Central Compact Objects in Supernova Remnants

George G. Pavlov, Divas Sanwal & Marcus A. Teter

Pennsylvania State University, Department of Astronomy & Astrophysics, 525 Davey Lab, University Park, PA 16802

Abstract. There are point-like sources in central regions of several supernova remnants which have not been detected outside the X-ray range. The X-ray spectra of these Central Compact Objects (CCOs) have thermal components with blackbody temperatures of 0.2–0.5 keV and characteristic sizes of 0.3–3 km. Most likely, the CCOs are neutron stars born in supernova explosions. We overview their observational properties, emphasizing the Chandra data, and compare them with magnetars.

1. Introduction

X-ray observations have shown a new population of radio-quiet compact objects, presumably isolated neutron stars (INSs), apparently different from both isolated rotation-powered pulsars and accretion-powered X-ray pulsars in close binary systems. About 10 of these objects (AXPs and SGRs), which show pulsations with periods in a 5–12 s range, large period derivatives, $\dot{P} \sim 10^{-11}–10^{-10}$, and/or strong bursts are believed to be magnetars (Thompson & Duncan 1996), i.e., INSs with superstrong magnetic fields, $B \sim 10^{14}–10^{15}$ G. The magnetars in quiescence have typical X-ray luminosities $10^{34}–10^{35}$ erg s$^{-1}$ and show two-component spectra, a thermal component with a blackbody (BB) temperature of 0.4–0.7 keV and a non-thermal component described by a power-law (PL) with a photon index around 3. At least two magnetars have associated supernova remnants (SNRs). The second class of radio-quiet INSs includes colder (apparently older) nearby objects, showing soft thermal spectra with temperatures in a 50–150 eV range and luminosities $\sim 10^{32}–10^{33}$ erg s$^{-1}$. At least some of these objects, sometimes dubbed Dim Isolated Neutron Stars, are likely ordinary rotation-powered pulsars whose radio beams are not observable from Earth. Third is a class of point-like X-ray sources found near the centers of SNRs that cannot be identified as active radio pulsars or magnetars. These Central Compact Objects (CCOs), presumably INSs, have thermal spectra with BB temperatures 0.2–0.5 keV and X-ray luminosities $L_x \sim 10^{33}–10^{34}$ erg s$^{-1}$. We define a CCO as an X-ray point source which (1) is found near the center of a SNR, (2) shows no radio/\gamma-ray counterpart, (3) shows no pulsar wind nebula (PWN), (4) has a soft thermal-like spectrum. Current observational status of CCOs is discussed below.

2. Classification and General Observational Properties

In the previous review by Pavlov et al. (2002a; P02 hereafter), five CCOs were discussed. Since then three additional CCO candidates have been suggested.
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(Seward et al. 2003; Lazendic et al. 2003; Koptsevich et al. 2003). Table 1 provides a list of the eight objects (the new ones marked with ‘n’), their associated SNRs, the age and distance to the SNR, the period, and the X-ray flux (in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$, for a range of 0.4–8 keV). We believe that two of these objects, marked with ‘x’ in Table 1, do not actually belong to the CCO class because of their distinctive properties, as discussed below.

| Object             | SNR      | Age  | d    | P   | $F_{x,-12}$ |
|--------------------|----------|------|------|-----|-------------|
| J232327.9+584843   | Cas A    | 0.32 | 3.3–3.7 | ... | 0.8         |
| J085201.4–461753   | G266.1–1.2 | 1–3 | 1–2  | ... | 1.4         |
| J161736.3–510225(x)| RCW 103  | 1–3 | 3–7  | 6.4hr | 0.9–60      |
| J082157.5–430017   | Pup A    | 1–3 | 1.6–3.3 | ... | 4.5         |
| J121000.8–522628   | G296.5+10.0 | 3–20 | 1.3–3.9 | 424ms | 2.3         |
| J185238.6+004020(n)| Kes 79   | ~9  | ~10  | ... | 0.2         |
| J171328.4–394955(n)| G347.3–0.5 | ~10 | ~6   | ... | 2.8         |
| J000256 +62465 (n,x)| G117.9+0.6[?] | ?  | ~3[?] | ... | 0.1         |

Table 1. Compact Central Objects in supernova remnants.

