ISOLATED NEUTRON STARS:
FROM THE SURFACE TO THE INTERIOR

Edited by:

Silvia Zane
University College London, United Kingdom

Roberto Turolla
University of Padova, Italy

Dany Page
Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico

Reprinted from Astrophysics and Space Science
Volume 308, Nos. 1–4, 2007
<table>
<thead>
<tr>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Victoria M. Kaspi / Recent progress on anomalous X-ray pulsars</td>
<td>1–11</td>
</tr>
<tr>
<td>Sandro Mereghetti, Paolo Esposito and Andrea Tiengo / XMM–Newton observations of soft gamma-ray repeaters</td>
<td>13–23</td>
</tr>
<tr>
<td>GianLuca Israel / MMIV: de SGR 1806–20 Anno Mirabili</td>
<td>25–31</td>
</tr>
<tr>
<td>Andrea Tiengo, Paolo Esposito, Sandro Mereghetti, Lara Sidoli, Diego Götz, Marco Feroci, Roberto Turolla, Silvia Zane, Gian Luca Israel, Luigi Stella and Peter Woods / Long term spectral variability in the soft gamma-ray repeater SGR 1900+14</td>
<td>33–37</td>
</tr>
<tr>
<td>Joseph D. Gelfand / The radio nebula produced by the 27 December 2004 giant flare from SGR 1806-20</td>
<td>39–42</td>
</tr>
<tr>
<td>Alaa I. Ibrahim, William C. Parke, Jean H. Swank, Hisham Anwer, Roberto Turolla, Silvia Zane, M.T. Hussein and T. El-Sherbini / The continuum and line spectra of SGR 1806-20 bursts</td>
<td>43–50</td>
</tr>
<tr>
<td>Diego Götz, Sandro Mereghetti and Kevin Hurley / Unveiling soft gamma-ray repeaters with INTEGRAL</td>
<td>51–59</td>
</tr>
<tr>
<td>Nanda Rea, Silvia Zane, Maxim Lyutikov and Roberto Turolla / Our distorted view of magnetars: application of the resonant cyclotron scattering model</td>
<td>61–65</td>
</tr>
<tr>
<td>Stefanie Wachter, Chryssa Kouveliotou, Sandeep Patel, Don Figer and Peter Woods / Spitzer space telescope observations of SGR and AXP environments</td>
<td>67–71</td>
</tr>
<tr>
<td>Ü. Ertan, M.A. Alpar, M.H. Erkut, K.Y. Ekși and Ş. Çalışkan / Anomalous X-ray pulsars: persistent states with fallback disks</td>
<td>73–77</td>
</tr>
<tr>
<td>E.V. Gotthelf and J.P. Halpern / The anatomy of a magnetar: XMM monitoring of the transient anomalous X-ray pulsar XTE J1810–197</td>
<td>79–87</td>
</tr>
<tr>
<td>M.E. Gonzalez, V.M. Kaspi, F. Camilo, B.M. Gaensler and M.J. Pivovaroff / PSR J1119–6127 and the X-ray emission from high magnetic field radio pulsars</td>
<td>89–94</td>
</tr>
<tr>
<td>Bryan M. Gaensler, Maura McLaughlin, Stephen Reynolds, Kazik Borkowski, Nanda Rea, Andrea Possenti, Gianluca Israel, Marta Burgay, Fernando Camilo, Shami Chatterjee, Michael Kramer, Andrew Lyne and Ingrid Stairs / Chandra smells a RRAT</td>
<td>95–99</td>
</tr>
<tr>
<td>Jeremy S. Heyl / QED can explain the non-thermal emission from SGRs and AXPs: variability</td>
<td>101–107</td>
</tr>
<tr>
<td>Matthew G. Baring and Alice K. Harding / Resonant Compton upscattering in anomalous X-ray pulsars</td>
<td>109–118</td>
</tr>
<tr>
<td>S. Dall’Osso and L. Stella / Newborn magnetars as sources of gravitational radiation: constraints from high energy observations of magnetar candidates</td>
<td>119–124</td>
</tr>
<tr>
<td>D.I. Jones / Astrophysical input for gravitational wave searches</td>
<td>125–132</td>
</tr>
<tr>
<td>M. Ali Alpar / Dim isolated neutron stars, cooling and energy dissipation</td>
<td>133–136</td>
</tr>
<tr>
<td>N.R. Ikhsanov / Accretion by isolated neutron stars</td>
<td>137–140</td>
</tr>
<tr>
<td>Klaus Werner, Thorsten Nagel and Thomas Rauch / Non-LTE modeling of supernova-fallback disks</td>
<td>141–149</td>
</tr>
<tr>
<td>M.C. Weisskopf, M. Karovska, G.G. Pavlov, V.E. Zavlin and T. Clarke / Chandra observations of neutron stars: an overview</td>
<td>151–160</td>
</tr>
<tr>
<td>Mark Cropper, Silvia Zane, Roberto Turolla, Luca Zampieri, Matteo Chieregato, Jeremy Drake and Aldo Treves / XMM-Newton observations of the isolated neutron star 1RXS J214303.7+065419/RBS1774</td>
<td>161–166</td>
</tr>
<tr>
<td>A. Treves, S. Campana, M. Chieregato, A. Moretti, T. Nelson and M. Orio / Persistent and transient blank field sources</td>
<td>167–169</td>
</tr>
</tbody>
</table>
B. Posselt, S.B. Popov, F. Haberl, J. Trümper, R. Turolla and R. Neuhäuser / The Magnificent Seven in the dusty prairie 171–179
Frank Haberl / The magnificent seven: magnetic fields and surface temperature distributions 181–190
M.H. van Kerkwijk and D.L. Kaplan / Isolated neutron stars: magnetic fields, distances, and spectra 191–201
V.M. Malofeev, O.I. Malov and D.A. Teplykh / Radio emission from AXP and XDINS 211–216
Christian Motch, Adriana M. Pires, Frank Haberl and Axel Schwope / Measuring proper motions of isolated neutron stars with Chandra 217–224
Jacqueline Faherty, Frederick M. Walter and Jay Anderson / The trigonometric parallax of the neutron star Geminga 225–230
A. De Luca, P.A. Caraveo, S. Mereghetti, A. Tiengo and G.F. Bignami / The puzzling X-ray source in RCW103 231–238
Peter M. Woods, Vyacheslav E. Zavlin and George G. Pavlov / Evidence for a binary companion to the central compact object 1E 1207.4-5209 239–246
Silvia Zane / Neutron star surface emission: Beyond the dipole model 259–265
Alexander V. Turbiner / Molecular systems in a strong magnetic field 267–277
Wynn C.G. Ho, David L. Kaplan, Philip Chang, Matthew van Adelsberg and Alexander Y. Potekhin / Thin magnetic hydrogen atmospheres and the neutron star RX J1856.5–3754 279–286
Oleg Kargaltsev and George Pavlov / Ultraviolet emission from young and middle-aged pulsars 287–296
Vyacheslav E. Zavlin / Studying millisecond pulsars in X-rays 297–307
Katherine E. McGowan, W. Thomas Vestrand, Jamie A. Kennea, Silvia Zane, Mark Cropper and France A. Córdova / X-ray observations of PSR B0355+54 and its pulsar wind nebula 309–316
Margaret A. Livingstone, Victoria M. Kaspi, Fotis P. Gavriil, Richard N. Manchester, E.V.G. Gotthelf and Lucien Kuiper / New phase-coherent measurements of pulsar braking indices 317–323
Janusz Gil, George Melikidze and Bing Zhang / Thermal X-ray emission from hot polar cap in drifting subpulse pulsars 325–333
V.S. Beskin and E.E. Nokhrina / The example of effective plasma acceleration in a magnetosphere 335–343
A.N. Timokhin / Impact of neutron star oscillations on the accelerating electric field in the polar cap of pulsar 345–351
Alexander Y. Potekhin, Gilles Chabrier and Dmitry G. Yakovlev / Heat blanketing envelopes and thermal radiation of strongly magnetized neutron stars 353–361
P. Haensel and J.L. Zdunik / Equation of state of neutron star cores and spin down of isolated pulsars 363–369
James M. Lattimer / Equation of state constraints from neutron stars 371–379
Sergei Popov, David Blaschke, Hovik Grigorian and Mikhail Prokhorov / Neutron star masses: dwarfs, giants and neighbors 381–385
G.F. Burgio, M. Baldo, O.E. Nicotra and H.-J. Schulze / A microscopic equation of state for protoneutron stars 387–394
N. Andersson / Modelling the dynamics of superfluid neutron stars 395–402
Dany Page, Ulrich Geppert and Manfred Küker / Cooling of neutron stars with strong toroidal magnetic fields 403–412
Andreas Reisenegger, Rodrigo Fernández and Paula Jofré / Internal heating and thermal emission from old neutron stars 413–418
A.N. Timokhin / Force-free magnetosphere of an aligned rotator with differential rotation of open magnetic field lines 575–579

Lars Samuelsson and Nils Andersson / Oscillations in the neutron star crust 581–583

Richard Dodson, Dion Lewis and Peter McCulloch / Two decades of pulsar timing of Vela 585–589

Tatiana V. Shabanova / Slow glitches in the pulsar B1822-09 591–593

S. Karpov, G. Beskin, A. Biryukov, V. Debur, V. Plokhotnichenko, M. Redfern and A. Shearer / Short time scale pulse stability of the Crab pulsar in the optical band 595–599

Armando Manzali, Andrea De Luca and Patrizia A. Caraveo / Using XMM-Newton to measure the spectrum of the Vela pulsar and its phase variation 601–605

Kostas Glampedakis, Lars Samuelsson and Nils Andersson / A toy model for global magnetar oscillation 607–611

A.G. Aksenov, M. Milgrom and V.V. Usov / Structure of pair winds from compact objects with application to emission from bare strange stars 613–617

Axel D. Schwope, Valeri Hambaryan, Frank Haberl and Christian Motch / The complex X-ray spectrum of the isolated neutron star RBS1223 619–623

Anna L. Watts and Tod E. Strohmayer / High frequency oscillations during magnetar flares 625–629

A.M. Beloborodov and C. Thompson / Magnetar corona 631–639

Martin Durant / Intrinsic spectra of the AXPs 641–645

P.R. den Hartog, L. Kuiper, W. Hermsen, N. Rea, M. Durant, B. Stappers, V.M. Kaspi and R. Dib / The first multi-wavelength campaign of AXP 4U 0142+61 from radio to hard X-rays 647–653
Recent progress on anomalous X-ray pulsars

Victoria M. Kaspi

Abstract I review recent observational progress on Anomalous X-ray Pulsars, with an emphasis on timing, variability, and spectra. Highlighted results include the recent timing and flux stabilization of the notoriously unstable AXP 1E 1048.1−5937, the remarkable glitches seen in two AXPs, and the newly recognized variety of AXP variability types, including outbursts, bursts, flares, and pulse profile changes. I also discuss recent discoveries regarding AXP spectra, including their surprising hard X-ray and far-infrared emission, as well as the pulsed radio emission seen in one source. Much has been learned about these enigmatic objects over the past few years, with the pace of discoveries remaining steady. However additional work on both observational and theoretical fronts is needed before we have a comprehensive understanding of AXPs and their place in the zoo of manifestations of young neutron stars.

