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The manyfold brotherhood of isolated neutron stars

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Abstract. The advances obtained in recent years thanks to observations in the X–ray and γ-ray energy bands have significantly changed our vision of isolated neutron stars, that was previously based mainly on the observations of the large population of radio pulsars. The new emerging picture based on the recognition of different new classes of objects (radio-quiet pulsars, γ-ray pulsars, central compact objects in supernova remnants, dim X–ray emitting neutron stars, magnetars), implies a much wider variety in the birth and evolution properties of neutron stars.
I will illustrate this variety of new objects by discussing some recent results on four isolated neutrons stars: the magnetar SGR 1806−20, the central compact objects in the supernova remnants G 296.5+10.0 and RCW 103, and the nearby isolated neutron star RX J1856.5–3754.

Key words. Neutron stars - Magnetars

1. Introduction

Radio pulsars, discovered 40 years ago, have been since then one of our major sources of information for the study of neutron stars. Despite their radio emission is energetically inconspicuous, typically only 10^{-9}–10^{-5} of the rotational energy loss, and the details of its origin are not yet completely understood, observations in the radio band permit to measure with extreme accuracy the pulsar rotational parameters that offer a wealth of diagnostic information on these objects. Currently more than 1700 neutron stars are detected as radio pulsars in our Galaxy and the Magellanic Clouds. They range in age from very young objects ($\lesssim 1000$ yrs), still surrounded by their supernova remnants, to very old ones, with characteristic ages longer than 10^8 years. The millisecond pulsars found in binary systems are even older, with ages up to $\sim 10^{10}$ years. They are believed to originate from recycling through accretion of mass and angular momentum in low mass X–ray binaries.

A small fraction of the radio pulsars have been detected at other wavelengths, typically the youngest, more energetic and/or the closest ones.

The Crab pulsar is quite bright at visible wavelengths (V=16.7) and its optical emission was discovered back in 1969. The next optically brightest pulsars are at least ~7 magnitudes fainter, and only five confirmed optical counterparts (plus a few candidates) of radio pulsars are currently known (Shearer & Golden

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2002; Mignani et al. 2004). Their optical emission is thought to be of non-thermal origin.

The situation is much more favorable at X–ray energies, where more than 80 radio pulsars have been detected, including many that are bright enough for detailed studies. The X–ray emission can be due to non-thermal processes, originating from charged particles accelerated in the magnetosphere at the expense of rotational energy, or to surface thermal emission of the neutron star primeval heat. The relative importance of these two components depends on the pulsar age. In young pulsars, characterized by small rotational periods and large magnetic fields, the non-thermal magnetospheric emission dominates, making the underlying thermal emission undetectable. The thermal emission becomes visible in older pulsars. For example, pulsars with characteristic ages of a few hundreds kyr show complex, phase-dependent X–ray spectra requiring a combination of one power-law and two blackbody-like components to be well fitted (see, e.g., De Luca et al. (2005)).

At γ-ray energies a few pulsars are also known since a long time. The Vela pulsar is the brightest point source in the MeV-GeV sky. Seven pulsars have been clearly seen at these energies, and a few more tentative detections needing confirmation have been reported (Thompson 2004). Quite interestingly, the efficiency of conversion of rotational energy into γ-rays increases with the pulsar age and there is evidence that the γ-ray radiation beams are much wider than the radio ones. This effect easily accounts for the presence of radio-quiet pulsars like Geminga. Undoubtedly many of the EGRET unidentified sources are radio(-quiet) pulsars not yet recognized as such. The AGILE and GLAST missions are thus expected to significantly enlarge the sample of γ-ray pulsars, with the hope of discriminating between the different theoretical models (e.g. polar cap vs. outer gap emission) which make different predictions for the fraction of γ-ray pulsars visible in the radio (Harding et al. 2007).

It is clear that optical, X–ray and γ-ray observations allow us to study many fundamental aspects of radio pulsars that would be otherwise unaccessible. In addition, high-energy observations have revealed in the last few years that the possible manifestations of isolated neutron stars are actually much more numerous than previously thought. New classes of (radio quiet) isolated neutron stars have been recognized, with properties much different from those of the classical radio pulsars. This points to a large variety of intrinsic properties, possibly related to the initial conditions at the NS formation during the collapse of massive stars.

