times measured with the *INTEGRAL* instruments could be performed to search for the pulsed signals at hard X-rays. A complete high-energy overview of the soft γ-ray pulsar population was published with a catalog containing 18 rotation-powered (non-recycled) pulsars with pulsed emission detected in the hard X-ray band above 20 keV (Kuiper and Hermsen, 2015). Surprisingly, most of these pulsars were not detected by *Fermi* at high-energy γ-rays. This catalog and the characteristics of this sample will be addressed at the end of this section. First, the *INTEGRAL* results from studies of the Crab pulsed emission will be presented, followed by the important results from polarization measurements.

4.1. The Crab pulsar

Early in the mission, the first *INTEGRAL* results were published for the archetypical Crab pulsar with a verification of the absolute timing capabilities of all high-energy instruments, JEM-X, IBIS/ISGRI and SPI (Kuiper et al., 2003; Brandt et al., 2003). It was shown that the X-ray main pulse was leading the radio pulse in phase by 285 ± 12 μs (IBIS/ISGRI) and 265 ± 23 μs (SPI) (Kuiper et al., 2003; statistical errors only), values that were more accurate than those reported earlier. Using six years of SPI telescope data (total exposure ∼ 4 Ms) comparable values (275 ± 15 μs) were found for the hard X-ray band (20–100 keV; Molkov, Jourdain, Roques, 2010). More interestingly, it was shown that the delay between the radio and X-ray signals varies in the 20–300 keV range. Namely, the delay was reported to be 310 ± 6 μs in the 3–20 keV soft X-ray band from an analysis of *RXTE* data (Molkov et al., 2010).

A coherent high-energy picture of the Crab nebula and pulsar spectra from soft X-rays up to high-energy γ-rays had been published shortly before the *INTEGRAL* launch (Kuiper et al., 2001), including a pulse-phase-resolved spectral analysis performed in seven phase slices over the 0.1 keV - 10 GeV energy band. In this high-energy picture of the Crab, data from the four narrow-field instruments aboard *BeppoSAX*, LECS, MECS, HPGSPC and PDS covered energies up to 300 keV (see Kuiper et al., 2001 for references). At higher γ-ray energies, data were used from COMPTEL and EGRET aboard *CGRO*. Early in the *INTEGRAL* mission, an accurate phase-resolved (now in 50 bins) spectral analysis for the Crab pulsar over the energy range 3–500 keV was achieved with multiple Crab calibration observations with JEM-X, IBIS/ISGRI & PICsIT and SPI, characterizing in detail the curved spectral shape over this energy range (Mineo et al., 2006). The combination of *INTEGRAL* timing and spectral results with those from the previous *BeppoSAX* and *CGRO* missions were input for a multi-component model for the broad-band emission of the Crab pulsar from the optical band to high-energy γ-rays (Massaro et al., 2006).

4.2. *Joint optical - γ-ray polarisation measurements with INTEGRAL*

Although a relatively weak radio pulsar and a strong emitter at X and γ-ray energies, the Crab pulsar is the brightest of all the known pulsars at optical wavelengths and consequently has been extensively studied. The pulsar's spin-down energy powers its surrounding nebula, which radiates at all electromagnetic frequencies from the radio band to TeV γ-rays (Hester, 2008). Our understanding of the high-energy emission process in pulsars is still very incomplete. However, polarisation observations can begin to unravel this conundrum through geometric considerations. Harding and Kalapotharakos (2017) have modelled the high-energy polarised emission from optical to γ-ray wavelengths. They predicted a polarisation degree and polarisation angle which depends upon location and specifically whether the radiation originates from inside or outside the pulsar's light cylinder. Matching the polarisation profile can give a unique restriction on the location of the production of high-energy emission (McDonald et al., 2011).

The Crab nebula was one of the first objects outside of the Solar System to have detectable X-ray polarisation (Weisskopf et al., 1978). This was followed by the first detection of γ-ray polarisation using *INTEGRAL* (Dean et al., 2008a; Forot et al., 2008). Optical polarised emission from the nebula and pulsar have been described by a number of authors (Smith et al., 1988; Słowikowska et al., 2009; Moran et al., 2012; 2013; 2016). Phase-resolved observations showed a change in polarisation consistent in shape with a beam of synchrotron radiation coming from both poles of an orthogonal rotator. Słowikowska et al. (2009, 2012) found the presence of a highly polarised continuous component which most likely corresponds to the nearby bright synchrotron emitting knot (Moran et al., 2013), also known as inner-knot, located 0.65 arcsec to the southest of the pulsar (Hester et al., 1995).

Optical and X-ray observations showed spatial and some flux variability of the inner nebula (Bietenholz et al., 2001). Indeed this had been observed in some early optical studies (Scargle, 1969). However, the flux from the whole nebula was expected to be constant at the level of a few percent (Kirsch et al., 2005; Weisskopf et al., 2010) and as such was often used as a standard candle calibration source. However since 2008, strong γ-ray flares have been observed at a rate of about 1 per year by the *Agile* and *Fermi* γ-ray telescopes (Abdo et al., 2011; Tavani et al., 2011; Striani et al., 2013). Around these γ-ray flaring events, there were no associated changes seen in the near-IR or X-ray fluxes (Weisskopf et al., 2013).

Since the original *INTEGRAL* γ-ray observations in 2008, the Crab has been observed twice a year improving the statistics for determining the γ-ray polarisation (Jourdain and Roques, 2019). This has allowed for comparisons between optical and MeV γ-ray polarisation. In particular, Moran et al., 2016 looked for any correlated changes in the polarisation at the two wavebands. Changes in the polarisation angle seemed to be correlated, albeit only at the 2.5 σ level (see Fig. 13). Whether this is indicative of reconnection or other events associated with γ-ray flares is not proven. Other suggestions include magneto-Bremsstrahlung emission which explain the lack of variability at lower photon energies (Weisskopf et al., 2013). More correlated observations simultaneous with a flare are required to address this problem, either looking at flux and polarisation changes in the nebula and/or in the immediate vicinity of the pulsar.