Keywords Pulsars · Magnetars · Variability · X-ray spectra · Timing

PACS 97.60.Jd · 97.60.Gb · 98.70.Qy

1 Introduction

Although very few in number, the eight, and possibly nine, known so-called “Anomalous X-ray Pulsars” (AXPs; see Table 1) are potentially very powerful for making progress on the physics of neutron stars. AXPs embody properties that are highly reminiscent of two other, very different classes of neutron star: the spectacular Soft Gamma Repeaters (SGRs; see contributions by Mereghetti and others in this volume), and conventional radio pulsars. The great similarity of AXPs to SGRs is what makes the case for AXPs being magnetars so compelling and also offers the hope of constraining magnetar physics. The intriguing similarities with radio pulsars offer the promise of solving long-standing problems in our theoretical understanding of the latter.

In this review, I describe the most recent observational progress on AXPs. The review will be divided into sections on timing (Sect. 2), variability (Sect. 3), and spectra (Sect. 4), choices that, unfortunately, may exhibit some personal bias, necessary given the limited space available. I hope to show that recent AXP progress has been significant, however ultimately, much observational and theoretical work remains to be done before a complete picture of AXPs and their place in the neutron-star zoo becomes clear.

Note that the most comprehensive and recent review of AXPs and magnetars in general is that by Woods and Thompson (2004). In this review, I make use of the detailed, online summary of magnetar properties and references maintained at McGill University by C. Tam (http://www.physics.mcgill.ca/~pulsar/magnetar/main.html).

2 Timing

Timing observations of AXPs hold considerable information about both their surroundings via the external torques they feel, as well as potentially about their internal structure, via the “glitches” they experience. Here we summarize what is known regarding AXP timing properties, highlighting the most interesting issues.
2.1 Stability and phase-coherent timing

Studies of the timing properties of AXPs can reasonably be categorized as pre- and post-Rossi X-ray Timing Explorer (RXTE), launched in late 1995. Prior to RXTE, timing studies were limited to occasional observations spread over many years. These characterized the overall spin-down behavior of several AXPs, and also suggested some deviations from simple spin-down (e.g. Baykal and Swank 1996; Corbet and Mihara 1997; Baykal et al. 2000; Paul et al. 2000). However the nature of these deviations could not be determined, because of the paucity of observations. Careful searches for Doppler shifts of the observed periodicities had been done (e.g. Iwasawa et al. 1992; Baykal and Swank 1996); typical upper limits on \( a \sin i \) were \( \sim 0.1 \) lt-s for a variety of orbital periods.

RXTE and its Proportional Counter Array (PCA) revolutionized the timing of AXPs. The first PCA studies of AXPs reduced the limits on \( a \sin i \) to 0.03 lt-s for 1E 2259+586 and 0.06 lt-s for 1E 1048.1–5937, effectively ruling out any main-sequence star companion and rendering binary accretion models highly problematic (Mereghetti et al. 1998).

Subsequently, a program of regular monthly monitoring of the AXPs with the PCA on RXTE was approved and showed that fully phase-coherent timing of AXPs could be done over years, assuming spin-down models consisting of very few parameters (Kaspi et al. 1999). For example, Gavriil and Kaspi (2002) showed that in 4.5 yr of RXTE monitoring, pulse times of arrival for 1E 2259+586 could be predicted to within 1% of the pulse period using \( \nu \), \( \dot{\nu} \) and \( \ddot{\nu} \) only. Such stability is comparable to that of conventional young radio pulsars and very much unlike the large amplitude torque noise commonly seen in accreting neutron stars. Long-term, regular monthly (or even bi-monthly) observations of AXPs continue today, with four of the five persistent confirmed Galactic sources (4U 014+61, 1RXS J170849.0–400910, 1E 1841–045 and 1E 2259+586) generally exhibiting stability that allows phase coherence with few parameters over years (Kaspi et al. 2000; Gavriil and Kaspi 2002; Gotthelf et al. 2002; Kaspi and Gavriil 2003; Dib et al. 2006). A summary of the timing properties of the known AXPs is given in Table 1.

One of the established persistent Galactic AXPs, 1E 1048.1–5937, has been much less stable than the others, such that phase-coherent timing with unambiguous pulse counting over more than a few weeks or months has been difficult to achieve (Kaspi et al. 2001; Gavriil and Kaspi 2004). This poor stability is apparent in the source’s frequency evolution (Fig. 1). Recently, however, during an extended period of pulsed flux stability following two long-lived X-ray flares (see Sect. 3.3), the timing has also become quite stable, such that unambiguous phase coherence could be maintained over a nearly 2-yr interval from MJD 53158 to 53858 using 4 spin parameters, although significant residuals remain (Fig. 2). Details of these results will be described elsewhere. It remains to be seen if an end to this stability will be accompanied by additional radiative events, a result that would hopefully be useful for strongly constraining models for the torque noise and flares.

2.2 Glitches

The impressive timing stability seen in most AXPs, in which pulse periods could easily be determined to better than a

### Table 1 Properties of known and candidate AXPs

<table>
<thead>
<tr>
<th>Name</th>
<th>( P ) (s)</th>
<th>( \dot{P} ) (( \times 10^{-11} ))</th>
<th>( B ) (( \times 10^{14} ) G)</th>
<th>Timing properties</th>
<th>X-ray Variability properties</th>
<th>Waveband detections</th>
<th>Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXOU J010043.1–721134</td>
<td>8.02</td>
<td>1.9</td>
<td>3.9</td>
<td>S?</td>
<td>S</td>
<td>X O?</td>
<td>SMC</td>
</tr>
<tr>
<td>4U 0142+61</td>
<td>8.69</td>
<td>0.2</td>
<td>1.3</td>
<td>S G?</td>
<td>M P</td>
<td>H X O I</td>
<td>…</td>
</tr>
<tr>
<td>1E 1048.1–5937</td>
<td>6.45</td>
<td>2.7</td>
<td>4.2</td>
<td>N</td>
<td>S F F B</td>
<td>H X I?</td>
<td>…</td>
</tr>
<tr>
<td>CXOU J164710.2–455216</td>
<td>10.61</td>
<td>0.16</td>
<td>1.3</td>
<td>G?</td>
<td>B P</td>
<td>X</td>
<td>Westerlund 1</td>
</tr>
<tr>
<td>1RXS J170849.0–400910</td>
<td>11.00</td>
<td>1.9</td>
<td>4.7</td>
<td>S G G</td>
<td>S</td>
<td>H X I</td>
<td>…</td>
</tr>
<tr>
<td>XTE J1810–197</td>
<td>5.54</td>
<td>0.5</td>
<td>1.7</td>
<td>N</td>
<td>O B</td>
<td>X I R</td>
<td>…</td>
</tr>
<tr>
<td>1E 1841–045</td>
<td>11.78</td>
<td>4.2</td>
<td>7.1</td>
<td>N</td>
<td>S</td>
<td>H X I?</td>
<td>SNR Kes 73</td>
</tr>
<tr>
<td>AX J1845–0258</td>
<td>5.97</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>O</td>
<td>X</td>
<td>SNR G29.6+0.1</td>
</tr>
<tr>
<td>1E 2259+586</td>
<td>6.98</td>
<td>0.048</td>
<td>0.59</td>
<td>S G</td>
<td>S O B P</td>
<td>H X I</td>
<td>SNR CTB 109</td>
</tr>
</tbody>
</table>
part in a billion, permitted for the first time the unambiguous detection of sudden spin-up glitches in AXPs. 1RXS J170849.0–400910 was the first pulsar seen to glitch (Kaspi et al. 2000). This glitch had a fractional frequency increase of $4 \times 10^{-6}$, which was accompanied by significant and truly remarkable recovery in which roughly a quarter of the frequency jump relaxed on a $\sim 40$-day scale. As part of that recovery, the measured spin-down rate of the pulsar was temporarily larger than the long-term pre-burst average by a factor of 2! This recovery was similar to, though better sampled than, the second glitch seen in 1RXS J170849.0–400910. The 1E 2259+586 event was the first (and still the only unambiguous, but see Sect 3.3) time a spin-up glitch in a neutron star was accompanied by any form of radiative change. This event suggests that large glitches in AXPs are generally associated with radiative events; perhaps such an event occurred at the time of the second glitch in 1RXS J170849.0–400910 but went unnoticed due to sparse monitoring. The very interesting recoveries of the 1E 2259+586 and second 1RXS J170849.1–400910 glitches seem likely to be telling us something interesting about the interior of a magnetar and how it is different from that of a conventional, low-field neutron star. This seems worth more attention than it has received in the literature thus far.

Recently a timing anomaly was reported in AXP 4U 0142+61 (Dib et al. 2006). This is work in progress and will be reported on elsewhere. However, Morii et al. (2005) and Dib et al. (2006) suggest that this pulsar may have glitched during a large observing gap in 1998–1999, a possibility
supported by apparent changes in the pulse profile that seem to have occurred in the same interval (Dib et al. 2006).

3 AXP Variability

Arguably one of the most interesting recent discoveries in the study of AXPs is the range and diversity of their X-ray variability properties. Pre-RXTE, there was variability reported (e.g. Baykal and Swank 1996; Corbet and Mihara 1997; Oosterbroek et al. 1998; Paul et al. 2000), however those relatively sparse observations were made using different instruments aboard different observatories, some imaging, some not, and were often presented without uncertainties, making their interpretation difficult. Moreover, given the sparseness of the observations, identifying a time scale for the variations, or being certain the full dynamic range was being sampled, was not possible.

Post-RXTE, and, additionally, with contemporaneous observations made using Chandra and XMM, the picture has become much clearer. Presently there appear to be at least four types of X-ray variability in AXP pulsed and persistent emission: outbursts (sudden large increases in the pulsed and persistent flux, accompanied by bursts and other radiative and timing anomalies, which decay on time scales of weeks or months), bursts (sudden events, lasting milliseconds to seconds), long-term flux changes (time scales of years), and pulse profile changes (on time scales of days to years). We examine each of these phenomena in turn.

3.1 Outbursts and Transients

The current best example of an AXP outburst is that seen in June 2002 from 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2004). This outburst, which lasted only a few hours, fortuitously occurred during a few-hour monthly RXTE monitoring observation. During the outburst, the pulsed and persistent fluxes increased by a factor of ~20 (see Fig. 4), there were over 80 short SGR-like bursts in a few-hour period (see Sect. 3.2), there were substantial pulse profile changes (see Sect. 3.4), there was a short-term decrease in the pulsed fraction, the spectrum hardened dramatically, there was a large glitch (see Sect. 2.2 above), and there was an infrared enhancement (see Sect. 3.5). All this came after over 4 yr of otherwise uneventful behavior (Gavriil and Kaspi 2002). Note that had RXTE not been observing the source during the outburst, the entire event would have appeared, from the monitoring data, to consist principally of a glitch. With only monthly monitoring, all but the longest-term radiative changes would have been missed. Interestingly, this outburst was notably different from SGR outbursts; for the AXP, the energy in the outburst “afterglow” (~10^{41} erg; see Fig. 4) greatly exceeded that in the bursts (~10^{37} erg). This is in direct contrast to the giant flares of SGRs. The reason for this difference is unknown.