J1617–5102: This central object in RCW 103 was the first radio-quiet X-ray point source found in a young SNR (Tuohy & Garmire 1980). X-ray observations have shown that its flux varies up to 2 orders of magnitude (Gotthelf, Petre & Hwang 1997). First Chandra observation showed a modulation of the light curve with about 6 hr period, also found in the ASCA data (Garmire et al. 2000). In the second Chandra observation the source flux had increased by a factor of 60. The source has been monitored with Chandra ACIS, including a 50 ks observation in Continuous Clocking (CC) mode which clearly showed a 6.4 hr period and multiple dips (Sanwal et al. 2002a). The spectrum can be described by an absorbed BB, with temperatures in a 0.4–0.6 keV range, anticorrelated with the flux. The size of the emitting region varied from 0.2 to 1.6 km. The flux variability, the 6.4 hr period, and the dips in the X-ray light curve suggest that this is an accreting object in a binary system. We observed the field of RCW 103 CCO in near-IR with VLT and HST/NICMOS and found 3 counterpart candidates within the 0′′7 Chandra error circle. The faintness of these objects (e.g., H=22–23) shows that the putative secondary companion is a dwarf of a very late spectral type (later than M4). Therefore, this source is likely an unusual accreting binary, the second known binary in a SNR (after SS 443) and the first LMXB in a SNR. Since the other CCOs show no evidence of accretion, we exclude this source from the CCO list.

J0002+6245: This soft X-ray point source near the CTB 1 SNR, with a possible period of 242 ms, was discovered by Hailey & Craig (1995). The ROSAT observation showed a hint on a shell near CTB 1 which could be a new SNR, G117.9+0.6, associated with this point source. This source has been recently observed with XMM for 30 ks (Koptsevich et al. 2003). Very strong background flares left large parts of this observation unusable. The spectrum is best fit by a two-component model, a soft BB with a temperature of 0.11 keV and a hard component, either a BB with temperature of 0.5 keV or a PL with photon index of 2.6. The 242 ms period is excluded by the XMM observation, and no other
periodicity is found. No SNR around the source is seen in the XMM images. The spectral parameters and a lack of a SNR suggest that the point source is a middle-aged pulsar rather than a CCO.

| Object         | $kT$ (keV) | $R$ (km) | $L_{\text{bol,33}}$ | $\Gamma$ | $L_{\text{pl,33}}$ | $n_{H,22}$ | $F_{\text{bb}}^*/F_{\text{pl}}^*$ |
|----------------|------------|----------|---------------------|----------|-------------------|-------------|----------------------|
| J2323+5848     | 0.43       | 0.6      | 1.6                 | 4.2      | 13                | 1.8         | 1.1                   |
|                | 0.43       | 0.7      | 1.9                 | 2.5      | 0.2               | [1.2]       | 4.5                   |
| J0852–4617     | 0.40       | 0.3      | 0.3                 | unconstr | ...               | 0.4         | ...                   |
| J0821–4300     | 0.40       | 1.0      | 3.3                 | unconstr | ...               | 0.3         | ...                   |
| J1210–5226     | 0.22       | 2.0      | 1.2                 | 3.6      | 1.2               | 0.13        | 3.0                   |
| J1852+0040     | 0.50       | 1.0      | 8.0                 | unconstr | ...               | 1.5         | ...                   |
| J1713–3949     | 0.38       | 2.4      | 15                  | 3.9      | 72                | 0.8         | 0.9                   |

Table 2. Best-fit parameters for BB+PL fits to the Chandra spectra.

