Central Compact Objects in Supernova Remnants

Andrea De Luca
IASF/INAF Milano, Via Bassini 15, 20133 Milano, Italy
IUSS Pavia, V.le Lungo Ticino Sforza 56, 27100 Pavia, Italy

Abstract. Central Compact Objects (CCOs) are a handful of soft X-ray sources located close to the centers of Supernova Remnants and supposed to be young, radio-quiet Isolated Neutron Stars (INSs). A clear understanding of their physics would be crucial in order to complete our view of the birth properties of INSs. We will review the phenomenologies of CCOs, underlining the most important, recent results, and we will discuss the possible relationships of such sources with other classes of INSs.

Keywords: Isolated Neutron stars; Supernova Remnants
PACS: 97.60.Jd, 97.60.Gb, 98.38.Mz

CCOs & THE MANY SPECIES OF INSS

Recent X-ray observations radically changed the classic idea that all Isolated Neutron Stars (INSs) are born as fast spinning radio pulsars. A rich phenomenology emerged, which led to the classification of INSs into different species. Radio-loud species include rotation-powered radio PSRs and Rotating Radio Transients (RRaTs, [48]). The other species are generally radio-quiet and include Anomalous X-ray Pulsars (AXPs, Woods, these proceedings; see also [91]), Soft Gamma Repeaters (SGRs, Woods, these proceedings; see also [91]), Central Compact Objects (CCOs, discussed here; see also [60, 61]) at the center of Supernova Remnants (SNRs) and X-ray Dim Isolated Neutron Stars (XDINSs, Kaplan, these proceedings; see also [33]).

The differences among the INSs’ species are certainly related to different properties of their magnetic fields. For instance, AXPs and SGRs are supposed to be close relatives, different from standard radio PSRs owing to their huge magnetic field (hence named “magnetars”). Unifying the rich phenomenological diversity in a coherent physical scenario is one of the most urgent tasks in INS astronomy. A clear picture, including evolutionary paths, possibly connecting different species, is still lacking.

To this aim, understanding the birth properties of INSs would be crucial. Indeed, the least understood members of the INSs family are the youngest ones, i.e. the CCOs.

CCOs (see Table 1 for a list of the seven members of the class) are a handful of sources characterized by (i) position close to the center of a young SNR; (ii) lack of radio/IR/optical counterparts, as well as of surrounding diffuse, non-thermal nebulae; (iii) constant, unpulsed X-ray emission ($L_X \sim 10^{33} \text{ erg s}^{-1}$) with thermal-like spectrum characterized by high temperatures (0.2-0.4 keV) over a very small emitting area (few % of the expected NS surface). Thus, while point (ii) implies that CCOs are not standard young radio PSRs, point (iii) separates them from “standard” AXPs and SGRs. The classification of a source as a CCO has been in some way a process by elimination, in the lack of a clear physical understanding of such sources.

We are not even sure that all CCOs be INSs. We only know for sure that they are young and that their formation in supernova explosions must be a rather common event. Indeed, inspecting all known SNRs within 5 kpc of the solar system, we find 14 radio PSRs (3 are beamed away from us, revealed by bright non-thermal nebulae), 6 CCOs and 1 AXP. New candidate CCOs are also being discovered at the centers of more distant SNRs.

Recently, results on specific sources shed light on their nature. We will review such new results and we will exam possible classification schemes.

SEARCHING FOR A CCO TEMPLATE

1) A very peculiar magnetar

1E 161348-5055 (1E 1613) was discovered with the Einstein satellite [85] very close to the geometrical center of the young [2,000 yr, [10] supernova remnant RCW103, located at a distance of $\sim 3.3$ kpc [73].

Historically, it was the first radio-quiet neutron star candidate found inside a SNR. While 1E 1613 was considered to be most probably a young, off-beamed pulsar, the lack of a surrounding, diffuse non-thermal nebula [85] made it very different from the Crab, the prototypical young pulsar. Such an interpretation was supported by its soft X-ray spectrum, pointing to the first detection of thermal radiation from the surface of a NS, as well as by the lack of a radio or optical counterpart [86, 29].
However, X-ray observations of 1E 1613 over the following years unveiled a puzzling temporal behaviour. Gotthelf et al. [30], using ASCA, ROSAT and Einstein data, found evidence for a factor 10 variability in flux on the few year time scale. More recently, such a variability was confirmed thanks to Chandra observations. Garmire et al. [25] discovered a large brightening (about two orders of magnitude) between September 1999 and March 2000, while two years later Sanwal et al. [77] (with Chandra) as well as Becker & Aschenbach [5] (with XMM-Newton) observed 1E 1613 at an intermediate flux level. Moreover, the first Chandra observation of 1E 1613 in its low state hinted a possible periodicity at ~ 6 hours [26]. The subsequent observations of the source in active state could not conclusively solve the issue, the periodicity was not detected in the very high state of early 2000, but was possibly seen again in 2002 by Sanwal et al. [77], while Becker & Aschenbach [5] did not find any periodicity, but observed a complex light curve including a possible “partial eclipse”.