The outburst of 1E 2259+586 seems likely to be a good model for the behavior of the “transient” AXP XTE J1810–197. This source, unknown prior to 2003, was discovered as a bright 5.5 s X-ray pulsar, upon emerging from behind the Sun in that year (Ibrahim et al. 2004), and has been fading ever since. The source’s spin down and spectrum are consistent with it being an AXP. Gotthelf et al. (2004) showed from archival ROSAT observations that in the past, the source, in quiescence, was nearly two orders of magnitude fainter than in outburst. See the contribution by Gotthelf et al. in this volume for more details. An important question raised by the discovery of XTE J1810–917 is “how many more such objects exist in our Galaxy”? This has important implications for AXP birthrates.

Such an outburst may also explain the behavior of the unconfirmed transient AXP AX J1845–0258 (see Table 1). Pulsations with a period of 7 s were observed in an archival 1993 ASCA observation (Torii et al. 1998; Gotthelf and Vasisht 1998), however subsequent observations of the target revealed a large drop in flux, and pulsations have not been redetected. Although no ν has been measured for this source, it seems likely it is an AXP given its period and location at the center of a supernova remnant (Gaensler et al. 1999). It is thus plausible that the 1993 outburst was similar to that of 1E 2259+586 or XTE J1810–197, although the likely dynamic range for this source is unprecedented for an
AXP. See the contribution to these proceedings by Tam et al. and Tam et al. (2006) for more details.

One of the most puzzling aspects of transient AXPs is why the quiescent source is so faint. In the standard magnetar model, the requisite magnetic field decay energy input is persistent, as is the magnetospheric twist for a fixed magnetar-strength magnetic field (Thompson and Duncan 1996; Thompson et al. 2002). Although much attention has been paid to why a magnetar’s flux might skyrocket suddenly—a sudden reconfiguration of the surface following a crustal yield—relatively little attention has been paid to how to stop or hide the bright X-ray emission from a neutron star presumably harboring a magnetar-strength field.

3.2 Bursts

During the 2002 1E 2259+586 outburst, over 80 short, SGR-like X-ray bursts were seen superimposed on the overall flux trend over the course of the few-hour RXTE observation (Kaspi et al. 2003). Some were super-Eddington, though only on very short (few ms) time scales. In a detailed analysis of these bursts, Gavriil et al. (2004) found that in most respects, they are identical to SGR bursts. Specifically, the durations, differential fluence distribution, the burst morphologies, the wait-time distribution, and the correlation between fluency and duration, are all SGR-like. However a few of the burst properties were different from those of SGR bursts: for example, the AXP bursts had a wider range of durations, the AXP bursts were on average less energetic than in SGRs, and the more energetic AXP bursts have the hardest spectra—the opposite of what is seen for SGRs. Unlike in SGRs, the AXP bursts were correlated with pulsed intensity.

Bursts in AXPs were first reported by Gavriil et al. (2002) who discovered two such events in archival RXTE data from the direction of 1E 1048.1–5937. A third burst, found nearly 3 yr later (Gavriil et al. 2006), unambiguously identified the AXP as the origin thanks to a simultaneous pulsed flux increase (by a factor of ∼4 relative to the long-term average) which decayed on a time scale of minutes. This suggests, as does the accompanying pulse profile change and timing anomaly, that this source may have entered an extended active phase.

With at least half of the known AXPs now established as capable of bursting, it is clear that the production of occasional though clustered short SGR-like bursts is a generic AXP phenomenon.

3.3 Long-term flux variations

Variability in AXP 1E 1048.1–5937 had been reported for years (e.g. Corbet and Mihara 1997; Oosterbroek et al. 1998; Baykal et al. 2000; Mereghetti et al. 2004). RXTE monitoring determined the time scale of the changes and the morphology of the pulsed light curve with far superior time sampling than in previous studies (Gavriil and Kaspi 2004). Specifically, the RXTE monitoring showed that over ∼7 yr, the source exhibited two extended pulsed flux “flares,” the first lasting ∼100 days and the second lasting over a year, each with rise times of several weeks. Assuming a distance to the source of 5 kpc (which is not especially well established), Gavriil and Kaspi (2004) estimated the total energy released in the pulsed components of the first and second flares to be 3 and 3 × 10^{40} erg, respectively. Subsequently, Tiengo et al. (2005), using XMM, which (unlike RXTE) is sensitive to pulsed fraction, showed that in fact the pulsed fraction is anti-correlated with the phase-averaged flux, suggesting the total energy released was at least twice that in the pulsed component.

During these flares, the spin-down rate fluctuated by at least a factor of 10 (Gavriil and Kaspi 2004). However, there was no obvious correlation between the detailed evolution of the spin-down rate and flux. Recently, while its flux has been stable, 1E 1048.1–5937 has shown much greater timing
stability (see Sect. 2). This suggests that the large torque noise and flux flaring were causally related; we must await another such event to confirm this.

The flaring observed in 1E 1048.1–5937, a new phenomenon not yet observed in any other AXP, is well understood in the context of the twisted magnetosphere model (Thompson et al. 2002). The flux enhancements can be seen as being due to increased twisting of the magnetosphere by currents originating from the stressed crust. If so, a harder spectrum is expected when the pulsar is brighter. Unfortunately the existing data cannot confirm this important prediction for this source. Decoupling of the torque from the pulsed flux can occur in this model depending on the location of the enhanced magnetospheric current; a current near the pole will have a disproportionate impact on the spin-down. Gavril and Kaspi (2004) argued that the absence of predicted torque–luminosity variations in this source are problematic for models in which the X-ray flux originates from accretion from a fossil disk (e.g. Chatterjee et al. 2000; Alpar 2001, but see Ertan et al. contribution, this issue).

The twisted magnetosphere model prediction that flux should be correlated with hardness, though unconfirmed in 1E 1048.1–5937, does seem to be borne out in observations of 1RXS J170849.0–400910 (Rea et al. 2005, see contribution by Rea et al., this volume). Moreover, those authors suggest that the epochs of greatest hardness occur near those in which glitches were detected in this source (see Sect. 2.2), with subsequent softening post-glitch. At least one additional glitch needs to occur, with better observational coverage, before this conclusion is firm.

Recently, much longer-term radiative variations have been identified in AXP 4U 0142+61, in which the pulsed flux appears to be increasing since 2000, such that there was a ∼ 20% change by early 2006, just prior to its exhibiting a sudden pulse profile change and bursts. This behavior is described in more detail in the contribution by Dib et al. to this volume as well as in Dib et al. (2006). One particularly interesting implication of an increase in total X-ray flux from this source is that the phenomenon provides a simple test of the irradiated fall-back disk model for the near-IR emission (see Sect. 4.3). If the source of irradiation, the AXP, increases in brightness, the disk ought to as well.

3.4 Pulse profile changes

The first observed pulse profile change in an AXP was reported by Iwasawa et al. (1992) using GINGA data obtained in 1989. They witnessed a large change in the ratio of the amplitudes of the two peaks in the pulse profile of 1E 2259+586, namely from near unity to over two. They also reported a contemporaneous timing anomaly which, in hindsight, is consistent with a spin-up glitch.

A very similar pulse profile change was witnessed during and immediately following the 2002 outburst of 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2004). Here, the ratio of the amplitudes of the two pulses in the profile went from unity pre-outburst to roughly two mid-outburst, relaxing back to normal on a time scale of a few weeks (Fig. 5). Curiously, the temporarily larger peak in the 2002 outburst appeared to be the temporarily smaller peak in 1989, suggesting that even if the physical origin of the events is the same, the details of the geometry were different. Given the nature of this event, a likely explanation for the pulse profile change is a magnetospheric reconfiguration following a crustal fracture that simultaneously affected the inside and outside of the star. This very strongly suggests that the Iwasawa et al. (1992) pulse profile change was observed not long after a similar event; this is consistent with their reported timing anomaly, and suggests such events occur roughly every 1–2 decades in this source.

Most recently, long-term (i.e. time scale of several years) pulse profile variations have been reported for AXP 4U 0142+61 (Dib et al. 2006, see contribution by Dib et al., these proceedings). These may accompany a long-term pulsed flux increase (see Sect. 3.3). The profile changes are consistent with a significant event having occurred some time between mid-1998 and 2000, in which the second and higher harmonics of the profile increased dramatically, and have been returning to their pre-event level ever since. This gradual evolution was, however, interrupted by an apparent sudden activity episode, in which an SGR-like burst was detected along with a timing anomaly in April 2006 (see Sect. 3.2; Kaspi et al. 2006). The analysis of the latter data are in progress.

3.5 Near-IR variability

The large number of recent near-IR detections of AXPs has revealed an interesting new variability phenomenon in these sources. Following the 2002 outburst of 1E 2259+586, there was an infrared (Ks) enhancement by a factor of ∼3, 3 days post-outburst. This then decayed together with the X-ray pulsed flux, with identical power-law indices (see Fig. 4, Sect. 3.1; Tam et al. 2004). Those authors concluded that the origins of both flux increases were magnetospheric (but see contribution by Ertan et al., these proceedings for the fossil-disk viewpoint). A similar correlation was also reported for AXP XTE J1810–197 (Rea et al. 2004).

Meanwhile, significant near-IR variability has also been reported for AXP 1E 1048.1–5937 (Israel et al. 2002; Wang and Chakrabarty 2002; Durant and van Kerkwijk 2005). However, if anything, the near-IR is anti-correlated with the X-ray flux. This is puzzling given the 1E 2259+586 and XTE J1810–197 results. It is worth keeping in mind, however, that there is now some evidence that 1E 1048.1–5937 has been in an active phase from which it may have recently emerged (see Sect. 2); it will be interesting to see how its
Fig. 5 Pulse profile changes in 1E 2259+586 following its 2002 outburst (Woods et al. 2004)

near-IR flux varies now that both the X-ray flux and timing have stabilized (see Fig. 1).

In addition, Durant and van Kerkwijk (2006a) report on near-IR observations of 4U 0142+61 and report no apparent correlation with the X-ray pulsed flux. They argue that the situation for this source is unclear and warrants additional, more frequent observations. Simultaneous far-IR observations would also be of interest to establish conclusively that they originate from a separate mechanism, namely radiation from a passive, irradiated fall-back disk (Wang et al. 2006).

4 AXP spectra

The description of spectra of AXPs has, until very recently, been limited to the soft (0.5–10 keV) X-ray band, as that is where AXPs were discovered and have been traditionally studied. However the recent discoveries of optical and near-IR emission have cast them firmly into the multi-wavelength regime, and the even more recent detections in the hard X-ray band as well as in the far-IR and radio bands broadens the situation even further.

4.1 X-ray spectra

In the traditional 0.5–10 keV X-ray band, AXPs have long been known to show two-component spectra, which are well described by a blackbody plus a power law (e.g. White et al. 1996; Israel et al. 2001; Morii et al. 2003). It is currently thought that the blackbody arises from internal heating due to the decaying intense magnetic field, while the non-thermal component is a result of resonant scattering of the thermal seed photons off magnetospheric currents in the twisted magnetosphere (Thompson et al. 2002). Detailed spectral modelling in this framework appears to describe the spectrum of 1E 1048.1–5937 (Lyutikov and Gavriil 2006), but see the contribution by N. Rea in these proceedings. Although some attempts were made to model the entire spectrum using a single blackbody distorted by the effects of the intense magnetic field on the atmosphere (e.g. Özel 2001),
these could not reproduce the non-thermal component adequately (e.g. Perna et al. 2001; Thompson et al. 2002; Lai and Ho 2003).