The spectral parameters for the remaining six CCOs, obtained from fits to Chandra ACIS spectra, are listed in Table 2 for the two-component BB+PL model, which became a standard description for INS spectra. The bolometric luminosities $L_{\text{bol}}$ for the BB components, and the luminosities $L_{\text{pl}}$ for the PL components (in the 0.4–8 keV band), are in units of $10^{33}$ erg s$^{-1}$. The hydrogen column densities are in units of $10^{22}$ cm$^{-2}$. Significant contributions to the spectra are given by thermal-like emission, with BB temperatures 0.2–0.5 keV and BB radii 0.3–2.4 km, smaller than the expected NS radii, $R_{\text{NS}} = 10–15$ km. Fits with the light-element (H or He) atmosphere models (Pavlov et al. 1995) give lower temperatures, by a factor of $\sim 2$, and larger radii, by a factor of 2–7, but still the radii remain $< R_{\text{NS}}$ for at least two CCOs (see P02). The PL component is unconstrained in at least some of the fits, which means that either the corresponding spectra are purely thermal or the PL component is too faint to be detected in these observations. Fits with the one-component PL model yield very steep slopes, $\Gamma \sim 5$ (see P02), and they are statistically unacceptable in the cases when many source counts were collected. Since the atmosphere spectra are harder than the BB spectra in the X-ray band, the PL components are, as a rule, unconstrained in the atmosphere+PL fits. Among the six CCOs, only one, J1210–5226, clearly shows spectral lines (see below) while the others are satisfactorily described by featureless continua. The J1210–5226 is also the only CCO for which a period has been detected. None of the six CCOs has shown any long-term variability.

3. Individual Sources

Here we describe the properties of the individual CCOs, with main emphasis on the new results obtained in the last two years. More details about the previous results and the references to earlier works can be found in P02.

Cas A CCO: This prototype CCO has been observed many times with Chandra since its discovery in the first-light Chandra observation (Tananbaum 1999). We have analyzed the archival Chandra observations to search for periodicity, look for long-term variability, and determine its spectral properties (Teter et al. 2003, in preparation). We searched for a period of the point source using
two 50 ks HRC observations (Dec 1999 and Oct 2000) and two 50 ks ACIS
observations (Jan 2000 and Feb 2002). No significant periods were found between
0.01 and 100 Hz. To search for long-term variability, we additionally used the
calibration observations done every 6 months (typical exposures 1–3 ks) and
found no statistically significant variations. The lack of variability during 4
years of Chandra observations suggests that it is not an accreting object (hence
not a black hole).

Spectral analysis was performed using the two 50 ks ACIS-S observations
and the 70 ks HETG/ACIS observation of May 2001. We find that the BB model
gives a better fit than the PL model, with $kT = 0.46 \pm 0.01$ keV and $R = 0.58 \pm
0.03$ km. The two-component models (BB+PL and BB+BB) provide significant
improvements over the BB fit, with the soft-BB temperature ($0.43 \pm 0.02$ and
$0.37 \pm 0.03$ keV) and radius ($0.6 \pm 0.1$ and $0.8 \pm 0.1$ km) similar to those obtained
from the single-component BB fit. The photon index of the PL
component is strongly correlated with the $n_H$ value: $\Gamma = 4.2 \pm 0.2$, $n_{H,22} = 1.8 \pm 0.1$ if $n_H$ is a
free parameter, while $\Gamma = 2.5 \pm 0.3$ for a more realistic (fixed) $n_{H,22} = 1.2$. The
hard-BB component has a temperature of $0.6 \pm 0.1$ keV and a radius of $0.2 \pm 0.1$
km, corresponding to $n_{H,22} = 1.2 \pm 0.1$. Substituting H atmosphere models for
the thermal emission gives somewhat better fits, with lower temperatures and
larger radii (e.g., $0.33 \pm 0.01$ keV and $2.2 \pm 0.2$ km for a single-component low-field
H atmosphere model), but the radii are still well below $R_{NS}$. The parameters of
the hard component in two-component fits are not very sensitive to the choice of
soft component model and are less constrained when the H atmosphere models
are used. Overall, we conclude that the mostly thermal radiation of the Cas A
CCO is emitted from a small, hot area ($R < 2$ km, $kT > 0.3$ keV), perhaps a
hot spot on the NS surface, and it is not associated with accretion.