A long (90 ks) observation with XMM-Newton, performed in 2005, caught 1E 1613 in a low state and yielded unambiguous evidence for a strong, nearly sinusoidal modulation at P=6.67±0.03 hours, with a 50% pulsed fraction [16]. The source spectrum, well described by an absorbed double blackbody model, varies significantly as a function of the 6.67 hour cycle and appears harder at the peak. The same 6.67 hour periodicity was then recognized also in the older XMM-Newton dataset, with a much lower pulsed fraction (~ 10%) and a remarkably different light curve, including two narrow minima (“dips”) per period. Such an “active state” was also characterized by a factor 6 higher flux and a harder spectrum. No faster pulsations are seen in the two XMM-Newton observations down to P=12 ms, with an upper limit of 10% to the pulsed fraction (at 99% c.l.).

Monitoring with Swift/XRT shows that the source (as of August, 2007) is still fading, although at a somewhat slower rate. A long observation with Chandra/HRC, performed in 2007, July by our group, shows again the nearly sinusoidal modulation at 6.67 hours, with a pulsed fraction as high as ~ 55% in 0.1-10 keV.

On the optical/IR side, VLT/ISAAC and HST/NICMOS images collected in 2001 and in 2002, respectively, unveiled a very crowded field, with a few objects possibly consistent with the X-ray position of 1E 1613 [77, 53, 61]. Deep observations with the VLT/NACO instrument were performed in 2006 (during the low state of 1E 1613) with the aim to search for 6.67 hours modulation of the four possible counterparts (Ks–18 -20) lying within the 3σ error region (Mignani et al., these proceedings; [17]). None was found. Comparison with the HST/NICMOS images does not show a clear variability correlated to the factor 3.5 fading of 1E 1613 during the same time span. Moreover, the possible counterparts do not stand out for peculiar colors with respect to the bulk of the very red (H-K ∼ 2, requiring A_V ∼ 20 – 25) stellar background population. Thus, there are no compelling reasons to associate any of them to 1E 1613, which remains undetected in the IR down to Ks ∼ 22.1. A search for a counterpart with Spitzer was also performed, with negative results [88].

Is 1E1613 a “braked magnetar”? 

The unique combination of 6.67 hour periodicity, dramatic long-term variability, young age and underluminous IR counterpart makes 1E 1613 a unique source among all compact objects.

Association of 1E 1613 to RCW103 seems very robust, based on several arguments. The point source lies within 15 arcsec of the apparent center of the 10 arcmin wide SNR. Moreover, the two system have consistent distances, as apparent by the same interstellar X-ray absorption [16], as well as by neutral H studies in radio, which also support the association on a morphological basis [73].

As discussed by De Luca et al. [16], 1E 1613 could be a binary system featuring a compact object, born in the supernova event which generated RCW103, and a very small companion star. In such a frame, the 6.67
TABLE 2. Optical/infrared results for the seven confirmed CCOs. In the case of 1E 1207 we give the magnitudes of an M dwarf located close to the Chandra position; updated astrometry questioned its possible association to 1E 1207 [71, 88]. A few IR sources have been found inside the Chandra error circle for the CCOs in the RCW103 and G347.3-0.5 SNRs. In such cases, the magnitudes refer to the source closest to the X-ray position, even if there are not compelling reasons to associate the IR sources to the X-ray ones. See text for references.