4.3. *The soft γ-ray pulsar catalog*

Despite the weakness of the pulsar signals in the *INTEGRAL* hard X-ray/soft γ-ray band, significant progress was achieved when the X-ray observatories *Chandra, RXTE, XMM-Newton, Suzaku, INTEGRAL* and later *NuSTAR*, discovered weak energetic point sources at soft/medium X-rays (0.1–10 keV) in young supernova remnants, often detected at radio frequencies or in location-error boxes of unidentified *CGRO* EGRET/*Fermi* LAT (≥ 100 MeV), *INTEGRAL* IBIS/ISGRI (20–300 keV) or *H.E.S.S./VERITAS/MAGIC* (≥ 30/100 GeV) sources. The pulsed signals of these new point sources could be identified at soft X-rays or in the radio band. Once the timing solutions were determined below 10 keV, phase folding of the event arrival times measured with *RXTE* PCA and HEXTE and *INTEGRAL* IBIS/ISGRI could be performed to search for the pulsed signals above 20 keV. In addition the imaging capabilities of IBIS/ISGRI allowed the detection and spectral characterization of the total emission (pulsar plus PWN), often up to energies above 100 keV. However, very long exposures were required to obtain secure detections, collecting over many years exposures each time a source was in the field-of-view of *INTEGRAL* and/or *RXTE*. This approach led to an *INTEGRAL/RXTE* soft γ-ray pulsar catalog containing 18 pulsars for which non-thermal pulsed emission has been securely detected at hard X-rays/soft γ-rays above 20 keV (Kuiper and Hermsen, 2015). That paper summarizes the history of the detection of each pulsar in different bands of the electromagnetic spectrum, and the X-ray timing and spectral characteristics. Below, we will present the role of *INTEGRAL* in the discovery and/or characterization of a few pulsars, followed by a comparison of the sample of hard X-ray/soft γ-ray pulsars with those in the second *Fermi* pulsar catalog (Abdo et al., 2013).

4.3.1. *IGR J18490–0000, IGR J14003–6326 and IGR J11014–6103 from INTEGRAL sources to pulsars*

Three pulsars were originally discovered as X-ray point sources by *INTEGRAL* in deep IBIS/ISGRI mosaic images, namely IGR J18490–0000/PSR J1849–0001 (Molkov et al., 2004), IGR J14003–6326/PSR J1400–6325 (Keek et al., 2006) and IGR J11014–6103/PSR J1101–6101 (Bird et al., 2010). Follow-up

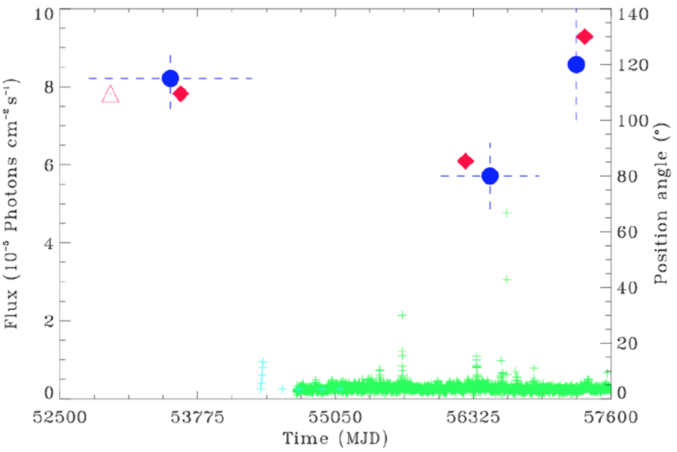

Fig. 13. Galway Astronomical Stokes Polarimeter (GASP, Collins et al., 2013, open triangle and filled diamonds) and *INTEGRAL* observations of the polarisation position angle of the Crab (blue filled circles; Moran et al., 2016; O'Connor et al., 2018). Green and cyan points show the flux observed by *Fermi* and *AGILE*, respectively. More recent Astrosat measurements (Vadawale et al., 2018) in the 0.1–0.38 MeV band indicate a polarisation angle of (143.5 ± 2.8)° consistent with the trend observed by GASP and *INTEGRAL*. Credit: Moran et al., MNRAS, 456, 2974 (2016), reproduced with permission of Oxford University Press on behalf of the Royal Astronomical Society (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

observations outside the *INTEGRAL* band led to their identification as rotation-powered pulsars.

Multiple follow-up observations of IGR J18490–0000 revealed the presence of a TeV source with HESS, a soft X-ray counterpart with *Swift*-XRT and *XMM-Newton* and, finally (Gotthelf et al., 2011), the 38.5-ms X-ray pulsation and a weak PWN with *Chandra* (for further references and derived (hard) X-ray characteristics see Kuiper and Hermsen (2015)), while no radio counterpart was detected with the GMRT. The discovery of IGR J14003–6326 triggered similar follow up observations, notably with *Chandra*, revealing the presence of a point source plus a PWN and a SNR (Renaud et al., 2010). The latter reference also reported the detection of a 31.2-ms pulsar with *RXTE* PCA. Improved (hard) X-ray characteristics are given with the catalog (Kuiper and Hermsen, 2015). Both these new hard X-ray pulsars were not detected by *Fermi* LAT. For the strongest of the two (PSR J1849–0001) one can conclude that the non-detection by the LAT means that maximum luminosity is reached at MeV energies.

IGR J11014–6103 and its surroundings were studied in great detail in X-rays, first by using all available archival X-ray data (Pavan et al., 2011) and subsequently with a dedicated *Chandra* observation (Pavan et al., 2014). It was shown that the putative pulsar counterpart is moving away from SNR MSH 11–61A, located at 11 arcmin from the X-ray point source. The latter was shown to have a hard spectrum in the 2–10 keV band (power-law photon index $\Gamma = 1.1 \pm 0.2$). Finally, *XMM-Newton* observations revealed the X-ray pulsations (62.6 ms) (Halpern et al., 2014) and allowed the characterisation of the pulsed-emission X-ray spectrum up to 10 keV (Kuiper and Hermsen, 2015). This pulsar is an excellent candidate to be detected at higher X-ray energies as a soft γ-ray pulsar.

