Abstract In the last years, optical studies of Isolated Neutron Stars (INSs) have expanded from the more classical rotation-powered ones to other categories, like the Anomalous X-ray Pulsars (AXPs) and the Soft Gamma-ray Repeaters (SGRs), which make up the class of the magnetars, the radio-quiet INSs with X-ray thermal emission and, more recently, the enigmatic Compact Central Objects (CCOs) in supernova remnants. Apart from 10 rotation-powered pulsars, so far optical/IR counterparts have been found for 5 magnetars and for 4 INSs. In this work we present some of the latest observational results obtained from optical/IR observations of different types of INSs.

1 Introduction

Being the first discovered Isolated Neutron Stars (INSs), rotation-powered pulsars (RPPs) were also the first ones identified in the optical. Recent summaries of the RPPs optical observations can be found in Mignani et al. (2004) and Mignani (2006). After the spectacular results of the 1990s, which yielded to seven of the ten present RPP identifications thanks to the ESO NTT (Mignani et al. 2000a) and to the HST telescopes (Mignani et al. 2000b), only PSR J0437-4715 (Kargaltsev et al. 2004) has been added to the record, despite several attempts carried out after the advent of the ESO VLT (e.g. Mignani et al. 1999, 2003, 2005; Mignani & Becker 2004). The optical emission properties of RPPs depend on the age, with the young ones featuring purely magnetospheric spectra and the middle-aged ones featuring composite spectra with an additional thermal component arising from the cooling neutron star surface. For older objects the situation is less clear although there is evidence for a dominant magnetospheric emission (Mignani et al. 2002; Zharikov et al. 2004), while only the very old PSR J0437-4715 features a purely thermal emission (Kargaltsev et al. 2004). Multi-wavelength observations carried out in the last decades have unveiled the existence of other groups of INSs, most of them radio-quiet, which have been later studied in the optical/IR. ROSAT observations lead to the identification of seven nearby (≤ 300 pc) INSs dubbed “The Magnificent Seven” (S. Popov) with purely thermal X-ray emission (Haberl, this conference). Being no unanimous consensus on the acronym to use (J. Trümper, this conference) from now on I will personally refer to these objects as X-ray Thermal INSs (XTINSs). Four XTINS have optical counterparts, with the identification of three of them secured via proper motion measures. Their inferred velocities have also allowed to rule
out surface heating from ISM accretion as the source of the thermal X-ray emission in favour of heating from the cooling neutron star core. The XTINS optical emission is mostly thermal and exceeds the extrapolation of the soft X-ray spectrum by a factor $\sim 10$, which suggests that it arises from a cooler and larger area on the neutron star surface with respect to the X-ray one (e.g. Mignani et al. 2004). Other peculiar INSs discovered through their X-ray/$\gamma$-ray emission are the AXPs and the SGRs which are bealiwed to be magnetars, neutron stars with hyperstrong magnetic fields ($\sim 10^{14-15}$ G). Out of the twelve magnetars so far identified (Woods & Thompson 2004), only four have been observed in the optical/IR. Very little is known on the optical/IR spectra of the magnetars, apart from the fact that they flatten with respect to the extrapolation of the soft X-ray spectrum. This flattening can be taken as an indication of either a turnover in the magnetar spectrum or of the presence of an additional emitting source (e.g. an X-ray irradiated fallback disk). Other very enigmatic, supposedly isolated, neutron stars are the so-called CCOs in SNRs (Pavlov et al. 2004). Out of the seven CCOs known only two have proposed optical/IR counterparts, classified as low-mass K or M stars (Sanwal et al. 2002; Pavlov et al. 2004). This would suggest that CCOs are indeed binary rather than isolated neutron stars. Last entry in the INS family are the newly discovered Rapid Radio Transients or RRATs (Gaensler et al. 2006) and features a compact pulsar-wind nebula (Townsley et al. 2006). Although its large energy output makes PSR J0537$-$6910 a natural target for multi-wavelength observations, it has not yet been detected outside the X-ray band. In radio it is undetected down to $F_{1.4\text{GHz}} \sim 0.01$ mJy (Crawford et al. 2005), which implies that it is significantly fainter than both the Crab and PSR B0540-69. First exploratory optical observations (Mignani et al. 2000c; Gouiffes & Ogelman 2000; Butler et al. 2002) also failed to identify the pulsar counterpart, mainly owing to the crowdliness of the field. More recently, deeper high-resolution observations were performed by Mignani et al. (2005) with the Advanced Camera for Surveys (ACS) aboard HST and three most likely counterparts were selected within the revised CXO position on the base of their spectral flux distributions and colors.