| CCO                          | optical/IR counterpart (mag) | optical/IR upper limit (mag) |
|------------------------------|-----------------------------|-----------------------------|
| 1E 1613 in RCW103            | H~ 21.4 (?), K~ 19.2 (?)    | I> 25, K> 21.1              |
| 1E 1207 in G296.5+10.0       | J~ 21.7, H~ 21.2, K~ 20.7  | R> 27.1, J> 23.5, H> 22.4, K> 22.0 |
| CXOU J1852 in Kes 79         | ...                         | R> 24.9                    |
| CXOU J2323 in Cas A          | ...                         | R> 27.8, J> 26.2, H> 24.6, K> 21.2 |
| RX J0822 in Puppis A         | ...                         | B> 26.5, R> 26.0, J> 21.7, H> 20.6, K> 20.1 |
| 1WGA J1713 in G347.3-0.5     | H~ 19.4 (?), Ks~ 18.3 (?)  | I> 24.6, H> 22, K> 20.5    |
| CXOU J0853 in VelJr.         | H~ 21.6 (?), Ks~ 21.4 (?)  | R> 25.6, J> 22.6, H> 22.5, Ks> 21.8    |

... hour modulation could be “naturally” interpreted as the orbital period of the system. However, 1E 1613 is dramatically different from any known Low-Mass X-ray Binary (LMXB) system, because of its low luminosity ($10^{33} - 10^{35}$ erg s$^{-1}$), purely thermal spectrum, large spectral evolution along the 6.7 hour cycle, long term variability in pulse shape and fraction, very long time scale for the recovery from the outburst. De Luca et al. [16] proposed that a peculiar “double accretion” (wind + disc) scenario could be at work in a very young LMXB, driven by a significant orbital eccentricity, expected on theoretical basis [40]. The recent IR results do not support such a picture [17]. None of the potential counterparts is consistent with a small star at the distance of 1E 1613. The upper limits leave room only for a very low-mass star (M6-M8), which seems unable to power via its wind the observed pulsed luminosity (an accretion rate of $\sim 10^{-13} M_{\odot}$ yr$^{-1}$ would be required). Moreover, it seems unlikely that a LMXB with such an extreme mass ratio could survive the supernova explosion. Such difficulties lead us to consider an alternative picture of 1E 1613 as a very peculiar isolated compact object [16]. Within such a frame, the picture best fitting to the unique phenomenology of 1E 1613 is the one of a “braked magnetar”, spinning at 6.7 hours. Indeed, most aspects of 1E 1613’s phenomenology easily fit in a magnetar scenario: spectrum, luminosity, long term variabilities are very similar to the ones shown by Anomalous X-ray Pulars [91]. However, all known AXPs spin in the 2-12 s range, i.e. thousands of times faster than 1E 1613. A very efficient braking mechanism is required to slow down 1E 1613 in 2000 yr from its presumably much faster spin rate at birth. De Luca et al. [16] show that propeller effect on the material of a fallback disc could provide such a mechanism, provided that the NS was born with a very high magnetic field ($\sim 5 \times 10^{15}$ G) and with a rather slow period ($\sim 300$ ms) to avoid an early “ejector” phase which could have pushed away any surrounding material. Recently, Li [46], using a different model for the interaction between the rotating INS’s magnetosphere and the surrounding fallback disc, showed that initial conditions may be relaxed and birth period down to a few ms could be allowed. Thus, 1E 1613 would be the first known example of a new class of very slowly rotating magnetars, whose spin down history is completely dominated by the role of fallback material.

2) Weakly magnetized INSs

1E 1207.4-5209 in G296.5+10.0

1E 1207.4-5209 (1E 1207) was detected with the Einstein satellite close to the center of the $\sim 7$ kyr old SNR G296.5+10.0 [75], located at a distance of $\sim 2$ kpc [27], quite high to the Galactic Plane (b $\sim 10^\circ$). It was the second thermally-emitting radio-quiet INS candidate found inside a SNR. Pulsations from 1E 1207 were discovered with the Chandra satellite [93], proving the source to be an INS.

Early timing investigations hinted a non-monotonous period evolution of 1E 1207, suggesting that the source could be a peculiar binary system [94, 92]. However, very recently, Gotthelf & Halpern [32], using at once all available X-ray data, provided conclusive evidence that 1E 1207 is a very stable rotator, with essentially no measurable period evolution (see also Gotthelf & Halpern, these proceedings). The upper limit to the period derivative ($\dot{P} < 2.5 \times 10^{-16}$ s$^{-1}$ at 2$\sigma$) yields

---

1 A different binary picture for 1E 1613, suggesting the system to be an analog of Cataclysmic Variables of the Polar or Intermediate Polar classes, originally proposed by Popov [69], has been studied by Pizzolato et al. [63]. Such a scenario, which could possibly avoid some of our drawbacks, features a magnetar in a binary system with a low-mass star. Magnetic and material interaction could have slowed down the NS rotation to $P$=6.67 hours, synchronous (as in Polars) or quasi-synchronous (as in Intermediate Polars) to the orbital period.
an INS characteristic age \( \tau_c > 27 \text{ Myr} \), exceeding by 3 orders of magnitude the age of the SNR, and a very small dipole magnetic field, \( B < 3.3 \times 10^{11} \text{ G} \). Such results point to a weakly magnetized INS, born with a spin period very close to the current one.