4.3.2. AX J1838.0–0655 / PSR J1838–0655, another ‘MeV’ pulsar

An interesting discovery turned out to be the detection of soft γ-ray emission up to $\sim$ 300 keV from the ASCA source AX J1838.0–0655 using *INTEGRAL* IBIS/ISGRI data (Malizia et al., 2005). Its location made an association with the TeV source HESS J1837–069 (Aharonian et al., 2005) plausible, suggesting a pulsar/PWN origin, later confirmed using RXTE PCA data (23.4 kyr-old pulsar with period 70.5 ms; Gotthelf et al., 2008; Kuiper et al., 2008). This young pulsar turned out to be the third pulsar in hard-X-ray flux after the Crab pulsar and PSR B1509–58, without a detection in the radio and *Fermi* high-energy γ-ray bands. Analysis of *RXTE*/HEXTE and *INTEGRAL* IBIS/ISGRI data revealed X-ray pulse profiles up to $\sim$ 150 keV with a pulse and spectral shapes similar to that of PSR B1509–58 (Kuiper and Hermsen, 2015). This pulsar turned out to be another prototype example of a pulsar with a spectrum reaching maximum luminosity at MeV energies.

4.3.3. PSR J1846–0258 showing magnetar-like behaviour

A very intriguing high-B-field (4.9×10^{13} G) pulsar is PSR J1846–0258, a relatively slow ($P \sim 324$ ms) radio-quiet pulsar, with the smallest characteristic age ($\tau \sim 723$ yr) of all known pulsars. It is located in the centre of SNR Kes75, showing up as a bright hard X-ray source surrounded by a diffuse PWN. *INTEGRAL* detected point-source emission up to $\sim$ 200 keV and pulsed emission up to $\sim$ 150 keV (see Kuiper and Hermsen, 2009 and references therein). Most surprisingly, this pulsar showed magnetar-like behaviour during 2006 June 7–12 with an increase by $\sim$ a factor five in luminosity due to a radiative outburst in soft X-rays lasting 55 days and accompanied by five magnetar-like bursts (Kumar and Safi-Harb, 2008; Gavriil et al., 2008). The onset of the radiative event was accompanied by a major spin-up glitch of the pulsar (Kuiper and Hermsen, 2009). IBIS/ISGRI could study the evolution of the total non-thermal flux (PSR J1846–025 + Kes75) during the years 2003 - 2006 before and after the outburst. The pulsar was found to be stable in X-rays before the spin-up glitch with a power-law spectrum (index $\Gamma = 1.80 \pm 0.06$). During the outburst the hard X-ray flux increased by $\sim$ 50%, the spectral shape remained the same, and after one year the non-thermal emission was back to its pre-outburst values. The X-ray pulse profile measured by IBIS/ISGRI, PCA and HEXTE, was a broad single asymmetric pulse that did not vary in shape over the 3–150 keV energy range and, remarkably, did not change during the magnetar-like outburst, nor did its non-thermal spectral shape (power-law index $\Gamma \sim 1.2$). The accurate IBIS/ISGRI measurement of the total and pulsed spectra showed that the pulsed fraction approaches 100% around 150 keV (Kuiper and Hermsen, 2009). In its steady state, also this pulsar exhibits very similar timing and spectral characteristics as PSR B1509–58 with a spectrum reaching its maximum luminosity at MeV energies, confirmed with the recent detection with *Fermi* LAT of a very weak pulsed emission between 30 and 100 MeV (Kuiper et al., 2018).

4.3.4. Hard X-ray pulsars, a distinct subset of the non-thermal population of rotation-powered pulsars

The hard X-ray/soft γ-ray ($E \geq 20$ keV) pulsar population counts only 18 members (Kuiper and Hermsen, 2015), all non-recycled pulsars, compared to a total of $\sim$ 160 (status in 2019) non-recycled pulsars detected by *Fermi* LAT above 100 MeV. As was expected, *INTEGRAL* could not detect the very weak pulsed emission from the recycled MSPs, even though *Fermi* had increased the number of MSPs detected above 100 MeV from one to $\sim$ 60. The question from the start of the *INTEGRAL* mission was: will *INTEGRAL* just detect/confirm the hard X-ray spectral tails of the high-energy γ-ray pulsars that reach their maximum luminosities at GeV energies and have predominantly narrow (double) pulse profiles, or will it rather provide new information on the total high-energy non-thermal pulsar population? In order to investigate this question, the characteristics of the 18 soft γ-ray pulsars were compared with those of the 77 non-recycled LAT-detected pulsars in the Second *Fermi* Pulsar Catalog (Kuiper and Hermsen, 2015). Surprisingly, it was found that the soft γ-ray pulsars are all fast rotators and on average $\sim$ 9.3 times younger and $\sim$ 43 times more energetic than the *Fermi* LAT sample (see also Coti Zelati et al., 2020 for a recent assessment). The majority (11 sources) exhibits broad, structured single pulse profiles, and only six have double (or even multiple, Vela) pulses (see Fig. 14). Fifteen soft γ-ray pulsars show hard power-law spectra in the hard X-ray band and reach maximum luminosities typically in the MeV range (see Fig. 15). Pulsed emission has also been detected by the LAT. For only seven of the 18 soft γ-ray pulsars , but 12 have a PWN detected at TeV energies. In conclusion, observations of rotation-powered pulsars at hard X-rays and MeV γ-rays revealed a subset of the total high-energy pulsar population that can not (yet) be observed with *Fermi* at energies above 100 MeV. This distinct subsample was originally not taken into account in population studies based on the *Fermi* catalog. However, Torres (Torres, 2018; Torres et al., 2019) recently presented a physical model for the non-thermal emission of pulsars above 1 keV to fit the spectra of the γ/X-ray pulsars along seven orders of magnitude over the *INTEGRAL* band up to the *Fermi* high-energy γ-rays. The spectra of all pulsars with detected non-thermal emission could be modeled with a continuous variation of only four model parameters, and it was proposed that their values likely relate to the closure mechanism operating in the accelerating region.

After the launch of *NuSTAR* in June 2012 (two orders of magnitude more sensitive than *INTEGRAL* in the energy band 3–79 keV) several of the rotation-powered pulsars in the soft γ-ray pulsar catalog have been observed. The published temporal and spectral characteristics were all confirmed, and so far no new entries to the pulsar catalog were reported. However, *NuSTAR* made some progress by detecting the non-thermal hard-X-ray pulsations of PSR B1821–24, PSR B1937+21 and PSR J0218+4232 for energies up to $\sim$ 50 keV, $\sim$ 20 keV and $\sim$ 25 keV, respectively (Gotthelf and Bogdanov, 2017), and confirming the earlier reported hard X-ray spectra with photon indices $\Gamma \sim 1.1$. Still, *INTEGRAL* remains unique in its capabilities to image point sources (pulsars + PWNe) up to few hundred keV, as well as to measure pulsed-emission from non-recycled pulsars above 80 keV.