Magnetars are believed to be the neutron stars with the highest magnetic fields, reaching B$\sim$ 10^{15} G (see Woods & Thompson (2006) for a review). They were discovered either as peculiar X–ray pulsars with periods of a few seconds and luminosity larger than their rotational energy loss (Anomalous X–ray Pulsars, AXPs, Mereghetti & Stella (1995)), or as sources of repeating, soft γ-ray bursts and occasional large flares (Soft Gamma-ray Repeaters, SGRs, Hurley (2001)).

A group of seven nearby (~100 pc) X–ray pulsars (P=3–12 s) is characterized by very soft thermal spectra with temperatures of ~50–100 eV. They are often called X–ray Dim Isolated Neutron Stars (XDINS), which is not particulary appropriate since many dimmer neutron stars have in fact been revealed after their discovery with the ROSAT satellite in the 90s. They are also known as "The Magnificent Seven" and, due to the complete absence of non-thermal emission and, in a few cases, the measurement of parallactic distances, they are ideal targets to infer the neutron star size and atmospheric composition through detailed modelling of their purely thermal emission (see Haberl (2007) for a recent review).

Another class of isolated neutron stars is composed by radio-quiet, X–ray point sources located at the geometrical center of shell like supernova remnants (Central Compact Objects, CCOs, Pavlov et al. (2004)). With some notable exception (see below) they are steady X–ray sources, with periods similar to those of radio pulsars, and thermal X–ray spectra. Recent measurements of moderate spin-down rates indicates that they might be characterized by relatively low magnetic fields and long initial periods (Halpern et al. 2007).

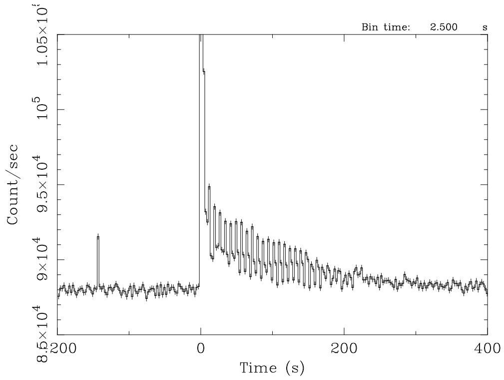

Fig. 1. Light curve at E> 80 keV of the 27 December 2004 giant flare from SGR 1806–20 as measured with the Anti-Coincidence Shield of the SPI instrument on INTEGRAL. Note that the peak of the flare at t=0, reaching an observed count rate $> 2 \times 10^6$ counts s^{-1}, is out of the vertical scale.

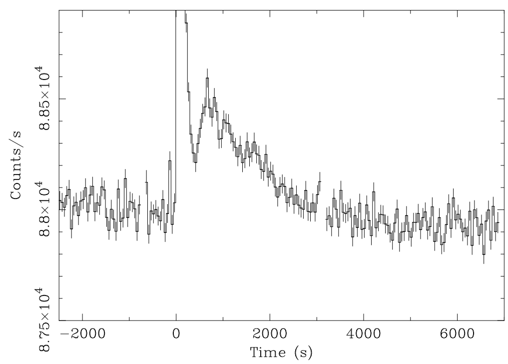

Fig. 2. SPI-ACS light curve of the SGR 1806–20 giant flare rebinned at 50 s to better show the emission lasting until one hour after the start of the outburst. Due to this rebinning the pulsations at 7.56 s in the time interval 0-400 s cannot be seen in this plot.

In the following I will illustrate a few examples of these new classes of neutron stars by presenting some recent results on four particularly interesting objects: the magnetar SGR 1806−20, the CCOs in the supernova remnants G 296.5+10.0 and RCW 103, and the XDINS RX J1856.5–3754.