**CXOU J185238.6+004020 in Kes 79**

A very similar picture emerged for another member of the CCO class. The source CXOU J185238.6+004020 (CXOU J1852) was discovered with a Chandra observation by Seward et al. [78] at the center of Kes 79 SNR, a 5.5-7.5 kyr old SNR [81], located at \( \sim 7 \text{ kpc} \). A follow-up observation with XMM-Newton allowed Gotthelf et al. [51] to discover a 105 ms pulsation from the source. Further observations with XMM-Newton and Chandra did not show a significant change in the period of CXOU J1852. Halpern et al. [55] set a 2σ upper limit to the period derivative \( \dot{P} < 2.0 \times 10^{-16} \text{ s s}^{-1} \), yielding a characteristic age \( \tau_c > 8 \text{ Myr} \) and a dipole magnetic field \( B < 1.5 \times 10^{11} \text{ G} \).

**Half-brothers or twins?**

Judging on the basis of their very similar spin parameters, 1E 1207 and CXOU J1852 should be close relatives. However, their spectra, as well as their phase-resolved behaviour, are very different.

1E 1207 stands out among CCOs because of its unique spectrum. Two large absorption features superimposed to the thermal spectrum, centered at 0.7 keV and at 1.4 keV, were discovered thanks to Chandra and XMM-Newton observations [77, 50]. Such features vary as a function of the rotational phase [50]. This was the first detection of spectral features in the X-ray spectrum of an INS, making 1E 1207 an outstanding source among all compact objects. A very deep (250 ks) observation performed with XMM-Newton in 2002 unveiled the presence of a third absorption feature at 2.1 keV and possibly of a fourth one at 2.8 keV [7, 15]. The actual significance of the third and fourth lines has been questioned by Mori et al. [56] who evaluated the dependence of such features’ equivalent width on the underlying continuum model. The very deep XMM dataset of 2002 showed that the 424 ms \( \sim 7\% \) pulsation is almost entirely due to phase variation of the absorption features (with a \( \sim 12\% \) variation), while the continuum has a much less pronounced modulation (\( \sim 3\% \)). Such a behaviour is unique among all INSs.

The nature of the spectral features of 1E 1207 has been debated since their discovery, possible interpretations being atomic transition lines in the NS atmosphere or cyclotron features in the plasma surrounding the star [77, 50]. The cyclotron interpretation was strongly supported by the detection of the third and of the possible fourth line [7, 15], since the four features have central energies in the harmonic ratio 1:2:3:4 and show a significant dependence on the NS rotational phase. Assuming the 0.7 keV feature to be the fundamental cyclotron line yields a measure of the magnetic field of \( 8 \times 10^{10} \text{ G} \), or \( 1.6 \times 10^{14} \text{ G} \), in case electron or protons responsible for the absorption, respectively. The scenario of 1E 1207 as a weakly magnetized neutron star is fully consistent with the electron cyclotron interpretation of the features. A difficulty with the cyclotron scenario is postulated by the similar equivalent widths observed for the first and second harmonic, at odds with theoretical expectations, since the oscillator strength of the second harmonic should be a factor \( \sim 2,000 \) lower than the one of the first harmonic. A possible solution to such a problem was proposed by Liu et al. [47], who suggested the magnetized plasma responsible for the absorption to be optically thick at the frequency of the first harmonic (so that a saturation absorption is achieved, independent on the particle density), but optically thin for the second and higher harmonics. Such a model requires a rather high particle column density in the surroundings of the NS, which could possibly be sustained by accretion of fallback material. Alternative interpretation for the lines are also proposed (Ho et al., these proceedings).