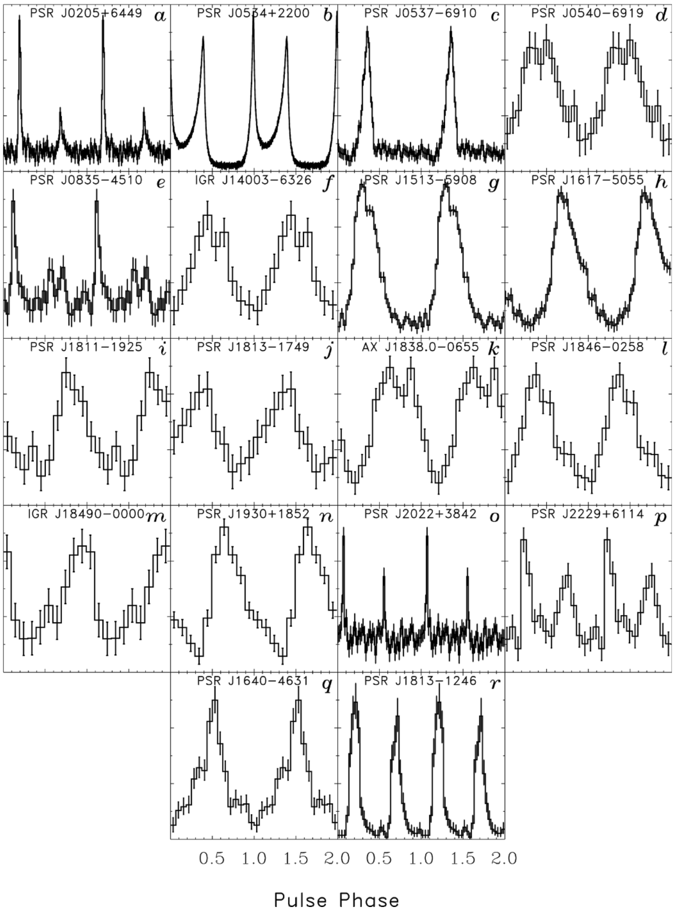

Fig. 14. The pulse shapes of all soft γ-ray pulsars in the catalog. The profiles are measured either with *INTEGRAL* IBIS/ISGRI or RXTE PCA or HEXTE. Exceptions are PSR J1640–4631 (*NuSTAR*) and PSR J1813–1246 (*XMM-Newton* EPIC). Credit: Kuiper & Hermsen, MNRAS, 449, 3827 (2015), reproduced with permission of Oxford University Press on behalf of the Royal Astronomical Society.

5. Magnetars

Magnetars are isolated NSs defined by the fact that the main source powering their persistent and flaring emission is magnetic energy (Thompson and Duncan, 1995; 1996). Their external magnetic field is estimated to reach 10^{15} G, and their internal field might be even higher. Although we know only about two dozens of magnetars in the Galaxy and in the Magellanic Clouds, the extreme properties of this small class of objects make them particularly interesting as laboratories to study physical processes in high magnetic fields. They emit predominantly in the X-ray and soft γ-ray energy range, where they show a variety of variable phenomena, ranging from short bursts on sub-second time-scales, to outbursts lasting several months.

Their magnetic field, much larger than in ordinary NSs, is likely produced thanks to a very short rotational period at birth, of the order of only 2–3 ms (Duncan and Thompson, 1992). Magnetars have been invoked as the central engine of γ-ray bursts, able to power the prompt emission and/or part of the afterglow, as a possible explanation for the enigmatic Fast Radio Bursts, as well as potential sources of gravitational waves.

For a thorough description of the magnetar observational properties and of the theoretical models proposed to explain them we refer to several recent reviews (Rea and Esposito, 2011; Mereghetti et al., 2015; Turolla et al., 2015; Kaspi and Beloborodov, 2017). Here, we concentrate on the results obtained with the *INTEGRAL* satellite. We first describe the discovery of hard X-ray emission in magnetars, then we summarize the results concerning the short bursts, and, finally, we describe the observations of the only giant flare emitted by a magnetar after the *INTEGRAL* launch.