There is evidence supporting a physical connection between the two components, such as the very slow evolution of the pulse profile with energy (e.g. Israel et al. 2001; Gavriil and Kaspi 2002). For some AXPs (for example 1E 1048.1–5937 and 1E 1841–045), there is little if any variation in the pulse profile, with no obvious difference between profiles in energy bands that are thermally and non-thermally dominated. Even in other AXPs for which the profile is energy-dependent, the profiles in bands that are thermally and non-thermally dominated are still very similar. This is in stark contrast to the situation for rotation-powered pulsars, for which the thermal and non-thermal components generally have radically different X-ray pulse profiles (e.g. Harding et al. 2002).

Recently, Halpern and Gotthelf (2005) have suggested on purely theoretical grounds that the spectrum of XTE J1810–197 is more appropriately described by a two-component model consisting of two blackbodies (see also contribution by Gotthelf et al. in this volume). Their main argument for this interpretation is that an extrapolation of the power-law component to low energies greatly exceeds that expected if the seeds are thermal photons from the surface, as the blackbody eventually runs out of photons to supply. Moreover, they argue, the expected blackbody cutoff would then result in a substantial underestimate of the infrared flux, assuming the latter is part of the non-thermal spectrum. Very recently, Durant and van Kerkwijk (2006c) have shown using independently measured interstellar column densities that the intrinsic spectra really are cut off, i.e. the power-law component does not in fact extend far below the observable band. If correct, the rationale for preferring the double blackbody over the blackbody plus power law would not apply.

This section would not be complete without some discussion of the interesting recent results of Durant and van Kerkwijk (2006b, 2006c), some of which are reported on by Durant et al. in this volume. Specifically, using high-resolution X-ray spectroscopy, they identified absorption edges whose amplitudes determine $N_{\text{H}}$ under reasonable assumptions, independent of the overall continuum spectral modelling. Using these newly measured values of $N_{\text{H}}$ and a novel distance estimation technique using reddening runs with distance for red clump stars, they were able to first improve the spectral fits for several AXPs significantly, and second determine much improved distance estimates for them. Amazingly, among other things, they find that the soft X-ray luminosities of practically all AXPs are consistent with the value $\sim 1.3 \times 10^{35}$ erg s$^{-1}$. Durant and van Kerkwijk (2006b) argue that this is consistent with the magnetar model’s prediction that there should be a saturation luminosity above which internal neutrino cooling is at work.

4.2 Hard X-ray spectra

A particularly interesting recent AXP discovery is that they are copious hard X-ray emitters (Molkov et al. 2004; Kuiper et al. 2004). Though their spectra in $\nu F_\nu$ appear to fall off in the softer X-ray band, they turn up again above $\sim 10$ keV. The luminosities above 10 keV independently greatly exceed the available spin-down power by factors of over 100. This requires a new mechanism for accelerating particles in the magnetosphere, in addition to an energy source, presumably the decaying magnetic field. SGR 1806–20 has also been detected in this energy range, though interestingly it is somewhat softer than the AXPs (Mereghetti et al. 2005). Kuiper et al. (2006) have further shown that the hard X-ray emission is a generic property of AXPs, and for at least three sources, extends without a break up to 150 keV. They also show from COMPTEL upper limits that the break must lie under $\sim 750$ keV. Determining the location of the break could greatly constrain emission models, possibly even providing independent evidence for the magnetar-strength field. See the contribution by P. den Hartog et al. in this volume for details regarding hard-X-ray emission from 4U 0142+61.

This hard X-ray emission, apart for being interesting for constraining the physics of magnetars, offers a unique way of detecting AXPs throughout the Galaxy, since the soft X-ray emission suffers from high absorption, especially in the inner Galaxy. A focussing hard X-ray instrument (like the NASA mission concept NuSTAR) would have the capability of detecting every magnetar in the Galaxy, provided their hard X-ray emission is generic, even in quiescence.

4.3 Optical and infrared spectra

Currently, five of the known AXPs have been conclusively detected in the near-IR, with only 4U 0142+61 (the closest, least absorbed AXP) having been detected optically. None of the SGRs has been detected optically, and only one has been seen in the near-IR (SGR 1806–20; Kosugi et al. 2005), and only during a particularly active phase. For a summary of these detections, see www.physics.mcgill.ca/~pulsar/magnetar/main.html and references therein.

The near-IR spectra of AXPs are an interesting puzzle. First, given the variability in the near-IR (Sect. 3.5), piecing together an accurate instantaneous spectrum using photometry requires contemporaneous observations, not always possible. Even more of a problem has been the generally unknown reddening toward the sources, which have an enormous impact on the inferred intrinsic spectrum. Nevertheless, some information regarding the optical and near-IR spectra of AXPs is known. Overall, the major mystery is how the optical and near-IR emission connects with the X-ray spectrum. The blackbody emission seen in X-rays grossly underpredicts that in optical/near-IR, while a simple extrapolation of the non-thermal component (when the
spectrum is described in this way—see Sect. 4.1) generally overpredicts it. Expecting at least the optical emission to connect spectrally with the X-rays is reasonable given that the latter is pulsed in 4U 0142+61 (Kern and Martin 2002; Dhillon et al. 2005) hence seems likely to originate in the magnetosphere, as does, presumably, the non-thermal X-ray emission.

Very recently, Wang et al. (2006) have shown using Spitzer data of 4U 0142+61 that in the far-IR, there appears to be a component that is spectrally distinct from the near-IR emission. They interpret this component as resulting from a passive debris disk irradiated by the central X-ray source. They suggest that such disks, which originate from matter that falls back following the supernova explosion, may be ubiquitous around neutron stars. They further suggest that the correlated near-IR/X-ray flux decay observed by Tam et al. (2004) following the 2002 outburst of 1E 2259+586 and for XTE J1810–197 (see Sect. 3.5) could be a result of a disk around that AXP as well, a possibility also discussed by Ertan et al. (2006) and Ertan et al. in these proceedings. If the fallback-disk interpretation is correct for 4U 0142+61, the pulsed X-ray flux change recently detected in this source (Sect. 3.3) may provide an opportunity for a test of the disk hypothesis (Dib et al. 2006, and Dib et al. in this volume), as there should be a correlated increase in the near-IR flux. This idea requires that the overall X-ray flux, not just the pulsed component, also be increasing, which requires observations with an imaging X-ray telescope to verify.

4.4 Radio spectrum

Very recently (in fact after this meeting took place!), Camilo et al. (2006) reported the detection of radio pulsations from XTE J1810–197. This was a magnetar first and in many ways a welcome discovery, having provided a nice radiative link between magnetars and radio pulsars, in addition to the similarity already established from timing observations (see Sect. 2). It also demonstrated that pulsed radio emission can definitely be produced in magnetar-strength fields in contrast to some predictions (e.g. Baring and Harding 1998). Previous searches of other non-transient AXPs had come up empty (e.g. Burgay et al. 2006; Crawford et al. 2006, and see contribution by Burgay et al., this volume), suggesting the radio emission here might somehow be related to this source’s transient nature. Given the small radio beaming fraction reasonably expected for such slow pulsars, the absence of radio pulsations from other sources could also be due to small-number statistics.

Also interesting is the unusual spectrum of the radio emission seen from XTE J1810–197. It has an unusually flat spectrum, with spectral index \(-0.5\), whereas radio pulsars have very steep spectra, with most indices between \(-1\) and \(-3\). XTE J1810–197 is the brightest radio pulsar known at frequencies >20 GHz. Why this should be the case is an interesting new puzzle for magnetar physics, one which has the potential to shed crucial new light on the long-standing problem of the origin of radio emission in rotation-powered pulsars.

4.5 Spectral features

Finally, there have been reports of features in AXP spectra. The first such report was for 1E 1048.1−5937 during the first of its two observed 2001 bursts (Gavriil et al. 2002). The feature, which was most prominent in the first 1-s of the burst, was extremely broad and seen apparently in emission at a central energy of 14 keV (see Fig. 6). In terms of flux, it was comparable to the burst continuum emission. It was very significant; Monte Carlo simulations showed that such a feature at any energy would be seen only 0.01% of the time. Gavriil et al. (2006) saw a similar feature in the third observed 1E 1048.1−5937 burst. In that case, the central energy measured was also \(\sim 13\) keV. In addition, Woods et al. (2005) observed a similar feature in one burst from XTE J1810−197, this time at energy 12.6 keV, with probability of chance occurrence \(4 \times 10^{-6}\). If interpreted as proton cyclotron lines, the energies of these features imply a magnetic field above \(10^{14}\) G, consistent with the magnetar hypothesis. However if the features are interpreted as electron
cyclotron lines, the implied field is correspondingly ~2000 times lower. The latter would not necessarily be inconsistent with the magnetar interpretation, as it is unclear what altitude above the neutron-star surface these lines originate.

Note that similar spectral features during SGR bursts have also been reported in the tails of a few SGR bursts (Ibrahim et al. 2002, 2003, see contribution by Ibrahim et al., these proceedings). However, recently their statistical significance has been questioned (see contribution by Woods et al.).

Rea et al. (2005) reported spectral features at certain rotational phases from 1RXS 170849.0–400910 from BeppoSax data. These were claimed at the time to be significant at the ~4σ level. Observations with XMM of the same source saw no such features, implying either that the BeppoSax features were spurious or that the effect is time variable. See the contribution by Rea et al. in these proceedings for more information.

5 Conclusions

My hope in writing this review is to demonstrate that there remain many important unsolved problems in the study of AXPs. Overall, the basic issue of what differentiates AXPs from SGRs remains, as does the origin of the intense magnetic fields inferred. Other important issues for which there simply was not enough space for discussion here include the possible association of AXPs (and SGRs) with massive star progenitors (e.g. Figer et al. 2006; Munro et al. 2006, see contribution by Gaensler et al.), the puzzling lack of “anomalously” bright X-ray emission from high-magnetic field radio pulsars (see contribution by Gonzalez et al.), and the proposed connection between magnetars and the so-called “RRATS” (McLaughlin et al. 2006, and see contribution by Lyne in this volume).

As for how some of these problems will be solved, continued monitoring observations with RXTE, as well as targeted studies with Chandra, XMM and INTEGRAL, will obviously be of use. Greater concerted efforts in the optical and near- and far-IR are warranted, as are careful and repeated radio searches for transient pulsations or other phenomena. Finally, target-of-opportunity observations at the times of the rare moments of AXP activity are definitely crucial for unravelling the overall physical picture of these very interesting sources.

Acknowledgements I thank C. Tam for maintaining the online McGill Magnetar Catalog as well as R. Dib, F. Gavriil, and P. Woods for useful conversations.

References

XMM–Newton observations of soft gamma-ray repeaters

Sandro Mereghetti · Paolo Esposito · Andrea Tiengo

Received: 20 July 2006 / Accepted: 24 August 2006 / Published online: 29 March 2007
© Springer Science+Business Media B.V. 2007

Abstract All the confirmed Soft Gamma-ray Repeaters have been observed with the EPIC instrument on the XMM–Newton satellite. We review the results obtained in these observations, providing the most accurate spectra on the persistent X-ray emission in the 1–10 keV range for these objects, and discuss them in the context of the magnetar interpretation.

