Optical, ultraviolet, and infrared observations of isolated neutron stars

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Abstract

Forty years passed since the optical identification of the first isolated neutron star (INS), the Crab pulsar. 25 INSs have been now identified in the optical (O), near-ultraviolet (nUV), or near-infrared (nIR), hereafter UVOIR, including rotation-powered pulsars (RPPs), magnetars, and X-ray-dim INSs (XDINSs), while deep investigations have been carried out for compact central objects (CCOs), Rotating RADio transients (RRATs), and high-magnetic field radio pulsars (HBRPs). In this review I describe the status of UVOIR observations of INSs, their emission properties, and I present the results from recent observations.

Key words: Astrophysics, neutron stars, multi-wavelength observations

1 Introduction

Interestingly enough, although isolated neutron stars (INSs) were discovered in the radio band as sources of strongly beamed radiation (Hewish et al. 1968), hence dubbed pulsars, one object of this class had been already observed for many years back in the optical band. This is the Baade’s star, a quite bright object ($V = 16.6$) located at the centre of the Crab Nebula in the Taurus constellation. It was only after the discovery of a bright radio pulsar (NP 0532) at the centre of the Crab Nebula (Comella et al. 1969) that the Baade’s star was indeed recognised to be a possible INS and certified as such by the discovery of optical pulsations at the radio period (Cocke et al. 1969). Almost a decade passed before the optical identification of another INS: the Vela pulsar (PSR B0833−45), one of the faintest objects ever detected on photographic plates ($V = 23.6$; Lasker 1976), soon after identified as an optical

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pulsar (Wallace et al. 1977). While the first optical studies of isolated neutron stars (INSs) initially focussed on radio pulsars, other classes of INSs, typically radio-silent, were progressively discovered at X-ray and γ-ray energies and became interesting targets for optical, near-ultraviolet (UV) and near-infrared (IR) observations. These are the Soft Gamma-ray Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs), the magnetar candidates (see Mereghetti 2008; 2009), the X-ray Dim INSs (XDINSs; Haberl 2007; Trümper 2009), and the central compact objects (CCOs) in SNRs (De Luca 2008). At variance with radio pulsars which are powered by the neutron star rotation (Gold 1968; Pacini 1968), and then are usually referred as rotation-powered pulsars (RPPs), these INSs radiate through different emission mechanisms like, e.g., the decay of an hyper-strong magnetic field, for the magnetars, or the cooling of the neutron star surface, for the XDINSs. At the same time, peculiar radio-loud INSs were also discovered, like the high-magnetic field radio pulsars (HBRPs; Camilo et al. 2000) and the Rotating RAdio Transients (RRATs; McLaughlin 2009). In many cases, optical or nIR counterparts have been identified both for the XDINSs and for the magnetars, while no counterpart has been found so far for the CCOs, the HBRPs, and the RRATs. Thus, despite of their intrinsic faintness which makes them very elusive targets, nUV, optical, and nIR (hereafter UVOIR) observations proved quite successful in detecting INSs outside the radio band, thanks to both the HST and to the new 8m-class telescopes, like the VLT.

Forty years after the optical identification of the Crab pulsar, UVOIR studies of INSs represent an important tile to complete an understand the multi-wavelength phenomenology of these objects (see also Mignani 2009a). This paper is organised as follows: I review the UVOIR identification status of RPPs, XDINSs, and magnetars in §2, while I describe their full observation database and their emission properties in §3 and 4, respectively. The observation status of the CCOs, the HBRPs, and the RRATs is described in §4. The importance of UVOIR observations for INS studies and future perspectives are summarised in §5.