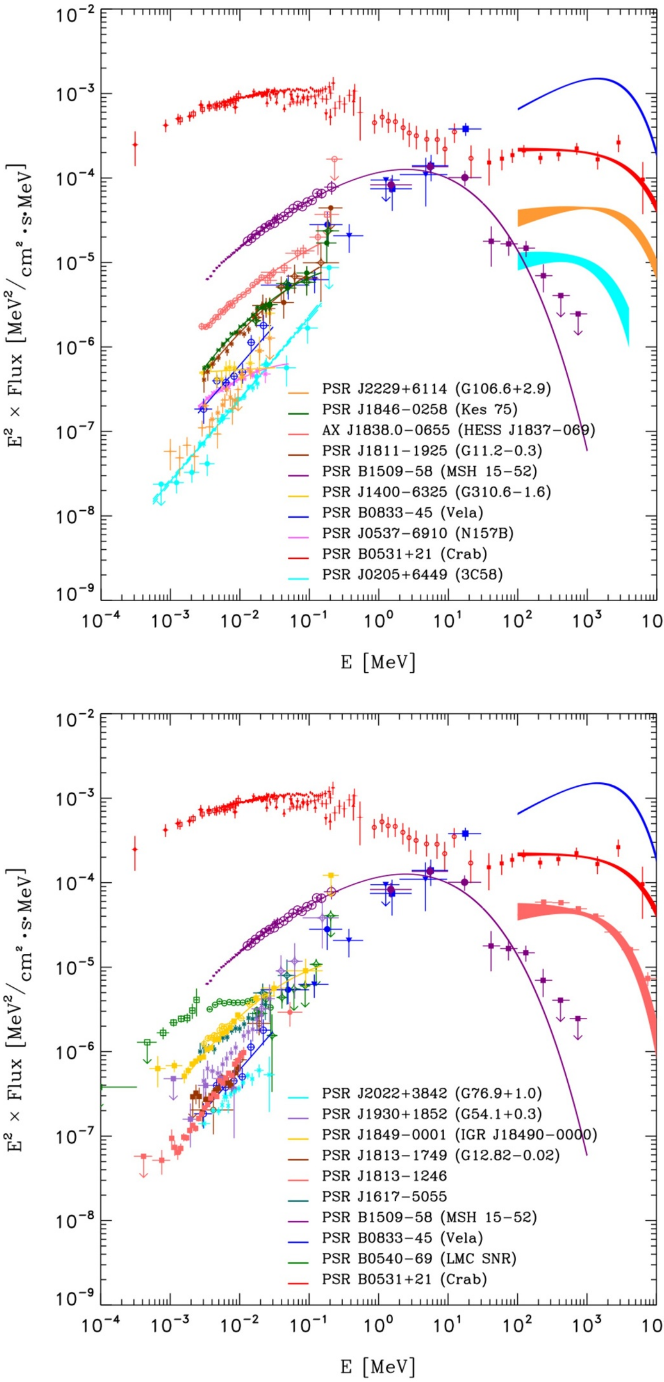

Fig. 15. The high-energy *pulsed* emission spectra for 17 of the 18 detected soft γ-ray pulsars from 0.1 keV - 10 GeV summarized in two panels. The spectra of PSR B0531 + 21 (Crab), PSR B0833–45 (Vela) and PSR B1509–58 are shown in both panels for reference purposes. The pulsed spectrum of PSR J1640–4631 is not shown, because its *total* spectrum has been reported up to hard X-rays but its *pulsed* spectrum just up to 25 keV. Credit: Kuiper & Hermsen, MNRAS, 449, 3827 (2015), reproduced with permission of Oxford University Press on behalf of the Royal Astronomical Society).

5.1. *The discovery of persistent hard X-ray emission*

Although magnetars were first discovered as Soft Gamma-ray Repeaters (SGRs) through the detection of bursts in the hard X-ray band

(Mazets et al., 1979), until the launch of *INTEGRAL* their persistent emission had been observed only in the classical $\sim 1-10$ keV X-ray range. At these energies, the persistent X-ray counterparts of the SGRs, as well as the Anomalous X-ray Pulsars (AXPs, another class of X-ray sources later recognized to be magnetars; Mereghetti and Stella, 1995), are characterized by rather soft X-ray spectra. These spectra were usually fitted with the sum of a thermal component, with typical blackbody temperature of the order of ~ 0.5 keV, and a steep power law with photon index Γ ranging between ~ 3 and ~ 4 (Mereghetti, 2008). Therefore, the *INTEGRAL* discovery of persistent hard X-ray emission from several magnetars was quite unexpected since a simple extrapolation of the X-ray spectra would lead to very small hard X-ray fluxes.

An *INTEGRAL* source with an average flux of 7 mCrab in the 60–120 keV range, and coincident with the AXP 1E $1841-045$ in the Kes 73 supernova remnant, was first reported in Molkov et al. (2004). This discovery prompted an analysis of archival *RXTE* data (Kuiper et al., 2004a, see also Götz et al., 2007 for a re-analysis of *BeppoSAX* data) that, thanks to the detections of pulsations up to ~ 150 keV, confirmed that the hard X-rays were indeed emitted by the magnetar and not by the supernova remnant. The pulsations were later found also in the IBIS/ISGRI data (Kuiper et al., 2006).

Hard X-ray spectral components were subsequently detected with *INTEGRAL* in other AXPs (1RXS $1708-4009$ and 4U $0142+61$; Revnivtsev et al., 2004; Kuiper et al., 2006; den Hartog et al., 2008b), as well as in the two brightest SGRs: $1806-20$ (Mereghetti et al., 2005a; Molkov et al., 2005; Esposito et al., 2007) and $1900+14$ (Götz et al., 2006c; Ducci et al., 2015). As an example, we show in Fig. 16 the spectrum of 4U $0142+61$. All these magnetars are persistently bright sources, but in the following years *INTEGRAL* detected hard X-ray tails also in transient magnetars, such as SGR $0501+4516$ (Rea et al., 2009) and 1E $1547.0-5408$ (Bernardini et al., 2011; Kuiper et al., 2012), when they went in outbursts.

The *INTEGRAL* results for the latter source are particularly interesting because they showed the appearance of a new transient component extending up to 150 keV after the onset of the January 2009 outburst (Kuiper et al., 2012). This pulsed component was shifted in phase with respect to the lower energy pulse profile and had a different spectral and flux evolution compared to that of the total hard X-ray emission.

These *INTEGRAL* observations, as well as further hard X-ray data obtained with other satellites (mainly *Suzaku* and *NuSTAR;* Enoto et al., 2010; Enoto et al., 2017; An et al., 2014), have clearly shown that the magnetar hard X-ray tails extending up to $\sim 150-200$ keV are not a simple extrapolation of their lower energy emission. In fact, they are fitted by flatter power-laws ($\Gamma_\gamma \sim 0.5-2$) and often show a pulse profile different from that seen below 10 keV (see, e.g., Fig. 17). The pulsed flux is generally harder than the unpulsed one, causing an increase of pulsed fraction with energy. The upper limits in the MeV region (Kuiper et al., 2006; den Hartog et al., 2008b; 2008a) imply a spectral turn-over of the hard components, which, nevertheless, contain an energy of the same order of that of the soft X-ray emission, or in some cases even larger.

While the soft X-rays are generally ascribed to thermal emission from the magnetar surface, modified by the effects of a strongly magnetized atmosphere, the hard X-ray tails are thought to originate from non-thermal particles in the magnetosphere (see, e.g., Beloborodov, 2013b), likely with an important contribution from resonant cyclotron scattering (Baring and Harding, 2007). In the twisted magnetospheres of magnetars, currents flow along bundles of closed field lines, which in turn can have a complicated geometry with time-dependent local structures. As a result, the computations of the emerging spectra (Zane et al., 2011; Beloborodov, 2013a; Wadiasingh et al., 2018), as well as their consistent comparison with the observational data (Hascoët et al., 2014; Tendulkar et al., 2015), were not simple. Nevertheless, this research field triggered by the *INTEGRAL* discovery offered in perspective a new important channel for the understanding of physical properties of magnetars and their emission processes.