Follow-up timing observations of the candidate counterparts have been performed with the Space Telescope Imaging Spectrometer (STIS) aboard the HST with the NUV-MAMA (Mignani at al. 2006a). The instrument was used in its spectroscopic configuration with the PRISM disperser ($1460-3270$ Å) and in TIME-TAG mode (125 $\mu$s time resolution). The target was observed for five Continuous Viewing Zone orbits, yielding a total integration time of 25 200 s. All objects of Mignani et al. (2005), with the exception of 1, 4 and 8, fall in the $52'' \times 2''$ slit - see Figure 1.

Unfortunately, two objects only are detected in the two-dimensional spectrum, of which only one (object 5) is one of the candidates. The timing analysis does not reveal evidence for pulsations at the expected period, which definitely rules out object 5. At the same time, the extinction corrected $[E(B-V) = 0.32$, Mignani et al. (2005)] near-UV flux upper limit ($Log F_\nu \sim -28.97$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) on the other candidates makes it unlikely that any of them be the pulsar counterpart, unless it has a very red spectrum. The optical counterpart of the more and more elusive PSR J0537-6910 is thus still unidentified. This implies that, as in the radio band, PSR J0537-

![Figure 1](image-url)
6910 is intrinsically fainter than the Crab pulsar and PSR B0540-69. This suggests that the optical luminosity of RPPs decreases very fast, a scenario so far based on the Vela pulsar case, which is about 10 times older than the Crab but four orders of magnitude fainter.

2.2 The optical polarization of the Vela Pulsar

Besides the radio band, optical polarimetric observations of RPPs and of their synchrotron nebulae are uniquely able to provide deep insights into the highly magnetized relativistic environment of young rotating neutron stars. Being the first and the brightest \((V \sim 16.5)\) RPP detected in the optical, polarization measures were first obtained for the Crab pulsar soon after its identification (Wanamper et al. 1969). However, despite the substantial increase in the number of optically identified RPPs, the Crab is still the only one which has both precise and repeated polarization measures (e.g. Smith et al. 1988). Recently, Wagner & Seifert (2000) performed phase-averaged polarization observations of other three young pulsars with the VLT. For the Crab “twin” PSR B0540-69 \((V \sim 22.5)\) they reported a polarization of \(\approx 5\%\) (with no quoted error bars), certainly contaminated by the contribution of the surrounding compact \((\sim 4”)\) diameter) pulsar-wind nebula (Caraveo et al. 2001a). For PSR B1509-58 the value of the optical polarization is also very uncertain as the newly proposed counterpart is hidden in the PSF wings of the Caraveo et al. (1994) original candidate \((V = 22)\). Thus, both PSF subtraction problems and the object faintness \((R = 26)\), whose existence was never independently confirmed so far, make the reported polarization measurement \((\approx 10\%\), also quoted with no error bars) tentative. A polarization measurement of \(8.5 \pm 0.8\%\) was finally reported for the Vela pulsar \((V \sim 23.6)\).

In order to add information on the polarizaton properties of Vela, e.g. the angle of maximum polarization, we have undergone a careful reanalysis of the data set used by Wagner & Seifert. The details of the observations and data reduction are described elsewhere (Mignani et al. 2006b). We obtained a polarization of \(9.4\% \pm 4\%\), qualitatively in agreement with the one of Wagner & Seifert but with a much larger error. This is justified by the fact that, owing to the faintness of the target, the uncertainty on the background subtraction dominates the photometric errors on the polarized fluxes, and ultimately on the Stokes parameters. We are thus akin to conclude that this large difference is ascribed to an error underestimation on their side, likely to be related to the neglect of the background subtraction contribution. Thus, the value of the optical polarization of the Vela pulsar, contrary to previous claims, is still uncertain. We have also computed the angle on the plane of the sky corresponding to the direction of maximum polarization. Interestingly, we found that its value \((\theta = 145^\circ \pm 14.7^\circ)\) is compatible, perspective wise, with the axis of the X-ray torus and jet observed by CXO (Pavlov et al. 2001) and with the pulsar’s proper motion vector (Caraveo et al. 2001b). Although we can not rule out a chance coincidence, it is tentative to speculate about the alignment between the polarization direction and the axis of symmetry of the X-ray structures as a tracer of the connection between the pulsar’s magnetospheric activity and its interactions with the environment. More precise measures of the pulsar maximum polarization direction, possibly supported by still to come polarization measures in X-rays, will hopefully provide a more robust observational grounds for theoretical speculations.