2 UVOIR identification summary of INSs

2.1 Rotation-powered pulsars (RPPs)

Being the first class of INSs detected at UVOIR wavelengths, the major observational effort has been devoted so far to the search and to the study of RPPs which, indeed, score the largest number of INS identifications. Out of the ∼ 1800 RPPs listed in the updated ATNF radio catalogue, twelve have been identified at UVOIR wavelengths, albeit with different levels of confidence.
After the identification of the Crab and Vela pulsars, the major advances in the UVOIR studies of INSs were achieved thanks to observations performed with the ESO NTT in the late 1980s and in the 1990s (see, e.g. Mignani et al. 2000 for a review). These yielded to the identification of the optical counterparts to the first radio-silent INS, Geminga (Bignami et al. 1993), to the first extragalactic INS, PSR B0540−69 in the LMC (Caraveo et al. 1992), and to PSR B0656+14 (Caraveo et al. 1994). The refurbishment of the HST in 1993 represented a major turn-off in UVOIR studies of INSs (see, e.g. Mignani 2007), yielding to the nUV identification of PSR B0950+08, PSR B1929+10 (Pavlov et al. 1996), PSR B1055−52 (Mignani et al. 1997), and of PSR J0437−4715, the first ms-pulsar detected at UVOIR wavelengths (Kargaltsev et al. 2004). Moreover, HST observations allowed to study, for the first time, the morphology and evolution of pulsar-wind nebulae (PWNe) around the Crab pulsar (Hester et al. 1995) and PSR B0540−69 (Caraveo et al. 2000). In the 2000s, observations with the VLT (see Mignani 2009 for a recent review) yielded to the identification of the optical counterparts to PSR B1509−58 (Wagner & Seifert 2000) and, more recently, to PSR B1133+16 (Zharikov et al. 2008) and PSR J0108−1431 (Mignani et al. 2008a). A possible counterpart to PSR J0108−1431 was indeed spotted a few years before by Mignani et al. (2003), barely detected against the halo of a nearby elliptical galaxy, but it was not recognised as such until recent Chandra observations discovered X-ray emission from the pulsar (Pavlov et al. 2009) and measured its proper motion ($\mu = 200 \pm 65$ mas yr$^{-1}$) through the comparison with the radio position. This allowed Mignani et al. (2008a) to find that the position of the candidate counterpart ($U = 26.4$) nicely fitted the backward proper motion extrapolation of the pulsar and, thus, to certify its identification a posteriori. For many objects, the faintness of the optical counterpart ($V \geq 25$) initially prevented the use of the straightforward optical timing identification technique, successfully used for the brighter Crab and Vela pulsars and for PSR B0540−69 (Shearer et al. 1994). In some cases, the proper motion measurement of the candidate counterpart, successfully tested for Geminga (Bignami et al. 1993), was used instead, confirming the identification of PSR B0656+14 (Mignani et al. 2000) and of PSR B1929+10 (Mignani et al. 2002), both achieved through high-resolution HST imaging. For both Geminga and PSR B0656+14, the identification was later strengthened by the detection of nUV pulsations with the HST (Kargaltsev & Pavlov 2007). For the others, the identification evidence mainly relies on the positional coincidence with the INS coordinates (PSR B1133+16 and PSR J0108−1431), on the peculiar colours or spectrum of the candidate counterpart (PSR B0950+08), on the possible evidence of optical polarisation (PSR B1509−58).

Recently, the optical identification of PSR B1055−52 was confirmed through new HST observations (Mignani et al. 2009a). The candidate counterpart was clearly detected in the nUV with the ACS/SBC (Fig. 1-left) and in the optical with the WFPC2 (Fig. 1-right). Together with the original U-band HST/FOC photometry of Mignani et al. (1997), the new HST flux measurements allowed
to measure the object peculiar colours which virtually certify it as the actual counterpart of PSR B1055−52. Moreover, the comparison between the relative position of the counterpart, as measured in the 1996 FOC observations and in the new ACS ones, allowed to measure the proper motion of PSR B1055−52, the first ever measured for this pulsar at any wavelength. This is the fourth proper motion measurement of a RPP obtained in the optical by the HST, after those of the Crab (e.g., Kaplan et al. 2008), Vela, Geminga (Caraveo et al. 2001, 1996), PSR B0656+14, and PSR B1929+10 (Mignani et al. 2000, 2002).

2.2 X-ray Dim Isolated Neutron Stars (XDINSs)

Soon after their discovery in the 1990s, XDINSs were the next class of INSs to attract interest from the neutron star optical astronomy community. Indeed, without the evidence coming from the detection of X-ray pulsations, detected only later with XMM-Newton (e.g., Haberl et al. 2007), the measurement of an extreme X-ray-to-optical flux ratios $F_X/F_{opt}$ was, at that time, the only way to certify these sources as INSs. Although no XDINS optical counterpart was initially identified from NTT observations, despite of a considerable observational effort, they were nonetheless crucial to pave the way to deeper observations.

The first XDINS to be detected in the optical was RX J1856.5−3754 which was indeed observed by the HST (Walter & Matthews 1997). Riding the wave, HST also detected likely optical counterparts for RX J1308.6+2127 and RX
J1605.3+3249 (Kaplan et al. 2002, 2003). From the ground, optical detections were obtained for RX J0720.4−3125 with the NTT (Motch & Haberl 1998) and with the Keck (Kulkarni & van Kerkwijk 1998) and for 1RXS J214303.7+065419 with the VLT (Zane et al. 2008) and the LBT (Schwope et al. 2009). Optical counterparts have been thus identified for almost all the XDINSs, although only for RX J1856.5−3754 (Walter et al. 2001), RX J0720.4−3125 (Motch et al. 2003), and RX J1605.3+3249 (Motch et al. 2005; Zane et al. 2006) the identification has been confirmed through proper motion measurements. For both RX J1308.6+2127 and 1RXS J214303.7+065419 the optical identifications are still based on the positional coincidence with the Chandra X-ray coordinates and on the $F_X/F_{opt}$ ratio. For the two XDINSs for which optical parallaxes were measured with the HST, RX J1856.5−3754 and RX J0720.4−3125 (van Kerkwijk & Kaplan 2007), the proper motion measurement also allowed to derive their projected space velocities and, thus, to rule out accretion from the interstellar medium (ISM). Recently, a possible candidate counterpart was identified for RX J0420.0−5022. Originally, a candidate counterpart was tentatively proposed by Haberl et al. (2004), based on VLT observations (Fig. 2-left). However, a re-analyses of their VLT data (Mignani et al. 2009b) showed that their candidate was detected only at the $\sim 2\sigma$ level and it was most likely a spurious detection produced by the halo of a very bright ($B = 10$) star located 40" away. At the same time, deeper VLT observations (Mignani et al. 2009b) allowed to find evidence for the detection ($\sim 4\sigma$) of a fainter object ($B = 27.5 \pm 0.3$) coincident with the Chandra position of RX J0420.0−5022 (Fig. 2-right).
2.3 Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs)