**CCO in “Vela Junior”:** The SNR G266.1–1.2 was discovered by Aschenbach
(1998) in the south-east corner of the Vela SNR in the RASS data. An imaging
observation with Chandra allowed Pavlov et al. (2001) to detect a point source
4′ from the SNR center and measure its position. The limiting optical magnitude
B $> 22.5$ gives high enough X-ray-to-optical flux ratio to believe that this source is
a NS, possibly the remnant of the SN explosion. The spectrum of the source was
measured by Kargaltsev et al. (2002) from a 30 ks Chandra ACIS observation
in the CC mode. The PL model does not fit, while the BB model fits very
well, giving $kT \approx 0.4$ keV and $R \approx 0.3$ km, assuming a distance of 1 kpc. No
significant pulsations are found from these data. A 25 ks XMM observation
(Becker & Aschenbach 2002) gave very similar parameters for the thermal-like
radiation and a poorly constrained PL component ($\Gamma = 2.85 \pm 1.0$, $F_{pl}/F_{bb} \approx
0.15$ in the 0.5–10 keV band). Based on the observed properties, we conclude
that this source is of the same nature as the Cas A CCO.

**Pup A CCO:** J0821−4300, located about 6′ from the center of Puppis A, was
discovered with Einstein (Petre et al. 1982) and studied with ROSAT, ASCA,
Chandra and XMM. Its X-ray spectrum is very similar to those of the Cas A
and Vela Junior CCOs. The spectrum observed with Chandra fits well with
one-component thermal (BB or light-element atmosphere) models (P02), while
fitting the XMM spectrum requires an additional hard component (PL with
$\Gamma = 2.0–2.7$ or hard BB with $kT = 0.5–1.1$ keV — Becker & Aschenbach 2002).
This CCO has a larger size of the emitting region ($R \sim 1$ km and $\sim 10$ km
for the BB and magnetic H atmosphere models, respectively). Observations with Chandra HRC have shown no PWN and no significant periodicity in the 0.003–300 s range (P02).

**CCO in PKS 1209–51/52:** J1210–5226 (a.k.a. 1E 1207.4–5209) was discovered by Helfand & Becker (1984). It is located about 6′ off the center of PKS 1209–51/52 (G296.5+10), at a distance of about 2 kpc. This source has been observed with all the X-ray observatories since Einstein (see P02 for references). The low-resolution spectra obtained in the pre-Chandra era can be described by thermal continuum models; e.g., the BB fits give \( kT \approx 0.25 \) keV and \( R \approx 1.6 \) km. Fits with magnetic NS atmosphere models show a lower temperature and a size compatible with that of a NS (Zavlin et al. 1998).

Two Chandra observation of this source resulted in the discovery of a period of 424 ms (Zavlin et al. 2000) and a surprisingly small period derivative, corresponding to a characteristic pulsar age of \( \sim 500 \) kyr (vs. 3–20 kyr for the SNR) and magnetic field \( \sim 3 \times 10^{12} \) G (Pavlov et al. 2002b). Spectral fits to the Chandra data show two broad absorption lines, near 0.7 and 1.4 keV (Sanwal et al. 2002b), the first lines detected in an INS spectrum. Further observations of this source with XMM have shown that there might be additional absorption lines near 2.1 and 2.8 keV (Bignami et al. 2003). The origin of the lines is not clear at present.

We found no long-term flux variations, neither between different observations nor within long separate observations, which suggests that the X-ray radiation is not associated with accretion. On the other hand, timing analysis of the Chandra and XMM observations have allowed us to discover apparent deviations from uniform spin-down, suggesting that the CCO could be in a wide binary system, with \( P_{\text{orb}} \sim 0.2–6 \) yrs (Zavlin et al. 2003). We observed the field with VLT and HST/ACS and found a faint, red object (\( V \approx 26.4 \), \( K_s \approx 20.7 \)) in the 1′ Chandra error circle, whose spectrum suggests an M4 or M5 dwarf (Moody et al. 2003, in preparation). If this is the CCO optical counterpart, then it would be the second LMXB (but not a usual one!) in a SNR, after the central source in RCW 103.

Thus, we see that J1210–5226, the coldest (the oldest?) among the six CCOs, is the only one showing spectral lines (but none of the others was observed for so long time), the only one for which a period was detected (albeit with a puzzling time dependence), and the only one that might be in a (non-accreting) binary. Solving the riddles exhibited by this best-studied CCO may give a clue to understanding the nature of the enigmatic CCO family, unless this “outstanding CCO” is a truly unique object.