2. A γ-ray afterglow after the December 2004 giant flare of SGR 1806−20

The magnetar SGR 1806−20 has been very active in the last few years (Mereghetti et al. 2005b; Götz et al. 2006) and in December 2004 it emitted the most powerful giant flare ever observed from a SGR (Mereghetti et al. 2005a; Hurley et al. 2005; Palmer et al. 2005). Giant flares are extremely rare events. Only three of them have been observed to date, each one from a different SGR: on 1979 March 5 from SGR 0525–66 in the LMC (Mazets et al. 1979), on 1998 August 27 from SGR 1900+14 (Hurley et al. 1999), and on 2004 December 27 from SGR 1806−20.

For an estimated source distance of 15 kpc, the SGR 1806−20 giant flare had isotropic luminosity above 50 keV of $\sim 6 \times 10^{47}$ erg s^{-1}, i.e. it was a factor 100 more intense than those previously observed from the other two SGRs. Its 200 ms long initial hard spike, the brightest extra-solar event ever recorded, was so intense to induce a significant perturbation in the Earth's ionosphere and to be detected also through its reflection on the Moon's surface (Mereghetti et al. 2005a; Frederiks et al. 2007). The total energy release of a few 10^{46} erg implies a catastrophic magnetic reconnection, associated to a major crustal fracture and leading to a global reconfiguration of the neutron star's magnetic field.

Fig. 1 shows the light curve of the giant flare, obtained with the Anti-Coincidence Shield (ACS) of the SPI instrument on board INTEGRAL. The main characteristics seen in all the SGR giant flares, i.e. a very intense, short and hard initial spike followed by a decaying tail lasting several minutes and modulated at the neutron star rotational period, can be easily recognized.

In addition, thanks to the very large effective area of the ACS, it was possible to detect an additional feature that could be the first evidence for a soft γ-ray afterglow following a SGR giant flare (Mereghetti et al. 2005a). As shown in Fig. 2, after the end of the pulsating tail the ACS count rate increased again, forming a long bump which peaked at t∼700 s, and returned to the pre-flare background level at t∼3000-4000. As discussed in Mereghetti et al.

(2005a), it is unlikely that this count rate increase be due to charged particles instrumental background. Its occurrence right after the exceptional flare from SGR 1806−20 points toward an association with this event. This has been confirmed by recent reports of independent detections, although with smaller statistics and covering different time intervals, obtained with Konus-Wind (Frederiks et al. 2007) and RHESSI (Boggs et al. 2007).

The time evolution of this "afterglow" component is well described by a power law, with the flux proportional to $\sim t^{-0.85}$. Its fluence, in ACS counts, is approximately the same as that in the pulsating tail (1-400 s time interval). Knowledge of the spectral shape is required to convert the counts fluence into physical units, but unfortunately the ACS does not provide any spectral resolution. Assuming a thermal bremsstrahlung with temperature kT=30 keV, Mereghetti et al. (2005a) reported a fluence in the 400-4000 s time interval of $\sim 3\times10^{-4}$ ergs cm^{-2} for E>80 keV (corresponding to $\sim 6\times10^{-3}$ ergs cm^{-2} for E>3 keV). Different values are obtained for a harder spectrum. For example, a power law with photon index 1.5 gives $\sim 2\times10^{-4}$ ergs cm^{-2} (80–1000 keV), which corresponds to $\sim 9\times10^{-5}$ ergs cm^{-2} (3-200 keV). Contrary to those derived with the kT=30 keV thermal spectrum, the latter values are in agreement with the fluence measured with RHESSI (Boggs et al. 2007). This provides evidence for a hard spectral shape, as also confirmed by the spectral analysis of the Konus-Wind data (Frederiks et al. 2007).

Both the power-law time evolution and the hard power law spectrum suggest a plausible interpretation of this long-lasting emission in terms of an afterglow emission, analog to the case of γ-ray bursts. With simple models based on synchrotron emission, it is possible to relate the bulk Lorentz factor Γ of the ejected material with the time t_0 of the afterglow onset. The observed values give $\Gamma\sim15(E/5\times10^{43}\,\mathrm{ergs})^{1/8}(n/0.1\,\mathrm{cm}^{-3})^{-1/8}(t_0/100)^{-3/8}$, where n is the ambient density. Γ is thus consistent with a mildly relativistic outflow, as also inferred from the analysis of the radio source that appeared after the giant flare (Granot et al. 2006).