3 Optical/IR Observations of X-ray Thermal Isolated Neutron Stars

3.1 The proper motion of RXJ 1605.3+3249

An optical counterpart to RX J1605.3+3249 was identified by Kaplan et al. (2003) in an apparently blue object detected with HST at the CXO position. As in the case of other XTINSs, e.g. RX J1856.5-3754 (Van Kerkwijk & Kulkarni 2001) and RX J0720.4-3125 (Motch et al. 2003), the optical flux of the candidate counterpart was found in excess with respect to the Rayleigh-Jeans tail of the X-ray blackbody, adding weight to the proposed identification. This was confirmed by the measure of the object proper motion \((\mu = 144.5 \pm 13.2\ \text{mas/year}, \ \text{position} \sim 350.19^\circ \pm 5.65^\circ)\) by Motch et al. (2003). We have obtained new observations of RX J1605.3+3249 with ACS to derive a more accurate proper motion measurement (Zane et al. 2006). By comparing the target position measured in our 2005 ACS image with the 2001 STIS one of Kaplan et al. (2003) we measured a proper motion \(\mu = 155.0 \pm 3.1\ \text{mas/year} \) with position angle \(344^\circ \pm 1^\circ\) (see Figure 2). This value confirms and updates the one of Motch et al. (2005) and settle the optical identification of RX J1605.3+3249. Furthermore, it strengthens the identification of the neutron star birth place (for an age of \(10^5\)–\(10^6\) years) with the Sco OB2 association, also suspected to be the birth place of other three XTINSs. The ACS photometry (filter 606W) has been compared with the one of Motch et al. (2005) and Kaplan et al. (2003) to characterize the source optical spectrum. While Kaplan et al. (2003), on the base of two HST points, suggested a blackbody, Motch et al. (2005), on the base of the Subaru B and R points only, claimed a non-thermal spectrum \((\alpha \sim 1.5)\). However, by using all available points we can not find any statistically acceptable fit (Figure 3), not even by excluding the ACS point (Zane et al. 2006). Thus, the optical spectrum of RX J1605+3249 is virtually unconstrained. New observations taken with the same telescope and instrument set-up to provide a consistent photometry are required.
3.2 The search for the optical counterpart of RBS 1774

The X-ray source 1 RXS 214303.7+065419 (aka RBS 1774) is the last entry in the XTINS family (Zampieri et al. 2001) and one of the three which still wait for an optical identification. As a part of dedicated campaigns, we have carried out VLT observations of RBS 1774 with FORS1. Unfortunately, out of the 8 hours observing time (B and V bands) originally allocated in Service Mode, only one hour in V was actually executed. Besides, the quality of the observations was heavily affected by the very bad atmospheric conditions, with a seeing constantly above 1.5". Figure 4 shows the V band image reduced through the FORS1 pipeline, with the 3" XMM error circle of RBS 1774 (Zampieri, private communication) overlaid. Although a few objects (1-4) are detected, none of them can be considered a realistic candidate counterpart to RBS 1774. First of all, they are at least a factor 10 brighter than the optically identified XTINS. Then, after comparing our photometry with the B band one of Komarava et al. (this conference) obtained with the Subaru they all turn out to be quite red, with $B - V > 0.5$. This is confirmed by their detection in IR VLT images (see next section). No other object has been detected down to $V \sim 25.5$, which we set as the upper limit on the RBS 1774 flux.