**CCO in Kes 79:** Kes 79 (G33.6+0.1) is a shell-like SNR (diameter \( \sim 11′ \)) at a distance of 10 ± 2 kpc, with an age of 6–12 kyr (Seward & Velusamy 1995). It has been observed in X-rays with Einstein, ROSAT, and ASCA. Chandra ACIS observation of Kes 79 (Seward et al. 2003) showed a point-like source at its center. Since neither PWN nor optical/radio counterparts have been detected, this source is a viable CCO candidate. The upper limit on pulsed fraction is about 30%, for periods longer than 6.4 s. The spectrum of this putative old CCO is thermal-like, its BB temperature, 0.48 keV, being even higher than that of the youngest Cas A CCO, is comparable to magnetar temperatures of similar ages.
**CCO in G347.3–0.5:** G347.3–0.5 is a radio-faint, shell-like SNR with a nonthermal X-ray spectrum, at a distance of about 6 kpc. ROSAT PSPC observations of G347.3–0.5 (Pfeffermann & Aschenbach 1996) showed a central point source, for which neither optical/radio counterpart nor X-ray pulsations have been detected (Slane et al. 1999). Results of the Chandra, XMM and RXTE observations of this source have been reported by Lazendic et al. (2003). The combined Chandra and XMM spectra of the CCO can be reasonably fit with either a single BB ($kT \approx 0.4$ keV, $R \approx 2.5$ km) or a steep PL ($\Gamma \approx 4.2$). The best fit to the CCO spectrum is given by a BB+PL model, with $kT = 0.38$ keV and $\Gamma = 3.9$, similar to other CCOs where the two-component model fits are constrained.

### 4. Evolution and H-R diagram for CCOs and Magnetars

The above-described spectral observations of CCOs make it possible to examine the age dependence of the spectral parameters. Figure 1 shows such dependences for the BB temperature and radius. Since the observed CCO spectra are similar to those of magnetars in quiescence, we added the data on a few AXPs and SGRs (from Mereghetti et al. 2002). We see from Figure 1 that CCOs,

![Figure 1. Age dependences of BB radius and BB effective temperature for CCOs (filled circles), AXPs (open diamonds) and SGRs (filled diamonds). For objects with known SNR association, estimated SNR ages are used (solid horizontal error-bars) while for four magnetars (marked with horizontal dash lines) we use spin-down ages.](image-url)
the magnetars show no temperature-age correlation. If we consider CCOs and magnetars as a single group, no significant temperature-age correlation is seen. On the other hand, the effective radii of CCOs and magnetars do show positive correlation with age (a hot spot spreads over the NS surface? a hole in a ‘screen’ gets bigger?), with magnetars being on average older than CCOs. In the luminosity-temperature diagram (an analog of Hertzsprung-Russell diagram — Fig. 2) the CCO and magnetar populations almost do not overlap (magnetars are hotter and more luminous), lying on the same ‘sequence’.

Thus, at least some CCOs appear to be relatives of AXPs and SGRs, but their relationship is not fully understood. On average, CCOs are younger, perhaps colder, and their emitting areas are smaller than those of AXPs and SGRs. Does it mean that CCOs are actually young magnetars, not mature enough to develop characteristic properties of AXPs/SGRs (e.g., they have not spun down to the 5–12 s period range, or their crusts are still too durable to crack and cause bursts)? This hypothesis could, at least, explain the lack of pulsar activity in CCOs, but it seems to be at odds with the properties of 1E 1207.4–5259, the best-studied CCO (unless it is a different kind of object).

To conclude, we now have strong reasons to believe that CCOs are not black holes, and their radiation is not powered by accretion. Very likely, they are isolated “neutron stars” (perhaps composed of more exotic particles, e.g., quarks), but at least most of them are not ordinary rotation-powered pulsars. Apparently, their thermal-like X-ray emission emerges from a part of NS surface. We can speculate that the internal heat of the NS is somehow channeled into these small areas (e.g., by superstrong localized magnetic fields) or most of the surface is covered by a thermo-isolating “blanket” or a “screen” opaque for soft X-rays. Alternatively, the hot spots could be heated by some local sources (dissipation of superstrong magnetic fields? nuclear reactions?). Future X-ray timing and spectral observations, together with deep NIR imaging, are needed to understand the true nature of CCOs.
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