3. The origin of the spectral features in 1E 1207–5209

1E 1207–5209, located close to the geometrical center of the shell-like supernova remnant G 296.5+10.0, is certainly one of the most interesting CCOs. With a relatively bright 0.3-3 keV flux of $\sim2\times10^{-12}$ erg cm^{-2} s^{-1}, it was well visible for early X–ray satellites like Einstein, ROSAT and ASCA. These observations, coupled to deep optical and radio searches for counterparts (Mereghetti et al. 1996), strongly suggested a neutron star nature, later confirmed by the discovery of pulsations at 424 ms (Zavlin et al. 2000).

What makes this object unique among CCOs, and more in general among isolated NS, is the presence of broad absorption features at ∼0.7 and ∼1.4 keV in its thermal spectrum (Fig. 3). They were discovered with *Chandra* (Sanwal et al. 2002) and shown to vary as a function of the spin phase with *XMM-Newton* (Mereghetti et al. 2002). A long *XMM-Newton* observation performed in August 2002, besides confirming the two lines at 0.7 and 1.4 keV, showed a statistically significant third line at ∼2.1 keV as well as a hint for a possible fourth feature at 2.8 keV (Bignami et al. 2003; De Luca et al. 2004). The nearly 1:2:3:4 ratio of the line energies, as well as the phase variation naturally following the pulsar B-field rotation, strongly suggest cyclotron resonance scattering for explaining the features. If the 0.7 keV line is the fundamental electron cyclotron frequency, then $B\sim6\times10^{10}(1+z)$, or $\sim8\times10^{10}$ G, assuming a 20% gravitational redshift (for protons, $B\sim1.6\times10^{14}$ G).

Alternative interpretations of the lines in 1E 1207–5209 have also been proposed. They were attributed to HeII transitions in a magnetar-like field $B\sim(1.4–1.7)\times10^{14}$ G (Pavlov & Bezchastnov 2005) or to heavier elements (e.g. He-like Oxygen or Neon) in a more conventional magnetic field $B\sim10^{12}$ G (Mori & Hailey 2006).

Until recently, claims of puzzling timing irregularities in the period evolution of 1E 1207–5209 (Woods et al. 2007) prevented a reliable estimate of B. However, an accurate reanalysis of the available observations demonstrated that such irregularities were due to data analysis problems and allowed to derive an upper limit of 2.8×10^{-16} s s^{-1} on the source spin-down (Gotthelf & Halpern 2007). This implies $B<3.6\times10^{11}$ G, thus favoring the interpretation of the spectral features in terms of electron cyclotron lines.

The cyclotron explanation, as opposed to the atomic one, would also naturally account for the uniqueness of the 1E 1207–5209 spectrum, since the powerful combination of throughput and energy resolution of the EPIC instrument on *XMM-Newton* is only effective for less than a decade in photon energy. Most isolated NS, with a more normal magnetic field, may have electron cyclotron features at energies above the EPIC range.

Another interesting implication of the small $\dot{P}$ of 1E 1207–5209 is that its characteristic age (>24 Myr) is clearly incompatible with the small true age testified by the association with a young supernova remnant. This indicates that 1E 1207–5209 was born with an initial period very similar to the current one. A similar conclusion holds for the CCO in Kes 79 (Halpern et al. 2007), suggesting the possibility that a causally connected combination of low B and long initial period might explain at least a fraction of the CCOs. The peculiar CCO discussed in the next section requires however a different interpretation.