Keywords Gamma-rays: observations · Pulsars: individual SGR 1806-20, SGR 1900+14, SGR 1627-41 · Pulsars: general PACS 97.60.Jd · 98.70.Qy

1 Introduction

Soft Gamma-ray Repeaters (SGRs) were discovered as sources of short intense bursts of gamma-rays, and for a long time were considered as a puzzling category of Gamma-ray bursts. Their neutron star nature was immediately suggested by the 8 s periodicity seen in the famous event of 5 March 1979, but it was only with the discovery of their pulsating counterparts in the few keV region that this was finally proved. Although the main motivations for the magnetar model (Duncan and Thompson 1992; Thompson and Duncan 1995) were driven by the high energy properties of the SGRs bursts and giant flares, X-ray observations of the “quiescent” emission have provided fundamental information to understand the nature of these objects (Woods and Thompson 2004).

Extensive observational programs have been carried out with the RossiXTE satellite, focusing mainly on the SGRs timing properties. Long term studies based on phase-connected timing analysis revealed significant deviations from a steady spin-down (Woods et al. 1999a, 2000, 2002), larger than the timing noise seen in radio pulsars and not linked in a simple way with the bursting activity. RossiXTE has also been used to investigate the variations of the pulse profiles as a function of energy and time (Göğüş et al. 2002), and to study the statistical properties of the bursts (Göğüş et al. 2001). However, the RossiXTE observations are not ideal to accurately measure the flux and spectrum of these relatively faint sources located in crowded fields of the Galactic plane, since its non-imaging instruments suffer from source confusion and large uncertainties in the background estimate. Imaging satellites like BeppoSAX, ASCA and Chandra have yielded useful spectral information, but it is only with the advent of the large collecting area XMM–Newton satellite that high quality spectra of SGRs have been obtained, in particular with the EPIC instrument (Strüder et al. 2001; Turner et al. 2001).

Here we review the results obtained with the XMM–Newton satellite for the three confirmed SGRs in our Galaxy. There are also some XMM–Newton data on SGR 0526-66 in the Large Magellanic Cloud, but they are of limited use due to the contamination from diffuse emission from the surrounding supernova remnant and will not be discussed here.
SGR 1806-20

SGR 1806-20 is probably the most prolific and the best studied of the known SGRs. It showed several periods of bursting activity since the time of its discovery in 1979 (Laros et al. 1986) and recently attracted much interest since it emitted the most powerful giant flare ever observed from an SGR (Hurley et al. 2005; Palmer et al. 2005; Mereghetti et al. 2005a).

The low energy X-ray counterpart of SGR 1806-20 was identified with the ASCA satellite (Murakami et al. 1994), thanks to the detection and precise localization of a burst simultaneously seen at higher energy with BATSE. Subsequent observations with RossiXTE led to the discovery of pulsations with $P = 7.5$ s and $\dot{P} = 8 \times 10^{-11}$ s$^{-1}$ (Kouveliotou et al. 1998).

Possible associations of SGR 1806-20 with the variable non-thermal core of a putative radio supernova remnant (Frail et al. 1997) and with a luminous blue variable star (van Kerkwijk et al. 1995) were disproved when a more precise localization of the SGR could be obtained with the Interplanetary Network (Hurley et al. 1999b) and later improved with Chandra (Kaplan et al. 2002). The transient radio source observed with the VLA after the December 2004 giant flare (Cameron et al. 2005) led to an even smaller error region and, thanks to the superb angular resolution (FWHM $\sim 0.1''$) available with adaptive optics at the ESO Very Large Telescope, a variable near IR counterpart ($K_v = 19.3 - 20$), could be identified (Israel et al. 2005), the first one for an SGR.

The distance of SGR 1806-20 is subject of some debate (Cameron et al. 2005), and is particularly relevant for its implications on the total energetics of the 2004 giant flare. A firm lower limit of 6 kpc can be derived from the HI absorption spectrum (McClure-Griffiths and Gaensler 2005), but the likely associations with a massive molecular cloud and with a cluster of massive stars indicate a distance of $\sim 15$ kpc (Corbel and Eikenberry 2004; Figer et al. 2005). In the following we will adopt this value.

Before the XMM–Newton observations, the most accurate spectral measurements for SGR 1806-20 in the soft X-ray range were obtained with BeppoSAX in 1998–1999 (Mereghetti et al. 2000). They showed that a power law with photon index $\Gamma = 1.95$ or a thermal bremsstrahlung with temperature $kT_\text{th} = 11$ keV were equally acceptable fits. All the observations indicated a fairly constant flux, corresponding to a 2–10 keV luminosity of $\sim 3 \times 10^{35}$ erg s$^{-1}$.

Being located at only $\sim 10^5$ from the Galactic center direction, SGR 1806-20 has been extensively observed with the INTEGRAL satellite since 2003. A few hundreds bursts have been detected with the IBIS instrument in the 15–200 keV range, leading to the discovery of a hardness intensity anti-correlation and allowing to extend the number-flux relation of bursts down to fluxes smaller than $10^{-8}$ erg cm$^{-2}$ (Götz et al. 2004, 2006b). In addition, it was discovered with INTEGRAL that the persistent emission from SGR 1806-20 extends up to 150 keV (Mereghetti et al. 2005b; Molkov et al. 2005). The hard X-ray emission, well fit by a power law with photon index $\Gamma \sim 1.5 - 1.9$, seems to correlate in hardness and intensity with the rate of burst emission, that reached a maximum in Fall 2004.

The bursting activity of SGR 1806-20 culminated with the giant flare of 2004 December 27 (Borkowski et al. 2004; Hurley et al. 2005; Palmer et al. 2005), that produced the strongest flash of gamma-rays at the Earth ever observed. The emission was so intense to cause saturation of most in-flight detectors, significant ionization of the upper atmosphere (Campbell et al. 2005), and a detectable flux of radiation backscattered from the Moon (Mazets et al. 2005; Mereghetti et al. 2005a). Other observations of this exceptional event, and their implications for the physics of neutron stars, are discussed during the High Energy Density Laboratory Astrophysics proceedings (Stella 2006; Israel 2006). Comparing this giant flare with those seen from SGR 0526-66 and SGR 1900+14, it is found that the energy in the pulsating tails of the three events was roughly of the same order ($\sim 10^{44}$ ergs), while the energy in the initial spike of SGR 1806-20 (a few $10^{46}$ ergs) was at least two orders of magnitude higher than that of the other giant flares. This indicates that the magnetic field in the three sources is similar. In fact the pulsating tail emission is thought to originate from the fraction of the energy released during the initial hard pulse that remains magnetically trapped in the neutron star magnetosphere, forming an optically thick photon-pair plasma (Thompson and Duncan 1995). The amount of energy that can be confined in this way is determined by the magnetic field strength, which is thus inferred to be of several $10^{14}$ G in these three magnetars.

SGR 1806-20 is the target of an ongoing campaign of XMM–Newton observations aimed at studying in detail the long term variations in the properties of its persistent emission. These observations, coupled with similar programs carried out with ESO telescopes in the infrared band (Israel 2006) and at hard X-ray energy with INTEGRAL (Götz et al. 2006a) and Suzaku, can be used to study the connection between the persistent emission and the source activity level, as manifested by the emission of bursts and flares.

2.1 XMM–Newton results

Seven XMM–Newton observations of SGR 1806-20 have been carried out to date (see Table 1). Four were obtained from April 2003 to October 2004, before the giant flare (Mereghetti et al. 2005c). At the time of the giant flare the source was not visible by XMM–Newton (and most other satellites) due to its proximity to the Sun, thus the next observation could be done only in March 2005 (Tiengo et al.
### Table 1: XMM–Newton observations and timing results for SGR 1806-20

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Date</th>
<th>Duration (ks)</th>
<th>Mode$^a$ and exp. time</th>
<th>Mode$^a$ and exp. time</th>
<th>Pulse period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2003 Apr 3</td>
<td>32</td>
<td>FF (5.4 ks)</td>
<td>LW (6 ks)</td>
<td>7.5311 ± 0.0003</td>
</tr>
<tr>
<td>B</td>
<td>2003 Oct 7</td>
<td>21</td>
<td>FF (13.4 ks)</td>
<td>LW (17 ks)</td>
<td>7.5400 ± 0.0003</td>
</tr>
<tr>
<td>C</td>
<td>2004 Sep 6</td>
<td>51</td>
<td>SW (36.0 ks)</td>
<td>LW (51 ks)</td>
<td>7.5559 ± 0.0005</td>
</tr>
<tr>
<td>D</td>
<td>2004 Oct 6</td>
<td>18</td>
<td>SW (12.9 ks)</td>
<td>Ti (18 ks)</td>
<td>7.5570 ± 0.0003</td>
</tr>
<tr>
<td>E</td>
<td>2005 Mar 7</td>
<td>24</td>
<td>SW (14.7 ks)</td>
<td>Ti/FF (24 ks)</td>
<td>7.5604 ± 0.0008</td>
</tr>
<tr>
<td>F</td>
<td>2005 Oct 4</td>
<td>33</td>
<td>SW (22.8 ks)</td>
<td>Ti/FF (33 ks)</td>
<td>7.56687 ± 0.00003</td>
</tr>
<tr>
<td>G</td>
<td>2006 Apr 4</td>
<td>29</td>
<td>SW (20.5 ks)</td>
<td>Ti/FF (29 ks)</td>
<td>7.5809 ± 0.0002</td>
</tr>
</tbody>
</table>

$^a$FF = Full Frame (time resolution 73 ms); LW = Large Window (time resolution 0.9 s); SW = Small Window (time resolution 6 ms); Ti = Timing (time resolution 1.5 ms)

Fig. 1 Folded light curves of SGR 1806-20 obtained with the EPIC pn instrument in the seven XMM–Newton observations. Note the flux increase in the two observations before the December 2004 giant flare and the small pulsed fraction in the first 2005 observation.

This was followed by another observation in October (Rea et al. 2005) and a most recent one in April 2006, the results of which are presented here for the first time.

The bursts detected in some of these observations (mostly in September-October 2004) were excluded by appropriate time selections to derive the spectral results reported below. After screening out the bursts, the source pulsations were clearly detected in all the observations. The corresponding folded light curves are shown in Fig. 1, where all the panels have the same scale in count rate to facilitate a comparison of the flux variations between the observations. The main spectral results are summarized in Table 2, where we have reported only the best fit parameters for the power law plus blackbody model (see Mereghetti et al. 2005c; Tiengo et al. 2005 for more details).