5.2. Bursts from soft gamma-ray repeaters

Two magnetars have been particularly active during the first years of the *INTEGRAL* mission, leading to the detection of several bursts: SGR 1806-20 and 1E 1547.0-5408. Many of these bursts, as well as a few ones from other magnetars, occurred within the field of view of the IBIS/ISGRI instrument and were detected and localized in real time by the INTEGRAL Burst Alert System (IBAS, Mereghetti et al., 2003). More recently, a particularly interesting result was obtained with the IBAS detection of a peculiar burst from the magnetar SGR $1935+2154$ (Mereghetti et al., 2020). This burst was characterized by the simultaneous emission of an extremely bright radio pulse with properties similar to those of the fast radio bursts (The CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020).

A detailed analysis of the bursts from SGR $1806-20$ was reported in Götz et al. (2004) and Götz et al. (2006b). Thanks to the high sensitivity of the IBIS/ISGRI imager in the 15–200 keV range, it was possible to study for the first time the faint end of the luminosity distribution of the SGR bursts. Indeed, the faintest bursts observed in October 2003 had fluences as low as 2×10^{-8} erg cm^{-2}. Several bursts showed a significant spectral evolution in the hard X-ray range and some evidence for an overall anticorrelation between spectral hardness and flux was found with a time resolved spectral analysis of the whole sample of bursts (Götz et al., 2004). This anticorrelation was later confirmed with the analysis of a larger sample of more than 200 bursts (Götz et al., 2006b). The *INTEGRAL* distribution of the burst fluences was found to be a power law with index (0.91 ± 0.09), for fluences in the range between 3×10^{-8} and 2×10^{-6} erg cm^{-2}. This rather flat slope implies that the integrated flux of fainter bursts below the detection threshold does not contribute significantly to the flux of the “persistent” hard X-ray emission.

1E $1547.0-5408$ is a transient magnetar that exhibited three major

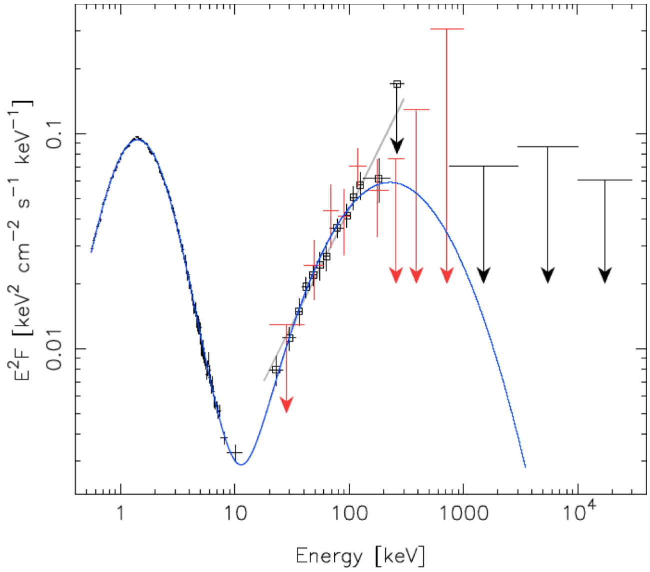

Fig. 16. The broad band spectrum of 4U $0142+61$. The data below 10 keV are from *XMM-Newton*, while those above 20 keV are from the *INTEGRAL* IBIS/ISGRI (black) and SPI (red) instruments. The upper limits in the 0.75–30 MeV range are from COMPTEL. The blue line is a best fit with a phenomenological model consisting of the sum of log-parabolic functions, that clearly illustrates the different components at soft and hard X-ray energies. Credit: den Hartog et al., A&A, 489, 245 (2008), reproduced with permission © ESO (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

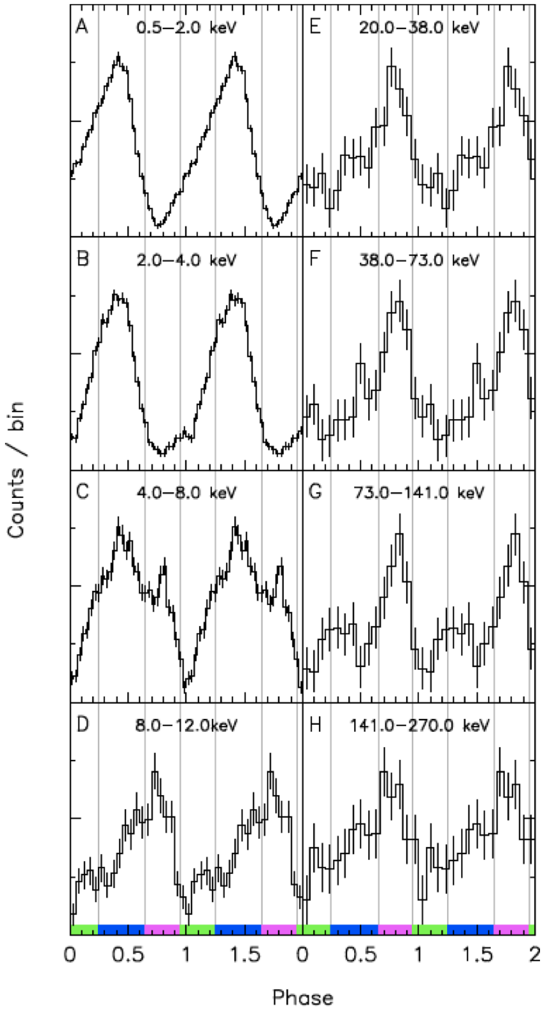

Fig. 17. Pulse profiles of 1RXS 1708 − 4009 obtained in the soft X-ray band with *XMM-Newton* (left panels) and in the hard X-ray band with *INTEGRAL* (right panels). Observations were not strictly simultaneous. Credit: den Hartog et al., A&A, 489, 263 (2008), reproduced with permission © ESO.

outbursts: in June 2007, October 2008 and January 2009 (Bernardini et al., 2011). During the latter outburst, this source emitted numerous short bursts reaching a particularly high rate on January 22, when more than 200 bursts were detected by *INTEGRAL* in a few hours (Mereghetti et al., 2009). Contrary to the case of SGR 1806 − 20, they showed a positive correlation between hardness and intensity (Savchenko et al., 2010). Some of these bursts were particularly bright, reaching a peak flux above 2×10^{-4} erg cm^{-2} s^{-1} at $E > 25$ keV. Two of them lasted several seconds, and had tails modulated at the NS spin period of 2.1 s. In particular, the time evolution of the burst shown in Fig. 18 resembled that of the giant flares. However, the energy released in this event was at most $\sim 10^{43}$ erg (for $d = 5$ kpc), which is orders of magnitude smaller than that of the three magnetar giant flares observed to date.