CXOU J1852, on the other side, has a thermal spectrum with no features within the statistics available, which is far less abundant than that for 1E 1207. However, CXOU J1852 has a striking peculiarity, i.e. it has a very large pulsed fraction, as high as \( \sim 80\% \). Such a value makes CXOU J1852 an outstanding source among all thermally emitting INS. Such a phenomenology would point to the picture of a small hot region on the NS surface, coming into view or being hidden as a function of the star rotation. However, this is quite at odds with the picture of CXOU J1852 as a weakly magnetized NS. First, the small magnetic field inferred from timing does not seem able to generate such a large surface temperature anisotropy (either due to anisotropic thermal conduction from the stellar interior, or due to surface bombardment by magnetospheric particles). Moreover, gravitational bending of the trajectories of photons escaping from the surface should significantly suppress the modulation. Indeed, Psaltis et al. [70] showed that a pulsed fraction larger than \( \sim 35\% \) cannot be expected even for an extremely small hot spot with a very large temperature contrast with respect to the surface. Beaming due to radiative transfer effects in a strongly magnetized plasma could explain the modulation, but would require presence of large multipole components in the magnetic field, in order to be consistent with the observed small spin-down. Alternatively, such problems could be solved in a picture invoking accretion of fallback material. Emis-
3) A dormant magnetar (?)

With an age of ~330 yr, as estimated with a HST study of the expansion of high-velocity debris [21], Cas A is the remnant of the last supernova explosion occurred in our Galaxy. Detection of O and Si-group abundances in the ejecta supports the picture of Cas A as the remnant of a massive star [14]. The central X-ray source, CXOU J23237.9+584843 (CXOU J2323) was discovered in the Chandra First-light image [82] and identified a posteriori in ROSAT and Einstein images. It lies ~7 arcsec off the apparent SNR expansion center [21], implying a (projected) velocity of order 350 km s\(^{-1}\). Extensive multiwavelength observations of both the CCO and the SNR have been performed [58, 13, 51, 21] and different hypotheses (either an INS, or an isolated black hole) have been considered to explain the CCO.

A very interesting result was obtained by Krause et al. [43] who discovered in multi-epoch Spitzer images (at 24 \(\mu\)m), spanning a 1 year time interval, fast moving features (10 – 20 arcsec yr\(^{-1}\)) located in the outskirts of the SNR. At the SNR distance, such proper motion corresponds to a velocity close to c. The most likely interpretation of such features is that they are infrared echoes from interstellar dust, heated by a travelling pulse of light. This points to a large flare from CXOU J2323, occurred around A.D. 1953, with an almost orthogonal beaming with respect to the line of sight, with a luminosity of ~2 \(\times\) 10\(^{46}\) erg s\(^{-1}\), which is comparable to the energetics of giant flares from SGRs. If such an interpretation is correct, CXOU J2323 could be a dormant magnetar. The spectrum and luminosity are consistent with that of of transient AXPs in quiescence, as well as with SGRs observed in low-luminosity state [52]. Current upper limits to long-term variability and pulsations in the soft X-ray band [51, 22], as well as upper limits to an IR counterpart [22, 88], are consistent with such an hypothesis.

OTHER CCOS: MORE OF THE SAME?

The central source in Puppis A

Puppis A is the remnant of the explosion of a very massive star [9], occurred ~3,700 years ago [89], at a distance of ~2.2 kpc [72]. The central X-ray source RX J0852.0-4622 (RX J0852), hinted in Einstein images [64] and later identified with ROSAT [65], is located ~6.1 arcmin off the geometrical center of the SNR. Association of RX J0852 to the SNR is supported by consistent distance estimates and HI morphological studies in radio [72]. Deep radio observations set very stringent upper limits to a radio nebula associated to RX J0852 [24]. The large offset between RX J0852 and the SNR center requires a high space velocity for the compact object, inherited from a natal kick during the supernova explosion. Indeed, evidence for a large proper motion in good agreement with the expected one (both in direction and in magnitude) has been reported, based on the analysis of multi-epoch Chandra images [57, 90].

Analysis of two XMM-Newton datasets did not confirm a pulsation at 75 ms hinted in ROSAT data [57] - excluded also by Chandra data [60] - but yielded some evidence for a candidate periodicity around 220 ms [37], with a pulsed fraction of ~5%. However, the significance of such a pulsation in each dataset is rather low, and the corresponding periods at the two epochs are rather different, which would imply a very large period derivative (~2 \(\times\) 10\(^{-10}\) s s\(^{-1}\)), among the largest ever observed for an INS, only comparable to the upper side of the values measured for an extreme object such as SGR 1806-20 [91]. The resulting characteristic age of ~17 yr would also require a non-steady spin down for the source. New observations are needed to confirm (or to rule out) such a peculiar periodicity. We estimate that the currently available photon statistics should allow to detect at 99% confidence level any modulation with a pulsed fraction higher than 7% and period in the range 12 ms - 20 s. Such a value (computed assuming a sinusoidal modulation and accounting for the number of trials) may be assumed as an upper limit to any undetected pulsation.