Indeed the strong requirement for a blackbody component is one of the main results of the high quality XMM–Newton spectra. In this respect the most compelling evidence comes from the September 2004 observation (obs. C), which, thanks to the high source count rate and long observing time, provided the spectra with the best statistics. A fit with an absorbed power law yields a relatively high \(\chi^2\) value (\(\chi^2_{\text{red}} = 1.37\)) and structured residuals, while a much better fit (\(\chi^2_{\text{red}} = 0.93\)) can be obtained by adding a blackbody component. The best fit parameters are photon index \(\Gamma = 1.2\), blackbody temperature \(kT_{BB} = 0.8\) keV and absorption \(N_H \sim 6.5 \times 10^{22}\) cm\(^{-2}\). Although some of the observations with lower statistics give acceptable fits also with a single power law, the results reported in Table 2 indicate that all the observations are consistent with the presence of an additional blackbody component with similar parameters. As an example we show in Fig. 2 (panels A and B) the power law plus blackbody fit of the April 2006 EPIC pn spectrum. The residuals (panel B) show a deviation at \(\sim 3\sigma\).
Table 2 Summary of the spectral results\(^a\) for SGR 1806-20

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Absorption (10^{22}) cm(^{-2})</th>
<th>Power law photon index</th>
<th>(kT_{BB}) (keV)</th>
<th>(R_{BB}) (km)(^b)</th>
<th>Flux(^c) ((10^{-11}) erg cm(^{-2}) s(^{-1}))</th>
<th>(\chi^2_{red}) (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.6 (5.6–8.4)</td>
<td>1.4 (1.0–1.7)</td>
<td>0.6 (0.4–0.9)</td>
<td>2.6 (0.7–13.9)</td>
<td>1.23</td>
<td>1.01 (56)</td>
</tr>
<tr>
<td>B</td>
<td>6.0 (4.9–6.6)</td>
<td>1.2 (0.5–1.4)</td>
<td>0.7 (0.6–1.0)</td>
<td>1.8 (1.2–2.9)</td>
<td>1.39</td>
<td>0.97 (68)</td>
</tr>
<tr>
<td>C</td>
<td>6.5 (6.2–6.9)</td>
<td>1.21 (1.09–1.35)</td>
<td>0.8 (0.7–0.9)</td>
<td>1.9 (1.6–2.6)</td>
<td>2.66</td>
<td>0.93 (70)</td>
</tr>
<tr>
<td>D</td>
<td>6.5 (5.9–7.1)</td>
<td>1.2 (0.9–1.4)</td>
<td>0.8 (0.6–0.9)</td>
<td>2.2 (1.6–3.5)</td>
<td>2.68</td>
<td>0.90 (69)</td>
</tr>
<tr>
<td>E</td>
<td>6.0 (5.8–6.2)</td>
<td>0.8 (0.5–1.0)</td>
<td>0.91 (0.86–1.05)</td>
<td>1.9 (1.6–2.1)</td>
<td>1.92</td>
<td>1.02 (70)</td>
</tr>
<tr>
<td>F</td>
<td>6.4 (6.0–6.8)</td>
<td>1.4 (1.1–1.7)</td>
<td>0.7 (0.6–0.8)</td>
<td>2.2 (1.7–3.3)</td>
<td>1.34</td>
<td>1.11 (69)</td>
</tr>
<tr>
<td>G</td>
<td>6.2 (5.6–6.6)</td>
<td>1.2 (0.9–1.4)</td>
<td>0.7 (0.6–0.8)</td>
<td>2.0 (1.6–2.7)</td>
<td>1.07</td>
<td>1.09 (68)</td>
</tr>
</tbody>
</table>

\(^a\)Errors are at the 90% c.l. for a single interesting parameter

\(^b\)Radius at infinity assuming a distance of 15 kpc

\(^c\)Absorbed flux in the 2–10 keV energy range

The observations performed before and after the giant flare show significant differences also in the source pulsed fraction and spectral shape. The pulsed fraction in the first observation after the flare was the smallest seen with XMM–Newton, while it increased again in the following observations. The spectral hardness followed a similar trend: the four pre-flare observations give marginal evidence for a gradual hardening, while the spectrum was definitely softer in the post-flare observations. This is illustrated in the bottom panel of Fig. 2, which shows the residuals of the April 2006 spectrum fitted with the pre-flare model (obs. C): the trend in the residuals clearly indicate the spectral softening.

As shown in Fig. 3, the changes in spectral hardness and spin-down rate of SGR 1806-20 follow the correlation between these quantities discovered in the sample of AXPs...

---

Fig. 2 A: EPIC pn spectrum of obs. G fitted with a power law (blue line) plus blackbody (red line) model. B: residuals of the fit in units of standard deviations. C: residuals of the spectrum of obs. G fitted with the best fit model of obs. C (rescaled in normalization) in order to illustrate the softening after the giant flare near 2.3 keV. However, this possible feature is not confirmed by the MOS data, and is not present in the spectra of the other XMM–Newton observations (see Sect. 6).

The second new result derived from these observations is the long term flux variability. All the observations of SGR 1806-20 in the 1–10 keV range obtained in the previous years with ROSAT, ASCA and BeppoSAX were consistent with a flux of \(\sim 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\). On the other hand, the XMM–Newton data showed a doubling of the flux in September-October 2004 followed by a gradual recovery to the “historical” level during the observations performed after the giant flare. Interestingly, the same trend was seen above 20 keV with INTEGRAL (Mereghetti et al. 2005b; Götz et al. 2006a), as well as in the flux of the NIR counterpart (Israel et al. 2005; Israel 2006).
and SGRs by comparing different objects: the sources with the harder spectrum have a larger long term spin-down rate (Marsden and White 2001). These results indicate, for the first time, that such a correlation also holds within different states of a single source.

3 SGR 1900+14

Bursts from this SGR were discovered with the Venera satellites in 1979 (Mazets et al. 1979). No other bursts were detected until thirteen years later, when four more events were seen with BATSE in 1992 (Kouveliotou et al. 1993). In the meantime the X-ray counterpart had been discovered with ROSAT (Vasisht et al. 1994), and later found to pulsate at 5.2 s with ASCA (Hurley et al. 1999c). Subsequent observations with the RossiXTE satellite confirmed the pulsations and established that the source was spinning down rapidly, with a period derivative of $\sim 10^{-11}$ s$^{-1}$ (Kouveliotou et al. 1999).

The peak of the activity from SGR 1900+14 was reached on 1998 August 27, with the emission of a giant flare (Hurley et al. 1999a; Feroci et al. 1999), resembling the only similar event known at that time, the exceptional burst of 5 March 1979. The 1998 giant flare from SGR 1900+14 could be studied much better than that of SGR 0526-66. The flare started with a short ($\sim 0.07$ s) soft spike, followed by a much brighter short and hard pulse that reached a peak luminosity of $\sim 10^{45}$ erg s$^{-1}$. The initial spike was followed by a softer gamma-ray tail modulated at 5.2 s (Hurley et al. 1999a; Mazets et al. 1999), which decayed in a quasi exponential manner over the next $\sim 6$ minutes (Feroci et al. 2001).

Integrating over the entire flare assuming isotropic emission, at least $10^{44}$ erg were released in hard X-rays above 15 keV (Mazets et al. 1999). SGR 1900+14 also emitted another less intense flare on 18 April 2001 (Feroci et al. 2003; Guidorzi et al. 2004), which based on its energetics was classified as an “intermediate” flare.

Despite being the less absorbed of the galactic SGRs ($N_H \sim 2 \times 10^{22}$ cm$^{-2}$) no optical/IR counterpart has been yet identified for SGR 1900+14. Its possible association with a young cluster of massive stars (Vrba et al. 2000), where the SGR could have been born, gives a distance of $\sim 15$ kpc, that we will adopt in the following.

Recently, persistent emission from SGR 1900+14 has been detected also in the 20–100 keV range thanks to observations with the INTEGRAL satellite (Götz et al. 2006b).

3.1 XMM–Newton results

SGR 1900+14 lies in a sky region that, until recently, was not observable by XMM–Newton due to technical constraints in the satellite pointing. Thus the first observation of SGR 1900+14 could be obtained only in September 2005 (Mereghetti et al. 2006b). This observation occurred during a long period of inactivity (the last bursts before the observations were reported in November 2002, Hurley et al. 2002).

The spectrum could not be fit satisfactorily with single component models, while a good fit was obtained with the sum of a power law and a blackbody, with photon index $\Gamma = 1.9 \pm 0.1$, temperature $kT = 0.47 \pm 0.02$ keV, absorption $N_H = (2.12 \pm 0.08) \times 10^{22}$ cm$^{-2}$, and unabsorbed flux $\sim 4.8 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). An acceptable fit could also be obtained with the sum of two blackbodies with temperatures of 0.53 and 1.9 keV.

The XMM–Newton power law plus blackbody parameters are in agreement with previous observations of this source carried out with ASCA (Hurley et al. 1999c), BeppoSAX (Woods et al. 1999b; Esposito et al. 2007) and Chandra (Kouveliotou et al. 2001), but the flux measured in September 2005 is the lowest ever seen from SGR 1900+14. A $\sim 30\%$ decrease of the persistent emission, compared to the “historical” level of $\sim 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, had already been noticed in the last BeppoSAX observation (Esposito et al. 2007), that was carried out in April 2002, six month earlier than the last bursts reported before the recent reactivation. The long term fading experienced by SGR 1900+14 in 2002–2005 might be related to the apparent decrease in the bursting activity in this period.

A second XMM–Newton observation was carried out on 1 April 2006, as a target of opportunity following the source reactivation indicated by a few bursts detected by Swift (Palmer et al. 2006) and Konus-Wind (Golenetskii et al. 2006). The spectral shape was consistent with that measured in the first observation, but the flux was $\sim 5.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (Mereghetti et al. 2006b).
The spin period was 5.198346 ± 0.000003 s in September 2005 and 5.19987 ± 0.00007 s in April 2006. In both observations the pulsed fraction was ~16% and no significant changes in the pulse profile shape were seen after the burst reactivation.

For both observations we performed phase-resolved spectroscopy extracting the spectra for different selections of phase intervals. No significant variations with phase were detected, all the spectra being consistent with the model and parameters of the phase-averaged spectrum, simply rescaled in normalization.

4 SGR 1627-41

From the point of view of the bursts and timing properties, SGR 1627-41 is one of the less well studied SGRs. This source was discovered during a period of bursting activity that lasted only six weeks in 1998 (Woods et al. 1999c; Hurley et al. 1999d; Mazets et al. 1999). Since then no other bursts were observed.

With a column density of $N_H \sim 10^{23} \text{ cm}^{-2}$, corresponding to $A_V \sim 40–50$, SGR 1627-41 is the most absorbed of the known SGRs. Thus it is not surprising that little is known on its possible counterparts. Near IR observations (Wachter et al. 2004) revealed a few objects positionally consistent with the small Chandra error region, but they are likely foreground objects unrelated to the SGR.

A distance of 11 kpc is generally assumed for SGR 1627-41, based on its possible association with the radio complex CTB 33, comprising the supernova remnant SNR G337.0-0.1 and a few HII regions (Corbel et al. 1999).

During the active period a soft X-ray counterpart with flux $F_1 \sim 7 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ was identified with BeppoSAX (Woods et al. 1999c). However it was not possible to reliably measure a periodicity (a marginal detection at 6.4 s was not confirmed by better data).

Observations carried out in the following years with BeppoSAX, ASCA and Chandra, showed a monotonic decrease in the luminosity, from the value of $\sim 10^{35} \text{ erg s}^{-1}$ (for $d = 11 \text{ kpc}$) seen in 1998 down to $\sim 4 \times 10^{33} \text{ erg s}^{-1}$.

4.1 XMM–Newton results

A 52 ks long XMM–Newton pointing on SGR 1627-41 was done in September 2004 (Mereghetti et al. 2006a), while some other information could be extracted from two observations in which SGR 1627-41 was serendipitously detected at an off-axis angle of ~10°. These ~30 ks long observations, whose main target was IGR J16358-4726, were carried out in February and September 2004.