3.3 Search for IR emission

It has been noted how the “Magnificent Seven” show intriguing similarities with the magnetars, which suggest a possible link between the two groups. Their spin periods are similar (3–12 s) and, through the observations of possible cyclotron X-ray absorption features, magnetic field of $B \sim 6 - 7 \times 10^{13}$ have been derived in three XTINSs. Although fainter than those of the magnetars, they are one order of magnitude stronger than those of the majority of radio pulsars. Also, for the two XTINSs with a measured period derivative the estimated X-ray luminosities turn out to be comparable or larger than the inferred spin-down energy. In magnetars, the X-ray luminosities indeed exceed their spin-down energy by at least 2 orders of magnitudes. Finding more similarities at other wavelengths is certainly of unvaluable help to strengthen a possible link between the “Magnificent Seven” and the magnetars. Both SGRs and AXPs are known to have peculiar IR spectra, where the optical/IR spectrum flattens
with respect to the extrapolation of the X-ray spectra (e.g. Israel et al. 2003; Israel et al. 2005). Whatever the origin of this spectral turnover, it is interesting to look for a similar behavior in the XTINSs. To this aim, the best targets are RXJ 0720.4-3125 and RXJ 1856-3754 since they are the only one with a rather accurate characterization of the optical spectrum (Motch et al. 2003; Kaplan et al. 2003). In both cases, a steep decline in the IR is expected, so that it would be easy to pinpoint a spectral flattening, if it is present.

IR observations of both RXJ 0720.4-3125 and RXJ 1856-3754, as well as for the three unidentified XTINSs RXJ 0420-5022, RXJ 0806-4122, RBS 1774 are available in the ESO archive. The observations were taken with the VLT between May 2004 and December 2005 using the ISAAC instrument with the $H$ band filter. Integration times are varying between 4000 and 6000 s, split in shorter dithered exposures to enable for sky subtraction. The data were retrieved from the ESO archive together with the closest in time associated calibrations, and reduced. For RXJ 0720.4-3125 and RXJ 1856-3754 we have used the coordinates of their optical counterparts, while for RXJ 0420-5022, RXJ 0806-4122 and RBS 1774 we have used the available $CXO$ and $XMM$ coordinates. In all cases, no object was detected at the target position, with the only exception of RBS 1774 where we identified the objects already detected in our FORS1 $V$ band image (see §3.2). We derived $H$ band upper limits of $21.9 _{-0.15} ^{+0.1}$, $22.1 _{-0.1} ^{+0.1}$, $22.4 _{-0.1} ^{+0.1}$, $21.6 _{-0.2} ^{+0.2}$ and $21.7 _{-0.2} ^{+0.2}$ for RXJ 0420-5022, RXJ 0720-3125, RXJ 0806-4122, RXJ 1856-3754 and RBS 1774, respectively. Unfortunately, these upper limits are not very compelling. For RXJ 0720-3125 and RXJ 1856-3754, a spectral flattening redward of the $R$ band would imply a $H$ band magnitude of $\geq 24$ and $\geq 23$, respectively. Similar expectation values can be assumed also for RXJ 0420-5022, RXJ 0806-4122 and RBS 1774 assuming similar optical spectra and a factor $\sim 10$ optical excess with respect to the extrapolation of their soft X-ray spectra. The derived constraints on a putative IR spectral flattening are not very compelling to constrain the presence of a fossil disk, either. By using the disk model of Perna et al. (2000) we were able only to exclude a disk extending at, or beyond, the light cylinder. Deeper IR observations to be performed with NACO at the VLT will allow us to improve these results.