Spectrum and luminosity of the CCO, as seen by XMM-Newton, are fully comparable to those of the other members of the family [37]. No variability is apparent on the few month time scale, with an upper limit of order 5%. Upper limits to an optical/IR counterpart leave room for a faint dwarf star as well as for a fallback disc [88].

The central source in G347.3-0.5

The supernova remnant G347.3-0.5 is the prototype of the peculiar class of “non-thermal” SNRs. Very faint in radio, and dominated, in the soft X-ray band, by non-thermal emission [42, 79], the SNR is very bright at TeV energies, where it has been beautifully resolved in HESS images [1]. The distance and age of the remnant are debated. A distance of order 6 kpc has been assumed in the past, based on a possible association of the SNR with surrounding molecular clouds and HII region [75].
Such a distance would imply an age of a few $10^4$ yr, assuming Sedov evolution. However, more recently, studies with XMM-Newton, coupled to new CO mm-wave high-resolution observations, unveiled a possible interaction of the SNR shock with molecular gas, pointing to a distance of $1.3 \pm 0.4$ kpc [11, 12, 23]. The revised distance implies a much younger age for the SNR (few thousands yr), in agreement with the idea that G347.3-0.5 could be the remnant of the supernova recorded in A.D. 393 [87].

The central X-ray source 1WGA J1713.4-3949 (1WGA J1713) was observed by ROSAT [62, 79] and ASCA [79]. XMM-Newton and Chandra observations confirmed its similarity to other CCOs, on the basis of its thermal-like spectrum and of the lack of any counterpart [44, 12]. At the revised SNR distance, the luminosity of 1WGA J1713 is fully consistent with that of other members of the CCO class.

Our analysis of multi-epoch XMM-Newton observations does not show any long-term flux variability larger than ~5% on years time scale, nor pulsations with pulsed fraction larger than ~7% in the 12 ms - 6 s range (at 99% confidence level, taking into account the number of trials).

In the optical/IR range, observations with VLT/NACO have been performed in the H and K band (Mignani et al., these proceedings; [54]). A few faint sources ($K_s \sim 18 – 19$) in a very crowded field are possibly consistent with the Chandra position; however, no firm conclusions may be drawn about their association with 1WGA J1713.

The central source in Vela Jr.

The supernova remnant was discovered in ROSAT data, superimposed to the large Vela SNR and emerging at energies above ~1 keV [4]. It is dubbed “Vela Jr.” because of its supposedly younger age than the surrounding Vela remnant. Indeed, the age and distance of the Vela Jr. SNR are a matter of controversy. Possible detection with Comptel of $\gamma$-ray line emission at 1.157 MeV - originating from the decay of $^{44}$Ti produced in the SN explosion - suggested a very young age (~700 yr) and small distance (~200 pc) for the remnant [38]. However, re-analysis of Comptel data questioned the significance of the 1.157 MeV feature [78]. A possible emission feature at 4.4 keV, detected at rather low significance (~4$\sigma$) in XMM-Newton data [35] and hinted in ASCA data [84] (but see also [80]), possibly due to $^{44}$Sc and $^{44}$Ti fluorescence, supported the picture of a very young and nearby system.

On the other side, the observed X-ray interstellar absorption is a factor ~6 larger than the one observed towards the Vela SNR, arguing for a significantly larger distance for Vela Jr. [80]. Considering all uncertainties, a distance in the range 0.5-1.5 kpc and an age in the range 1000-3000 yr seem reasonable estimates. Vela Jr. is another member of the class of non-thermal SNRs. It has a purely non-thermal soft X-ray emission [84, 80], and it has been detected at TeV energies [2]. Thus, it appears very similar to G347.3-0.5, considering the fact that both sport a CCO close to their center.