All the XMM–Newton data showed a rather faint source ($\sim 9 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$) with a soft spectrum. Unfortunately the source faintness did not allow a sensitive search for periodic pulsations. Both a steep power law (photon index $\Gamma = 3.7 \pm 0.5$) and a blackbody with temperature $kT_{BB} = 0.8^{+0.2}_{-0.1} \text{ keV}$ gave acceptable fits. The absorption was consistent with that measured in all the previous observations, $N_H = 9 \times 10^{22} \text{ cm}^{-2}$. There is evidence that the spectrum softened between the two Chandra observations carried out in September 2001 and August 2002 (Kouveiotou et al. 2003). The photon index measured with XMM–Newton is consistent with that of the last Chandra observation but, due to the large uncertainties, also a further softening cannot be excluded.

The XMM–Newton flux measurements are compared with those obtained in previous observations in Fig. 4. The two panels refer to the observed (top) and emitted (bottom) fluxes in the 2–10 keV range and for a common value of the absorption in all the observations ($N_H = 9 \times 10^{22} \text{ cm}^{-2}$, see Mereghetti et al. 2006a for details). The long term decrease in luminosity is clear, but, owing to the source spectral variations, the details of the decay light curve are different for the observed and unabsorbed flux.

If one considers the observed fluxes, the Chandra and XMM–Newton data suggest that SGR 1627-41 continued to fade also after September 2001, while the unabsorbed values indicate a possible plateau level at $\sim 2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. It is important to realize that the quantity most relevant for theoretical modeling, i.e. the emitted
flux, is subject to the uncertainties in the spectral parameters. This is particularly important for high \( N_H \) values and small fluxes, as in the case of SGR 1627-41.

The long term luminosity decrease of SGR 1627-41 was interpreted as evidence for cooling of the neutron star surface after the deep crustal heating that occurred during the period of SGR activity in 1998. The decay light curve was fitted with a model of deep crustal heating requiring a massive neutron star \((M > 1.5M_\odot)\) which could well explain a plateau seen between days 400 and 800 (Kouveliotou et al. 2003). However, the evidence for such a plateau is not so compelling, according to our reanalysis of the BeppoSAX data. In fact all the BeppoSAX and ASCA points in the top panel of Fig. 4, before the rapid decline seen with Chandra in September 2001, are well fit by a power law decay, \( F(t) \propto (t - t_0)^{-0.6} \), where \( t_0 \) is the time of the discovery outburst.

### Table 3 Main properties of the four confirmed SGRs

<table>
<thead>
<tr>
<th></th>
<th>SGR 1627-41</th>
<th>SGR 1806-20</th>
<th>SGR 1900+14</th>
<th>SGR 0526-66</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates</td>
<td>16( ^{\circ} ) 35( ^{\prime} ) 51.83( ^{\prime\prime} )</td>
<td>18( ^{\circ} ) 08( ^{\prime} ) 39.33( ^{\prime\prime} )</td>
<td>19( ^{\circ} ) 07( ^{\prime} ) 14.33( ^{\prime\prime} )</td>
<td>05( ^{\circ} ) 26( ^{\prime} ) 00.89( ^{\prime\prime} )</td>
</tr>
<tr>
<td>Error</td>
<td>0.2( ^{\prime\prime} ) [a]</td>
<td>0.06( ^{\prime\prime} ) [b]</td>
<td>0.15( ^{\prime\prime} ) [d]</td>
<td>0.6( ^{\prime\prime} ) [g]</td>
</tr>
<tr>
<td>Distance</td>
<td>11 kpc</td>
<td>15 kpc</td>
<td>15 kpc</td>
<td>50 kpc</td>
</tr>
<tr>
<td>Period</td>
<td>–</td>
<td>7.6 s</td>
<td>5.2 s</td>
<td>8 s</td>
</tr>
<tr>
<td>Period derivative (s s(^{-1}))</td>
<td>–</td>
<td>((8.3-81) \times 10^{-11} ) [c]</td>
<td>((6.1-20) \times 10^{-11} ) [e]</td>
<td>(6.6 \times 10^{-11} ) [g]</td>
</tr>
<tr>
<td>Magnetic field( ^{d} )</td>
<td>–</td>
<td>((8-25) \times 10^{14} ) G</td>
<td>((6-10) \times 10^{14} ) G</td>
<td>(7 \times 10^{14} ) G</td>
</tr>
<tr>
<td>Flux range( ^{b} ) (erg cm(^{-2} ) s(^{-1} ))</td>
<td>((0.025-0.6) \times 10^{-11} )</td>
<td>((1.3-3.8) \times 10^{-11} )</td>
<td>((0.5-2.7) \times 10^{-11} )</td>
<td>(0.07 \times 10^{-11} )</td>
</tr>
<tr>
<td>Typical flux( ^{b} ) (erg cm(^{-2} ) s(^{-1} ))</td>
<td>(~3 \times 10^{-13} )</td>
<td>(~1.5 \times 10^{-11} )</td>
<td>(~10^{-11} )</td>
<td>(~10^{-12} )</td>
</tr>
<tr>
<td>20–60 keV flux (erg cm(^{-2} ) s(^{-1} ))</td>
<td>–</td>
<td>((3-5) \times 10^{-11} )</td>
<td>(~1.5 \times 10^{-11} )</td>
<td>–</td>
</tr>
<tr>
<td>Optical/IR</td>
<td>(J &gt; 21.5, H &gt; 19.5, K_s &gt; 20.0 ) [a]</td>
<td>(J &gt; 22.8, K_s &gt; 20.8 ) [f]</td>
<td>(V &gt; 27.1, I &gt; 25 )</td>
<td>(I &gt; 20.0 ) [a]</td>
</tr>
<tr>
<td>Luminosity( ^{c} ) (erg s(^{-1} ))</td>
<td>(~4 \times 10^{33} )</td>
<td>(~4 \times 10^{35} )</td>
<td>(~3 \times 10^{35} )</td>
<td>(~2 \times 10^{35} )</td>
</tr>
<tr>
<td>Photon index</td>
<td>3</td>
<td>1.2</td>
<td>2</td>
<td>3.1</td>
</tr>
<tr>
<td>Blackbody kT</td>
<td>–</td>
<td>0.8 keV</td>
<td>0.45 keV</td>
<td>0.53 keV</td>
</tr>
<tr>
<td>(N_H)</td>
<td>(9 \times 10^{22} ) cm(^{-2} )</td>
<td>(6.5 \times 10^{22} ) cm(^{-2} )</td>
<td>(2.2 \times 10^{22} ) cm(^{-2} )</td>
<td>(0.55 \times 10^{22} ) cm(^{-2} )</td>
</tr>
<tr>
<td>Giant Flare</td>
<td>–</td>
<td>December 27, 2004</td>
<td>August 27, 1998</td>
<td>March 5, 1979</td>
</tr>
<tr>
<td>Initial spike energy (erg)</td>
<td>–</td>
<td>((1.6-5) \times 10^{46} )</td>
<td>(&gt; 6.8 \times 10^{45} )</td>
<td>(1.6 \times 10^{44} )</td>
</tr>
<tr>
<td>Pulsating tail energy (erg)</td>
<td>–</td>
<td>(1.3 \times 10^{44} )</td>
<td>(5.2 \times 10^{43} )</td>
<td>(3.6 \times 10^{44} )</td>
</tr>
</tbody>
</table>

References: [a] Wachter et al. (2004); [b] Israel et al. (2005); [c] Woods et al. (2007); [d] Frail et al. (1999); [e] Woods et al. (2002); [f] Kaplan et al. (2002); [g] Kulkarni et al. (2003); [h] Kaplan et al. (2001)

\( ^{a} \)Assuming spin-down due to dipole radiation: \( B = 3.2 \times 10^{19}(P \dot{P})^{1/2} \) G

\( ^{b} \)Unabsorbed flux in the 2–10 keV energy range

\( ^{c} \)Luminosity in the 2–10 keV energy range assuming the distances reported above

### 5 XMM–Newton results on the SGRs bursts

Up to now limited spectral information has been obtained for SGR bursts below 20 keV. In particular, before our XMM–Newton observations, spectra with good energy resolution and sensitivity at a few keV were lacking. However, some studies have provided evidence that the optically thin thermal bremsstrahlung model, which gives a good phenomenological description of the burst spectra in the hard X-ray range, is inconsistent with the data below 15 keV (Fenimore et al. 1994; Olive et al. 2004; Feroci et al. 2004). We therefore tried to address this issue using the XMM–Newton data.

Several tens of bursts were detected during some of the XMM–Newton observations of SGR 1806-20 (while none was seen in SGR 1900+14 and SGR 1627-41). These bursts had durations typical of the short bursts more commonly observed at higher energy. Since the individual bursts had too few counts for a meaningful spectral analysis, we extracted a cumulative spectrum by summing all the bursts detected
during the 2004 observations. The resulting spectrum corresponds to a total exposure of 12.7 s and contains about 2000 net counts in the 2–10 keV range. We checked that pile-up effects were not important (see Mereghetti et al. 2005c for details). The spectrum of the remaining observing time was used as background.

All the fits with simple models (power law, blackbody, thermal bremsstrahlung) gave formally acceptable $\chi^2$ values, but the power law and the bremsstrahlung required a large absorption ($N_H = 10^{23}$ cm$^{-2}$), inconsistent with the value seen in the persistent emission. We therefore favor the blackbody model, which yields $kT_{BB} = 2.3 \pm 0.2$ keV and $N_H = 6 \times 10^{22}$ cm$^{-2}$, in agreement with the value determined from the spectrum of the persistent emission.

The residuals from this best fit showed a deviation at 4.2 keV. Although the deviation is formally at 3.3$\sigma$, it could not be reproduced in spectra obtained with different data selections and binning criteria. Therefore we consider it as only a marginal evidence for an absorption line (Mereghetti et al. 2005c).

6 (Absence of) spectral lines

In models involving ultra-magnetized neutron stars, proton cyclotron features are expected to lie in the X-ray range, for surface magnetic fields strengths of $\sim 10^{14} - 10^{15}$ G. Detailed calculations of the spectrum emerging from the atmospheres of magnetars in quiescence have confirmed this basic expectation (Zane et al. 2001; Ho and Lai 2001). Model spectra exhibit a strong absorption line at the proton cyclotron resonance, $E_{c,p} \sim 0.63z_G(B/10^{14}$ G) keV, where $z_G$, typically in the 0.70–0.85 range, is the gravitational red-shift at the neutron star surface. No evidence for persistent cyclotron features has been reported to date in SGRs, despite some features have been possibly detected during bursts (see e.g. Strohmayer and Ibrahim 2000; Ibrahim et al. 2003).

A sensitive search for spectral lines was among the main objectives of the XMM–Newton observations of SGRs. However no evidence for emission or absorption lines, was found by looking at the residuals from the best fit models. In the case of SGR 1806-20 and SGR 1900+14 the upper limits are the most constraining ever obtained for these sources in the $\sim 1$–10 keV energy range. They are shown in Fig. 5 for the most sensitive observation of each source, i.e. those of September 2004 for SGR 1806-20 and of September 2005 for SGR 1900+14. The plotted curves represent the upper limits on the equivalent widths as a function of the assumed line energy and width. They were derived by adding Gaussian components to the best fit models and computing the allowed range in their normalization.