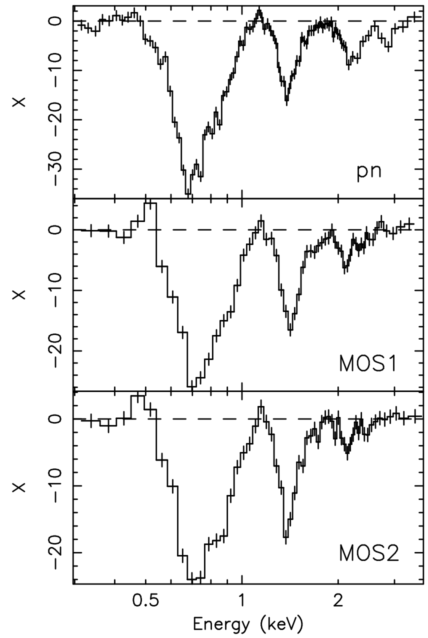

Fig. 3. Residuals in units of sigma obtained from comparing the data of the three EPIC cameras with the best fit continuum model, consisting of two blackbodies with kT_1=0.163 keV and kT_2=0.319 keV.

4. The CCO in RCW 103: a magnetar with a long initial period?

The X–ray source 1E 161348–5055 at the center of the supernova remnant RCW 103 has unique variability properties (De Luca et al. 2006) setting it apart from the other members of the CCO class that are remarkably constant sources. It showed secular luminosity variations in the range 10^{33}–10^{35} erg s^{-1} (Fig. 4), and its flux is strongly modulated with a period of 6.7 hours (Fig. 5). No faster periods have been detected. The pulsed fraction larger than 40%, the light curve variability, and the optical limits, ruling out companion stars of spectral type earlier than M5, exclude the interpretation of the 6.7 hr modulation as the orbital period of a normal low mass X–ray binary, a possibility that is also ruled out by the young age ($\lesssim$ 3000 yrs) provided by the association with the supernova remnant. It seems thus more likely that the periodicity is due to the slow rotation of an isolated NS and that the X–ray emission is magnetically powered. In this scenario one is faced with the problem of slowing down the magnetar to such a long rotation period within the short lifetime of only a few thousand years implied by the age of the RCW 103 supernova remnant.

A viable possibility (De Luca et al. 2006) is that the braking was provided by the propeller effect due to the presence of a fossil disk formed from the supernova material fall-back. However, such an evolutive path requires that the neutron star initial period be longer than ~300 ms in order to avoid the disk disruption by the relativistic outflow of the newly born active radio pulsar.

If this interpretation is correct, it would support other recent evidence that high mag-

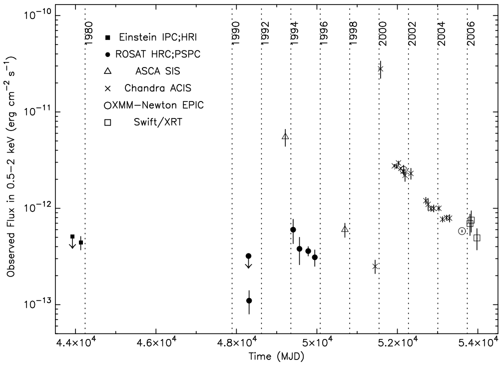

Fig. 4. Long term flux evolution of the CCO in RCW 103.

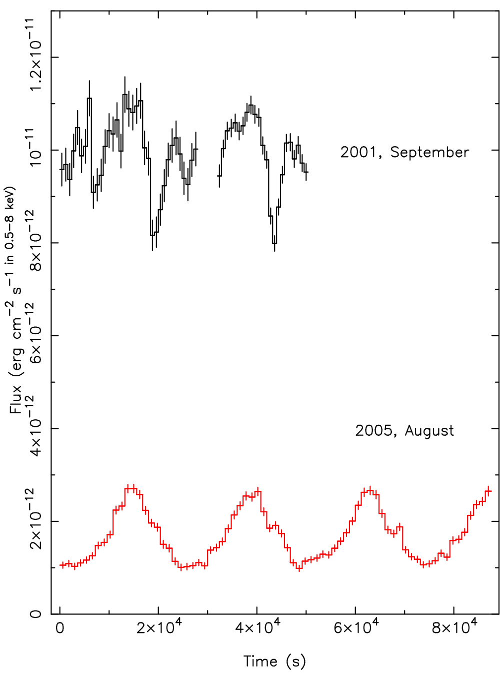

Fig. 5. Light curves of the CCO in RCW 103 showing the 6.7 hours periodicity. The shape of the modulation changed significantly between the high (2001) and low (2005) state.

netic fields might also be present in NS born with long spin periods (Ferrario & Wickramasinghe 2006), contrary to the standard magnetar formation scenario that foresees rapidly spinning (<2-3 ms) proto-neutron stars in order to generate a strong magnetic field through an efficient dynamo process (Thompson & Duncan 1993).