The central source, hinted by ROSAT images [4], was observed in BeppoSAX data [49] and was finally localized with high accuracy with Chandra [59]. The lack of an optical counterpart points to an INS nature. The CCO, CXOU J085201.4-461753 (CXOU J0852), is located ~4 arcmin North wrt. the geometrical center of the SNR. The region is rather complex and radio observations yield evidence for a diffuse source (possibly a planetary nebula) very close (in projection) to the position of CXOU J0852 [74].

CXOU J0852 has been repeatedly observed with XMM-Newton [6] and Chandra [59, 41]. It has a thermal featureless spectrum and a luminosity of ~2.5 x $10^{32}$ erg s$^{-1}$ (at 1 kpc), the smaller among the CCO group. Our analysis of the entire XMM dataset allows to set an upper limit of 5% to any long-term variability, as well as an upper limit of 7% to the pulsed fraction of any undetected pulsation in the range 12 ms - 20 s (at 99% confidence level, taking into account the number of trials).

A small H$\alpha$ nebula has been discovered at a position fully consistent with the coordinates of CXOU J0852 [63]. Such a nebula, if physically related to the CCO, could either be a velocity-driven bow-shock (which would imply that CXOU J0852 is powering a relativistic particle wind), or a photo-ionization nebula. Evidence of such a diffuse structure was confirmed by ESO/VLT observations [54], which also unveiled the presence of a faint IR source ($K_s \sim 21.4$) close to the position of CXOU J0852. However, no firm conclusion about the nature of such source, nor on its possible association with the CCO, could be drawn. Planned HST observations in the H$\alpha$ band will shed light on the nature of the diffuse structure.

“Candidate” CCOs

Few more X-ray sources have been observed inside supernova remnants, with a phenomenology pointing to a classification as CCOs.

Chandra images have unveiled a possible CCO at the center of the ~3000 yr old SNR G330.2+1.0 [62], a member of the class of non-thermal supernova remnants [83], located at 5-10 kpc, very similar to G347.3-0.5 and Vela Jr. Such a point source (~600 counts) shows spectrum and luminosity very similar to other CCOs; a
marginal evidence for pulsations at 7.5 s has also been obtained.

A possible CCO has been discovered with Chandra close to the center of the very young (1000-3000 yr) shell-type SNR G15.9+0.2, located at $\sim 8.5$ kpc. The spectrum and luminosity of the point source, highly absorbed, together with the lack of radio or optical counterpart, seem typical for a CCO, although a very small statistics is available ($\sim 100$ counts).

Chandra images unveiled an X-ray source close to the center of the G349.7+0.2, a $\sim 4000$ yr old SNR located at $\sim 22$ kpc. The small number of photons ($\sim 30$ counts) hampers any further consideration. However, if the source is associated to the SNR, its luminosity would point to a CCO interpretation.

RX J0002+6245, an X-ray source located close to the CTA1 supernova remnant, was proposed by Hailey & Craig to be an INS, on the basis of the thermal-like spectrum and possible pulsation at 242 ms. Fault surrounding diffuse emission was proposed to be a previously unknown SNR, associated to the INS. XMM-Newton observations do not confirm such a picture and clearly show that RX J0002+6245 is a normal F-type star.

**CONCLUSIONS**

Sensitive multiwavelength observations point to the picture of CCOs as an heterogeneous sample of intrinsically different objects. We are pretty sure that 1E1207 and CXOU J1852 are neutron stars with a weak magnetic dipole field. On the other side, 1E 1613 is possibly a very peculiar magnetar, and the central source in Cas A could also be a magnetar in a long-lasting quiescent phase. What could the remaining CCOs be? The birth rate of objects like 1E 1613 (be it a braked magnetar, or a young binary) is expected to be very low, thus it seems unlikely to find similar sources hidden (in quiescence?) behind other CCOs. Most probably, CCOs include both weakly magnetized INSs and dormant magnetars. Thus, they represent the two wings of the distribution of newborn neutron stars as a function of their magnetic fields, bracketing the radio pulsars which account for the bulk of the population. Ironically, our current view of the CCO phenomenology in several cases prevents us from distinguishing between two alternative scenarios requiring totally different physical properties.

The scenario of weakly magnetized INSs is based on the link between slow rotation of the proto-neutron star, inefficient magnetic field generation and accretion of fallback material, which would quench standard “radio PSR” emission. A sort of unified picture, in which the evolution of an INS depends on initial spin/magnetic field properties, driving the star’s interaction with fallback material, could be considered (as suggested a few years ago by [8]). The biggest problem within the weakly magnetized INSs scenario is accounting for the details of the X-ray emission, explaining the rich phenomenologies of the prototypes 1E 1207 and CXOU J1852 and the less spectacular properties of the other candidates. Why do we see multiple spectral features in 1E 1207 only? How can the pulsed fraction in CXOU J1852 be so high? Why the pulsed fraction of the other sources is so low? Where are X-rays ultimately produced? Are we seeing the neutron star surface?