The *INTEGRAL* results on 1E 1547.0–5408 triggered follow-up observations with other facilities. X-ray images obtained on 2009, January 23, and in the following two weeks with *Swift* and *XMM-Newton* showed the presence of three expanding rings around the source position (Tiengo et al., 2010), caused by scattering from relatively thin dust layers along the line of sight. By fitting the expansion rate of the rings it was possible to determine the time of the burst(s) responsible for the scattered X-ray radiation and it was found to be well in agreement with the period of highest bursting activity seen with *INTEGRAL*. Furthermore, with a spectral analysis of the scattered X-rays it was also possible to estimate a distance of 4–5 kpc for 1E 1547.0–5408.

A particularly interesting burst was discovered at 14:34:24 UTC of April 28, 2020, by the IBAS software, that automatically identified its origin from the transient magnetar SGR 1935 + 2154 and distributed a public alert after less than 10 seconds. This event was indepentently discovered at radio wavelengths (The CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020) and represents the first, and so far unique, SGR burst from which simultaneous radio emission has been detected. The INTEGRAL data obtained with IBIS, as well as those obtained by other high-energy satellites (Li et al., 2020; Ridnaia et al., 2020), showed that its spectrum was harder than that of typical magnetar bursts. On the other hand, this event was not particularly luminous, with a 20–200 keV emitted energy of the order of $\sim 10^{39}$ erg (assuming isotropic emission and a distance of 4.4 kpc, Mereghetti et al. (2020)). In the 400–800 MHz band the burst consisted of two narrow pulses separated by 29 ms and with a total fluence of 700 kJy ms. Interestingly, two narrow pulses with the same separation are visible also in the IBIS light curve and have a delay of 6.5 ms with respect to the radio ones. The discovery of simultaneous fast bursting emission at radio and high-energies from SGR 1935 + 2154 gives strong support to models based on magnetars that have been proposed to explain the enigmatic class of sources known as fast radio bursts (Petroff et al., 2019; Platts et al., 2019).

5.3. The 2004 giant flare from SGR 1806–20

On December 27, 2004, a very bright burst was detected in the Anti-Coincidence Shield (ACS) of the SPI instrument and the corresponding light curve derived by the IBAS software was automatically published on-line in real time. Due to the large peak flux reached in the first 200 ms of the burst, the following tail was almost invisible on a linear scale, but, after a closer examination, its presence was noticed. The clear periodicity at 7.6 s visible in the burst tail unequivocally identified this event as a giant flare from SGR 1806–20 (Borkowski et al., 2004), similar to the two giant flares observed on 1979 March 5, from SGR 0525–66 and on 1998 August 27, from SGR 1900 + 14. This giant flare, first reported by *INTEGRAL*, was the culmination of two years of increasing bursting activity from SGR 1806–20, that was accompanied by a spectral hardening and an increase in the spin-down rate (Mereghetti et al., 2005c; Götz et al., 2006b).

Despite the downward revision in the source distance (from an initial estimate of 15 kpc, to the most likely value of 8.7 kpc; Bibby et al., 2008) the SGR 1806 − 20 giant flare has been the most energetic observed so far, with a peak isotropic luminosity of $\sim 10^{47}$ erg s^{-1}. The

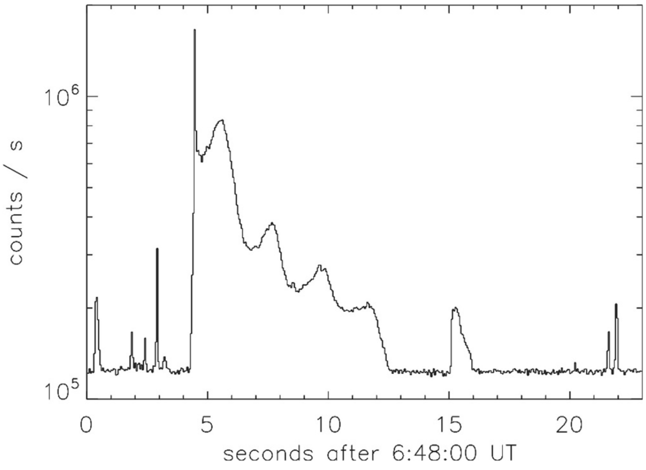

Fig. 18. The SPI/ACS light curve at $E > 80$ keV of a bright burst observed from 1E 1547.0 − 5408 on January 22, 2009. The tail following the bright initial pulse clearly shows the NS rotation period of 2.1 s. Credit: Mereghetti et al., ApJ, 696, L74 (2009), reproduced with permission of the AAS.

total energy release of $\sim 10^{46}$ erg implies a catastrophic magnetic reconnection, associated to a major crustal fracture, and leading to a global reconfiguration of the NS's magnetic field.

Detailed results on the 2004 giant flare were obtained with different satellites (Palmer et al., 2005; Terasawa et al., 2005; Hurley et al., 2005). In addition to the features reported in these works, thanks to the very large effective area of the ACS, *INTEGRAL* could discover a long-lasting emission that might be the first evidence for a soft γ-ray afterglow following a SGR giant flare (Mereghetti et al., 2005b). As it can be seen in Fig. 19, after the end of the pulsating tail, the ACS count rate increased again, reaching a peak at $t \sim 700$ s, and then returned to the pre-flare background level at $t \sim 3000 - 4000$ s. The presence of this long-lasting emission was later confirmed with *Konus-Wind* (Frederiks et al., 2007) and *RHESSI* (Boggs et al., 2007) data, although with smaller statistics and on different time intervals.