4 Optical Observations of Compact Central Objects (CCOs)

4.1 1E 1207-5209 in G296.5+10.0

The CCO 1E 1207-5209 is one of the very few which pulsates in X-rays, with a period of 424 ms (Zavlin et al. 2000) and a period derivative $\dot{P} \sim 1.4 \times 10^{-14}$ (Pavlov et al. 2002; Mereghetti et al. 2002; De Luca et al. 2004). Strangely, the characteristic age ($\sim 470,000$ years) is about two orders of magnitude higher that the age ($\sim 7000$ years) of the associated SNR (Roger et al. 1988). In absolute, the most striking peculiarity of 1E 1207-5209 is the presence of three (possibly four) X-ray absorption features at regularly spaced energies. These features were interpreted in terms of electron or proton cyclotron absorption occurring in a magnetic field of $B \sim 8 \times 10^{10}$ G or $B \sim 1.6 \times 10^{12}$ G, respectively (Bignami et al. 2003; De Luca et al. 2004). These values are about two orders of magnitude lower/higher with respect to the value of the magnetic field inferred from the pulsar spin down ($B_d \sim 2 \times 10^{12}$ G). Different hypotheses to solve the age and B-field discrepancies have been proposed, including the possible influence of a fossil disk in the neutron star spin-down history. Recently, Zavlin et al. (2004) reported evidence for a non monotonous spin evolution which could imply that 1E 1207-5209 is either a strong glitcher or it is a binary. To understand the nature of the source, very deep optical observations have been performed both with the VLT and with the HST. De Luca et al. (2004) set upper limits of $R \sim 27.1$ and $V \sim 27.3$ on the optical brightness of the source. Soon after, optical HST and IR VLT observations unveiled a faint source (‘star A’, see Figure 9), apparently compatible with the CXO position. The source colors, $m_{F555W} \sim 26.8$, $m_{F814W} \sim 23.4$, $J \sim 21.7$, $H \sim 21.2$ and $K_s \sim 20.7$, identify it as a late M star (Pavlov et al. 2004), thus implying that the 1E 1207-5209 is a binary. The fact that star A was not detected in the optical images of De Luca et al. (2004) would also imply that it is variable.

In order to investigate the proposed identification, we have carefully reassessed the CXO astrometry of 1E1207-5209 and we have compared its position with the one of star A. Our best CXO coordinates are $\alpha(J2000) = 12 h 10^m 0.826^s$, $\delta(J2000) = -52^\circ 26' 28.43''$ with an associated uncertainty of 0.6''. The $HST$/ACS images of the field have been retrieved from the ESO archive after on-the-fly reduction and recalibration. Single exposures have been combined using the $multidrizzle$ task in IRAF, which also corrects for the CCD geometrical distortions. For each final image we have then recomputed the astrometry using as a reference a number of stars extracted from the GSC2 catalogue. The final error of the target position is $0.7''$, inclusive of the accuracy of our astrometry ($0.17''$). The CXO position is shown in Figure 10 overlaid on the ACS image taken with the 814W filter. The CXO error circle falls within the intersection of the MOS1 and MOS2 ones and it is significantly offset from the position of the candidate counterpart, which is right at the edge of the MOS1 error circle. We thus conclude that star A is unlikely to be the counterpart to 1E 1207-5209, although the ultimate piece of evidence should be obtained by its proper motion measurement, now in progress with the HST.
4.2 CXO J085201.4-461753 in Vela Jr

Vela Jr. (G266.1-1.2) is a very young (a few thousands years) and relatively nearby (≤1 kpc) supernova remnant discovered in the ROSAT All Sky Survey (Aschenbach 1998). The CCO in Vela Jr was first studied with ASCA and BeppoSax (Mereghetti 2001) and later with CXO which also provided its sub-arcsec position (Pavlov et al. 2001). The CXO J085201.4-461753 X-ray emission is characterized by a thermal-like spectrum, as in other CCOs, with no evidence of pulsations (Kargaltsev et al. 2002). First optical observations of CXO J085201.4-461753 were presented by Pellizzoni et al. (2002) using archived B and R observations taken with the ESO/MPG 2.2m telescope. Although no counterpart was detected down to $B = 23$ and $R = 22$, the digitized $H_\alpha$ plates taken with the UK Schmidt telescope unveiled the presence of an extended emission blob ($\sim 6''$ diameter) which was interpreted as a bow-shock nebula seen face-on. We have performed deeper observations of the Vela Jr. CCO with FORS1 at the VLT. To minimize the light pollution from an object (“star Z” of Pavlov et al. 2001) located $\sim 1.5''$ away from our target, we split the integration time in 20 exposures of 260 s each. In order to achieve the best possible spatial resolution, FORS1 was used in its High Resolution mode with a corresponding pixel size of 0.1''. A very bright star located 40'' away from the target was masked using the FORS1 occulting bars. Observations were collected with good seeing ($\sim 0.9''$) and airmass ($\sim 1.3$) conditions. A $17'' \times 17''$ zoom of the FORS1 $R$ band image of the field is shown in Figure 6 after pipeline reduction and average combination of the single exposures. While no point-like source appears at the CXO position down to $R \sim 26$, a compact optical nebula is detected. We exclude that this nebula is an artifact due to a PSF anomaly in star Z, to a defect in the image flat fielding or to any instrumental effect. Both its position and extent though are consistent with the one of the putative $H_\alpha$ nebula seen by Pellizzoni et al. (2002), which clearly indicates that they are the same object. Unfortunately, the available $B$ band upper limit is too shallow to constraint the nebula spectrum. It is thus unclear whether it is indeed a bow-shock or it is some kind structure similar to the pulsar-wind nebulae seen around RPPs. Follow-up VLT observations, carried out at the time of writing, will hopefully help to unveil both the nature of this nebula and of the CCO.