A lot of theoretical work will be needed. Other interesting issues are the birth rate of such weakly magnetized INSs, and their “fate”. After the host SNR fades away, such sources, which were found during observations devoted to the study of their SNRs, could quickly become much harder to detect, replenishing the large expected (but not observed) Galactic population of INSs. Or, alternatively, could they begin at a later stage a radio PSR activity? Sensitive searches for radio pulsations from 1E 1207 and CXOU J1852 would be very interesting, especially in view of the possible detection of 1E 1207 as a radio PSR by Parkes [8].

The picture of dormant magnetars is also a viable possibility. Assessing a magnetar nature for one or more CCOs would have important consequences on our estimate of the Galactic population of magnetars (many more could hide in a long-lasting quiescent state) and of the birth rate of such sources.

Sensitive X-ray (and radio) searches for pulsations and for long-term variability, coupled to deep observations in the infrared (to search for a possible debris disc - current upper limits are not constraining) will be crucial to address the nature of CCOs. It will be a rewarding investment, since it will complete our view of the birth properties of neutron stars. This will be a fundamental piece of information in order to derive a coherent, unified scenario for different species of INSs, elucidating which differences are related to the objects’ nature (birth properties) and which ones are related to the objects’ evolution. Indeed, as noted by Woods (these proceedings), the combination of the estimated birth rates for different INSs species [see, e.g. 20, 28, 68, for radio PSRs, magnetars, RRaTs and XDINSs, respectively] exceeds the overall estimated Galactic core-collapse supernova rate [18]. Although such estimates should be taken with caution, this suggests the possibility of an evolutionary path linking at least few INSs species. We could also expect at least few Galactic SNRs to host an Isolated Black Hole (IBH) and thus we cannot exclude that some IBH be hidden among CCOs (as it was considered for the source in Cas A [58, 13]). Such an hypothesis seems rather unlikely because there are no IBH emission models able to fit the observed X-ray emission properties [13]. Furthermore, we would be facing some sort of conspiracy, rendering
undistinguishable the phenomenologies of astrophysical objects as diverse as weakly magnetized neutron stars, dormant magnetars and IBHs.

ACKNOWLEDGMENTS

I warmly thank the organizers of the conference “40 years of Pulsars: Millisecond Pulsars. Magnetars and more” for the invitation. I thank P.A.Caraveo and P.Esposito for a critical reading of the manuscript, and S.Mereghetti, R.P.Mignani, A.Pellizzoni, A.Tiengo and G.F.Bignami for many useful discussions. My research work on the topic of the manuscript is supported by the Italian Space Agency (ASI).

REFERENCES

1. Aharonian, F.A., Akhperjanian, A.G., Aye, K.-M., et al., 2004, Nature 432, 75
2. Aharonian, F., Akhperjanian, A.G., Bazer-Bachi, a.R., et al., 2005, A&A 437, L7
3. Alpar, M.A., 2001, ApJ 554, 1245
4. Arentoft, J.L., 2002, in “Neutron Stars and Their Environments”, ed. W.Becker, H.Lesch and J.Truemper, MPE Report 278, 64
5. Becker, W., Hui, C.Y., Aschenbach, B., 2006b, A&A 457, L33
6. Bignami, G.F., Caraveo, P.A., De Luca, A., Mereghetti, S., 2003, Nature 423, 725
7. Camilo, F., De Luca, A., Caraveo, P.A., 2003, Nature 423, 725
8. Cassam-Chenai, G., Decourchelle, A., Ballet, J., et al., 2004, A&A 427, 199
9. Cassam-Chenai, G., Decourchelle, A., Ballet, J., Sauvageot, P., Dubner, G. 2004b, in Young Neutron Stars and Their Environments, ed. F. Camilo, & B. M. Gaensler, San Francisco, CA: ASP, p.73
10. Chevalier, R.A., Kirshner, R.P., 1978, ApJ 219, 931
11. Chackrabarty, D. & Pivovaroff, M.J., Hernquist, L.E., Heil, S.M., 2006, ApJ 643, 332