5. The discovery of pulsations in RX J1856.5–3754

RX J1856.5–3754 is the brightest member of the XDINS class. In fact it was the first of the Magnificent Seven discovered in the ROSAT data (Walter et al. 1996), and it has extensively been studied with several *XMM-Newton* and *Chandra* observations. Its X–ray spectrum is a featureless blackbody with kT=63 eV (Burwitz et al. 2003), contrary to the other Magnificent Seven, which have broad spectral features that are interpreted either as cyclotron resonances due to protons (or heavy ions), or as atomic lines (implying in both cases magnetic fields of several 10^{13} G, see Haberl (2007)).

As mentioned above, the XDINS are ideal targets to constrain the NS radius through modelling of the atmospheric emission, since contrary to all the other known NS where there is a mix of thermal and non-thermal emission that complicates the spectral analysis, their X–ray spectra are purely of thermal origin. Furthermore, for a few of them, including RX J1856.5–3754, a parallactic distance has been measured through observations of their faint optical counterparts. Note that a good knowledge of the distance is a necessary condition to infer the radius of the thermally emitting surface.

Until recently the spin period of RX J1856.5–3754 was not known, despite extensive observations, and at variance with the other members of the class that show pulsations with P in the 3–12 s range and pulsed fractions between 4% and 18%. The limits obtained for RX J1856.5–3754 imply pulsed fractions <1.3% (2σ) for periods between 0.02 and 1000 s (Burwitz et al. 2003). This led to the speculation that RX J1856.5–3754 could be a millisecond pulsar, but further data yielding an upper limit on the pulsed fraction of 2.1% (at 1σ) for periods in the range 1-20 ms made also this hypothesis unlikely (Zavlin 2007).

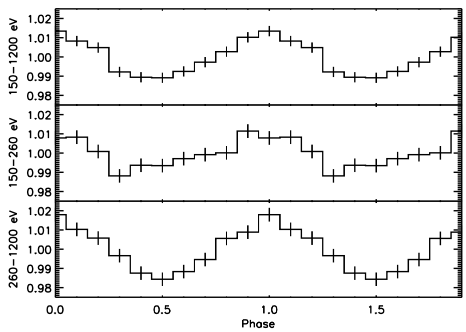

Fig. 6. Folded light curves of RX J1856.5–3754 in the 0.15-1.2 keV, 0.15-0.26 keV, and 0.26-1.2 keV energy ranges. The pulsed fractions are (1.17±0.08)%, (0.88±0.11)%, and (1.5±0.11)%, respectively.

The puzzle was finally solved by the discovery of a periodicity at 7 s in *XMM-Newton* data obtained in October 2006 (Tiengo & Mereghetti 2007). Reanalysis of all the previous *XMM-Newton* observation, as well as of two further ones carried out in March 2007 confirmed the presence of the pulsations. The pulsed fraction is the smallest every observed in an isolated NS: 1.2% in the 0.15-1.2 keV energy range.

This result indicates that, except for the striking absence of deviations from a pure blackbody in its X–ray spectrum, RX J1856.5–3754 shares most of the properties of the other members of the XDINS family. The small pulsed fraction poses strong constraints on the surface emission temperature gradients and on the angles between rotation axis, magnetic axis and line of sight (see, e.g., Ho (2007)). More importantly, the discovery of pulsations opens the way for the determination of $\dot{P}$ and hence the magnetic field. As seen above in the case of 1E 1207–5209, this is crucial for a detailed modelling and correct interpretation of the star's surface X–ray emission. The available observations can only give an upper limit on $\dot{P}$ of 1.9×10^{-12} s s^{-1}, corresponding to B< 1.2×10^{14} G. Future *XMM-Newton* observations could provide more accurate timing results if they are performed with an appropriate strategy allowing to perform phase coherent timing analysis.

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