The time evolution of the "afterglow" component seen by the *INTEGRAL* ACS above ~ 80 keV is well fitted by a power-law decay with $F(t) \propto t^{-0.85}$. For a thermal Bremsstrahlung spectrum with temperature $kT = 30$ keV, the fluence at $E > 80$ keV in the 400–4000 s time interval was $\sim 3 \times 10^{-4}$ erg cm^{-2}, which is of the same order as that in the pulsating tail (i.e. in the 1–400 s time interval). However, since the ACS does not provide spectral information, an estimate of the total energy, i.e. including the contribution at energies below ~ 80 keV, is affected by a significant uncertainty due to the spectral extrapolation.

The power-law time evolution, as well as the hard power-law spectrum (photon index $\Gamma \sim 1.6$, Frederiks et al. (2007)), suggest to interpret this long-lasting emission as radiation caused by the interaction of relativistic ejecta from SGR 1806–20 with the circumstellar material (Mereghetti et al., 2005b), similar to the afterglows seen in γ-ray bursts. With standard models for γ-ray burst afterglows based on synchrotron emission, it is possible to relate the bulk Lorentz factor of the ejected material, γ_{ej}, with the time t_0 of the afterglow onset. The values observed with *INTEGRAL* give $\gamma_{ej} \sim 15(E/5 \times 10^{43}\ \mathrm{erg})^{1/8}(n/0.1\ \mathrm{cm}^{-3})^{-1/8}(t_0/100\ \mathrm{s})^{-3/8}$, where n is the ambient density. γ_{ej} is thus consistent with a mildly relativistic outflow, as also inferred from the analysis of the radio source that appeared after the giant flare (Granot et al., 2006).

6. Future prospectives

INTEGRAL has been successfully operated in Space for almost 18 years, and no major degradation of the instrument capabilities has been recorded so far. In principle, the mission scientific operations could continue until 2029, when the satellite is already planned to re-enter the Earth atmosphere. As emphasized multiple times in this review, the unique combination of sensitivity, timing resolution, large field of view and angular resolution of the *INTEGRAL* instruments has led to crucial advancements in our understanding of the pulsating hard X-ray sky.

For the study of the AMSPs and transitional millisecond X-ray pulsars in outburst, *INTEGRAL* will certainly continue to provide the means to discover additional rare members of these classes of sources. Any newly discovered object has provided unique insights into the accretion physics, leading to advancements in the understanding of the interaction between the accretion flow and the intense magnetic/gravitational field of the NS, as well as the enrichment of the interstellar medium through the thermonuclear explosions that often go off close to the compact object surface. So far, only one transitional X-ray pulsar has been caught during a bright X-ray outburst state, indeed thanks to *INTEGRAL* observations. It is thus of paramount importance to continue hunting for these peculiar objects in order to solve the unknown mechanisms driving their atypical behavior. Similar considerations hold for other transient NS sources, as the magnetars. The past 18 years of observations have proven that these objects are well at reach for the *INTEGRAL* instrumentation and we expect that additional outbursting events revealed during the *INTEGRAL* monitoring of the sky will produce rich data-sets to improve our understanding of the complex magnetospheric phenomenology that is driving the high energy emission from these systems.

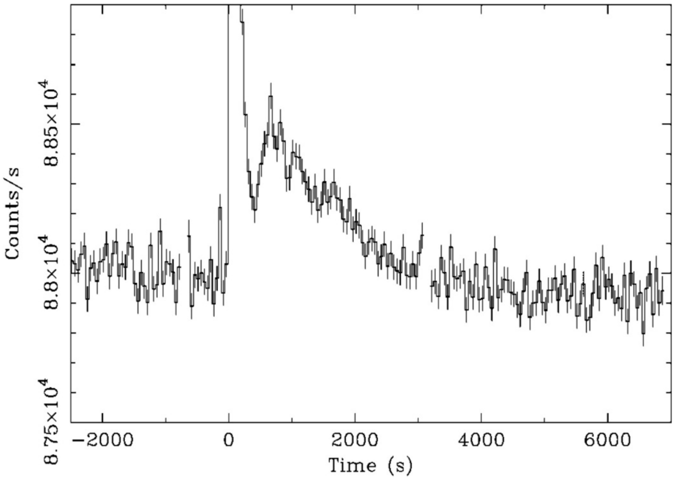

Fig. 19. SPI/ACS light curve ($E > 80$ keV) of the December 27, 2004 giant flare from SGR 1806–20 (from Mereghetti et al., 2005b). Due to the rebinning at 50 s, the 7.6 s pulsations in the tail time interval (1 - 400 s) are not visible in this figure. After the pulsating tail, the flux increases again, peaking ~ 700 s after the beginning of the flare and decreasing below the background level about one hour later. Note that the peak of the flare at $t = 0$, reaching an observed count rate $> 2 \times 10^6$ counts s^{-1}, is out of the vertical scale. Credit: Mereghetti et al., ApJ, 624, L105 (2005), reproduced with permission of the AAS.

The complementarity of the instruments on-board *INTEGRAL* with those of other last generation X-ray facilities, as *XMM-Newton, Chandra, NuSTAR*, and *NICER*, proved fundamental to go beyond the simple identification of new isolated and/or binary systems with rapidly rotating NSs. It also allowed to dig deeply inside the properties of their high energy emission, with *INTEGRAL* providing a unique contribution in the hardest X-ray energy band ($\gtrsim 80$ keV). Efforts are on-going to improve the rapidity of the response of the different facilities to the frequent *INTEGRAL* discoveries and to coordinate sub-sequent observations in a multi-messenger fashion (see, e.g., Middleton et al., 2017, and references therein).

Continued observations of the hard X-ray sky with *INTEGRAL* in the coming years will also certainly improve our sensitivity to detect fainter and fainter new hard sources. This will clearly increase the chances of discovering new multiwavelength sources, such as transitional millisecond pulsars. In this case, the *INTEGRAL* contribution will help us address fundamental questions such as which evolutionary channels produce transitional objects, how frequent is the occurrence of the faint disk state observed from these systems and ultimately which physical mechanism powers it and makes these objects different from standard AMSPs. Based on this and similar past experiences, we expect that the improved synergies between *INTEGRAL* and the other operating facilities in the multi-messenger context will help unveil the true nature of the newly discovered sources, providing further exciting discoveries and unexpected challenges in the decade to come.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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