![Fig. 5](image-url) Upper limits (at 3$\sigma$) on spectral features in the persistent emission of SGR 1806-20 (top) and SGR 1900+14 (bottom)

Some reasons have been proposed to explain the absence of cyclotron lines in magnetars, besides the obvious possibility that they lie outside the sampled energy range. Magnetars might differ from ordinary radio pulsars because their magnetospheres are highly twisted and therefore can support current flows (Thompson et al. 2002). The presence of charged particles ($e^-$ and ions) produces a large resonant scattering depth and since (i) the electron distribution is spatially extended and (ii) the resonant frequency depends on the local value of the magnetic field, repeated scatterings could lead to the formation of a hard tail instead of a narrow line. A different explanation involves vacuum polarization effects. It has been calculated that in strongly magnetized atmospheres this effect can significantly reduce the equivalent width of cyclotron lines, thus making difficult their detection (Ho and Lai 2003).

7 Conclusions

Many of the results presented above fit reasonably well with the magnetar model interpretation. However, there are also a few aspects that require more theoretical and observational efforts to be interpreted in this framework, in particular when one considers the variety of different behaviors shown by these sources and their close relatives like the Anomalous X-ray pulsars (Kaspi 2006).
The long term variations seen in SGR 1806-20, the source observed more often with XMM–Newton, are qualitatively consistent with the predictions of the magnetar model involving a twisted magnetosphere (Thompson et al. 2002). As mentioned above, according to this model, resonant scattering from magnetospheric currents leads to the formation of a high-energy tail. A gradually increasing twist results in a larger optical depth that causes a hardening of the X-ray spectrum. At the same time, the spin down rate increases because, for a fixed dipole field, the fraction of field lines that open out across the speed of light cylinder grows. In addition, the stresses building up in the neutron star crust and the magnetic footprints movements lead to crustal fractures causing an increase in the bursting activity. Since spectral hardening, spin-down rate, and bursting rate increase with the twist angle, it is not surprising that these quantities varied in a correlated way in SGR 1806-20 (see Fig. 6 and Götz et al. 2006a). However, as visible in Fig. 6, while the spectral hardening took place gradually over several years, the spin-down variation occurred more rapidly in 2000. A recent analysis of RossiXTE data around the time of the giant flare (Woods et al. 2007) shows that the correlation between spectral and variability parameters is indeed rather complex.

The long term flux evolution of SGR 1900+14 is shown in Fig. 7. It can be seen that, excluding the enhancements seen in correspondence of the flares, the luminosity remained always at the same level in the years 1997–2001, and then decreased slightly until the lowest value seen with XMM–Newton in September 2005. The following observation of April 2006 showed that the decreasing luminosity trend has been interrupted by the recent onset of bursts emission. However, the moderate flux increase was not as-

Fig. 6 From top to bottom: long term evolution of the pulse period, photon index, X-ray flux (2–10 keV), hard X-ray flux (20–60 keV), and infrared magnitude of SGR 1806-20. Fluxes are in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The vertical dashed line indicates the December 2004 giant flare.

Fig. 7 From top to bottom: long term evolution of the pulse period, photon index, X-ray flux (2–10 keV), and hard X-ray flux (20–60 keV) of SGR 1900+14. Fluxes are in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The vertical dashed lines indicate the 27 August 1998 giant flare and the 18 April 2001 intermediate flare.
associated with significant changes in the X-ray spectral and timing properties, probably because the source is, up to now, only moderately active.

The luminosity now reached by SGR 1627-41, \( \sim 3.5 \times 10^{35} \text{ erg s}^{-1} \) is the smallest ever observed from a SGR, and is similar to that of the low state of the transient anomalous X-ray pulsar XTE J1810-197 (Ibrahim et al. 2004; Gotthelf et al. 2004). This low luminosity might be related to the long period (\( \sim 6 \) years) during which SGR 1627-41 has not emitted bursts. However, the behavior of this source differs from that of the other SGRs that during periods of apparent lack of bursts changed only moderately their luminosity. In fact no bursts were detected from SGR 1900+14 in the three years preceding the XMM–Newton observations: had its luminosity decreased with the same trend exhibited by SGR 1627-41 it would have been much fainter than observed by XMM–Newton. Even more striking is the case of SGR 0526-66, which has a high luminosity (\( \sim 2 \times 10^{35} \text{ erg s}^{-1} \)), despite no signs of bursting activity have been observed in the last 15 years (unless weak bursts from this source have passed undetected due to its larger distance and location in a poorly monitored sky region).

It thus seems that, similarly to the case of Anomalous X-ray Pulsars, SGRs comprise both “persistent” sources (SGR 1806-20, SGR 1900+14 and SGR 0526-66) and “transients” (SGR 1627-41). The reasons behind this difference are currently unclear and not necessarily the same that differentiate between SGRs and AXPs.

Acknowledgements This work has been supported by the Italian Space Agency through the contract ASI-INAF I/023/05/0. XMM-Newton is an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

References

Gőtz, D., Mereghetti, S., Hurley, K.: These proceedings (2006a)
MMIV: de SGR 1806–20 Anno Mirabili

Unveiling the AXP/SGR connection

GianLuca Israel

Received: 27 July 2006 / Accepted: 23 August 2006 / Published online: 21 March 2007
© Springer Science+Business Media B.V. 2007

Abstract
On 27th December 2004 SGR 1806–20, one of the most active Soft γ-ray Repeaters (SGRs), displayed an extremely rare event, also known as giant flare, during which up to $10^{47}$ ergs were released in the $\sim 1$–1000 keV range in less than 1 s. Before and after the giant flare we carried out IR observations by using adaptive optics (NAOS-CONICA) mounted on VLT which provided images of unprecedented quality (FWHM better than 0.1″). We discovered the likely IR counterpart to SGR 1806–20 based on positional coincidence with the VLA uncertainty region and flux variability of a factor of about 2 correlated with that at higher energies. Moreover, by analysing the Rossi-XTE/PCA data we have discovered rapid Quasi-Periodic Oscillations (QPOs) in the pulsating tail of the 27th December 2004 giant flare of SGR 1806–20. QPOs at $\sim 92.5$ Hz are detected in a 50 s interval starting 170 s after the onset of the giant flare. These QPOs appear to be associated with increased emission by a relatively hard unpulsed component and are seen only over phases of the 7.56 s spin period pulsations away from the main peak. QPOs at $\sim 18$ and $\sim 30$ Hz are also detected $\sim 200$–300 s after the onset of the giant flare. This is the first time that QPOs are unambiguously detected in the flux of a Soft Gamma-ray Repeater, or any other isolated neutron star. We interpret the highest QPOs in terms of the coupling of toroidal seismic modes with Alfvén waves propagating along magnetospheric field lines. The lowest frequency QPO might instead provide indirect evidence on the strength of the internal magnetic field of the neutron star.

Keywords
Stars: neutron · Stars: oscillations · Pulsars: individual: SGR 1806–20 · Infrared: stars · X-rays: bursts

PACS 97.10.Sj · 97.60.Gb · 97.60.Jd · 98.38.Jw · 98.70.Qy

1 Introduction

Soft Gamma-ray Repeaters (SGRs) are characterized by short and recurrent bursts (<1 s) of soft γ rays. Only four confirmed SGRs are known, three in the Galaxy and one in the Large Magellanic Cloud (see Woods and Thompson 2006 for a recent review). The nature of SGRs has remained a mystery for many years. The $\sim 8$ s periodicity clearly seen in the tail of the 1979 March 5th giant flare of SGR 0526–66 suggested an association of SGRs with neutron stars. Several observational properties of SGRs are successfully modelled in terms of “magnetars,” isolated neutron stars in which the dominant source of free energy is their intense magnetic field ($B \sim 10^{14}$–$10^{15}$ G; Duncan and Thompson 1992; Thompson and Duncan 1995). The “magnetar” model is founded on two observational facts: firstly, the rotational energy loss inferred from the SGR and AXP spin-down is insufficient to power their persistent X-ray luminosity of $\sim 10^{34}$–$10^{36}$ erg s$^{-1}$; secondly, there is no evidence for a companion stars which could provide the mass to power the X-ray emission through accretion.

Bursting activity from SGR 1806–20 resumed at the end of 2003 displaying an increase in both the γ-ray burst rate and the hard X-ray persistent emission (Mereghetti et al. 2005b) throughout 2004, and culminating with the giant flare of 27th December 2004 (Borkowski et al. 2004, during which $\sim 10^{47}$ erg were released for a distance of about 10 kpc; Cameron et al. 2005; McClure-Griffiths and Gaensler 2005). The event was so intense that caused a
strong perturbation in the Earth ionosphere and saturated the detectors on every high-energy satellite. Few days after this event, SGR 1806–20 was detected in the radio band for the first time, providing a very accurate position (VLA; Cameron et al. 2005; Gaensler et al. 2005a). The radio polarization and flux decay were consistent with synchrotron radiation from an expanding nebula (Gaensler et al. 2005b).

Thanks to a Target of Opportunity (ToO) observational campaign on SGR 1806–20 carried out during 2004 with the ESO VLT we likely discovery of the IR counterpart to SGR 1806–20 based on positional coincidence with the radio position and flux variability. Moreover, based on serendipitous high-time resolution data obtained with the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA), we carried out the first detailed X-ray timing analysis of the 2004 December 27th hyperflare of SGR 1806–20, and we discovered rapid quasi periodic oscillations (QPOs) in its X-ray flux few minutes after the onset of the giant flare.

2 VLT NAOS-CONICA IR observations

The data were acquired at VLT with the Nasmyth Adaptive Optics System and the High Resolution Near IR Camera (NAOS-CONICA). Data were reduced following standard procedures for photometry and astrometry (see Israel et al. 2005a for details of the observations and data reduction). Absolute photometry was derived by analysis of the best seeing frames, and cross-checked by means of archival ISAAC data of the same region and about 100 isolated stars taken from the 2MASS catalog and within the instrument FOV: the results were in agreement to within 0.05 Ks magnitudes. In particular, the final astrometric image accuracy is of ∼0.1″ (2MASS absolute accuracy included).

Source A, a relatively faint (Ks ∼ 20) object, at the sky position R.A. = 18° 08′ 59.337″, Dec. = −20° 24′ 39.85″ (equinox 2000, 90% uncertainty of 0.06″), is found to be consistent with the Chandra and VLA positional uncertainty circles superimposed on our IR astrometry–corrected frame (see Fig. 1). Objects B and C (∼0.23″ and 0.27″ away from A, respectively) are only marginally consistent with the X-ray and radio positions, though statistically plausible. Light curves of the A, B and C objects are shown in Fig. 2. Candidate A is the only one showing a clear brightening (a factor of ∼2) in the IR flux between June and October 2004 (see Israel et al. 2005a for more details).

Both the XMM-Newton (Mereghetti et al. 2005a) and INTEGRAL (Mereghetti et al. 2005b) persistent fluxes of SGR 1806–20 showed an increase across the two semesters of 2004 by a factor of 1.94±0.01 and 1.7±0.4 in the 2–10 keV and 20–100 keV bands, respectively.1 During the same time interval the NAOS-CONICA Ks flux increased by a factor of 2.4±0.9, consistent with high energy flux variations, supporting the identification of object A as the correct IR counterpart of SGR 1806–20.

Independent from our work, the object A has been proposed as the IR counterpart to SGR 1806–20 (Kosugi et al. 2005; their object B3). A comparison of their photometry

---

1 For the 2–10 keV 2004 first semester flux we assumed that of October 2003, based on the unvaried INTEGRAL flux between October 2003 and February–April 2004.