5 Infrared Observations of High Magnetic Field Pulsars

5.1 PSR J1119-6127

About 40 radio pulsars have been detected by the Parkes Pulsar Survey with magnetic fields larger than $10^{13}$ G (Camilo et al. 2000). In particular, five of them have magnetar-like magnetic fields larger than the quantum critical field $B_c = 4.33 \times 10^{13}$ G above which radio emission is expected to be suppressed, meaning that they are not expected to be radio radio pulsars at all. Despite having such high magnetic fields, these high-magnetic field radio pulsars (HBRPs) do not behave as magnetars. First
of all, they are radio pulsars, while pulsed radio emission has been discovered so far only in the transient AXP XTE J1810-197 (Camilo et al. 2006). Second, only two HBRPs, PSR J1119-6127 (Gonzalez & Safi-Harb 2003) and PSR J1718-3718 (Kaspi & McLaughlin 2005) have been detected in X-rays, with luminosities $L_X \sim 10^{32-33}$ ergs s$^{-1}$ lower than those of the magnetars. Finally, they do not show bursting emission, either in X-rays or in $\gamma$-rays, as AXPs and SGRs instead do. These differences might be explained assuming, e.g., that HBPSS are dormant transients, that their lower X-ray luminosities are a consequence of their lower magnetic fields, or simply assuming that different evolutionary paths or stages account for the different phenomenologies. Of course, one possibility is that these HBRPs are not genuine magnetars because the spin-derived magnetic field values are polluted by the torques produced by a fossil disk. The possible existence of fossil disks around INSs has been demonstrated by the recent Spitzer discovery of a disk around the AXP 4U 0142+61 (Wang et al. 2006). Thus, if HBRPs do have fossil disks, they should be detectable through deep, high-resolution, IR observations. To this aim, we have started a program of IR observations of HBRPs with the VLT. Since the IR luminosity of a disk scales with the X-ray one (Perna et al. 2000), our primary candidates are those HBRPs detected in X-rays. The field of PSR J1119-6127 was observed in Service Mode between January and February 2006 with NAos-CONica (NACO), an adaptive optics imager and spectrometer at the VLT. In order to provide the best combination between angular resolution and sensitivity, NACO was operated in its S27 mode with a corresponding field of view of $28'' \times 28''$ and a pixel scale of 0.027''. Observations were performed in the $J$, $H$, and $K_s$ bands for a total integration time of 2 hours each, dithered and split in short exposures of 55 s for sky subtraction requirements. The seeing conditions ($\sim 0.6''$) allowed for an optimal use of the adaptive optics. The data were reduced independently using the ESO NACO pipeline and procedures run under the eclipse package. The pulsar is undetected in any of the three observing passbands down to limiting magnitudes of $\sim 24$, $\sim 23$ and $\sim 22$ in the $J$, $H$ and $K_s$ passbands, respectively. We have then compared these upper limits with the disk models of Perna et al. (2000). With the due caution that the data analysis is still in progress, the results of our simulations do not presently allow to rule out the presence of a disk extending down to the magnetospheric radius. Further theoretical and simulation work will allows to better constrain wether, and how, the putative disk interact with the neutron star.

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