Optical/IR observations of AXPs and SGRs, the magnetar candidates, were originally carried out (e.g., Davies & Coe 1991; van Paradijs et al. 1996) to investigate the nature of these sources and to test models based on accretion from a companion star or a debris disc. Unfortunately, optical/nUV observations of magnetars are hampered by the high interstellar extinction (up to $A_V \approx 30$) in the direction of the galactic plane, where most of them were discovered. This makes the nIR the only spectral band suitable for observations, although they are complicated by the field crowding.

Indeed, nIR identifications of magnetars were boosted when deep adaptive optics (AO) observations became possible with 8m-class telescopes like the VLT, Gemini, as well as with the CFHT, allowing to perform high-resolution imaging and to resolve potential candidate counterparts within the Chandra X-ray source error circles. It is interesting to note how all magnetar identifications were achieved with ground-based telescopes, most ly with the VLT, while the HST did not play a significant role, partially because its nIR camera (NICMOS) was unavailable between 1999 and 2002. However, unless a more accurate source position is available from radio observations like, e.g. in the case of the two transient radio AXPs XTE J1810–197 and 1E 1540.0–5408 (Camilo et al. 2007a,b) and of SGR 1806–20 (Cameron et al. 2005), the positional coincidence alone is not sufficient to pinpoint the actual counterpart. Given the source distance and the longer required time span, proper motion measurements are not a very efficient identification tool like, e.g. in the case of RPPs and XDINSs, while the search for nIR pulsations at the X-ray pe-
riod requires suitable instruments which are usually not available at most telescopes. Indeed, optical pulsations have been detected from two AXPs (see below) using guest instrument facilities. Moreover, the still significant interstellar extinction, together with the uncertainty on the source distance and the difficulty of finding a well-defined spectral template for magnetars, makes a colour-based identification uncertain. Thus, in most cases the best recipe for nIR identifications of magnetars is based on the measurement of correlated IR/X-ray variability. The application of this recipe, of course, benefited from the possibility of performing prompt Target of Opportunity (ToO) observations with ground-based telescopes in response of triggers from high-energy satellites.

Out of the five currently known SGRs, SGR 1806−20 has been the first to be firmly identified in the nIR (Israel et al. 2005; Kosugi et al. 2005). Recently, a second nIR identification has been obtained for the newly discovered SGR 0501+4516 thanks to prompt follow-up observations with the UKIRT, the WHT, and the Gemini (Rol et al. 2009) which pinpointed a $K_s \sim 19.1$ counterpart at the boresight-corrected 0.1” Chandra position (Woods et al. 2008). The same observations also showed a possible evidence for nIR variability, although not evidently correlated with that observed in the X-ray band. The counterpart was also detected in the optical (see Rol et al. 2009 et references therein). At the same time, four out of the eight known AXPs have been identified in the nIR: 4U 0142+61 (Hulleman et al. 2004), 1E 1048.1−5937 (Wang & Chakrabarty 2002; Israel et al. 2002), XTE J1810−197 (Israel et al. 2004; Rea et al. 2004), and 1E 2259+586 (Hulleman et al. 2001). In addition, both 4U 0142+61 (Hulleman et al. 2000) and 1E 1048.1−5937 (Durant & van Kerkwijk 2005) have been identified in the optical. 4U 0142+61 and 1E 2259+586 are the only AXPs/SGRs which have been detected in the mid-IR by Spitzer (Wang et al. 2006; Kaplan et al. 2009), while upper limits have been obtained for XTE J1810−197, 1RXS J170849.0−400910 (Wang et al. 2007a) and 1E 1048.1−5937 (Wang et al. 2007a; 2008). nIR counterparts were also proposed for SGR 1900+14 and for the AXP 1E 1841−045 (Testa et al. 2008), based on possible long-term nIR variability. Optical flares of a possible candidate SGR, SWIFT J195509.6+261406, were detected by Stefanscu et al. (2008) using the OPTIMA instrument at the 1.3-m telescope of the Skinakas Observatory (Crete), with the possible evidence of periodicity (6-8s) in the strongest flares. Recently, a nIR counterpart was identified for the second radio-transient AXP, 1E 1540.0−5408, through VLT observations performed in January 2009, right after the source underwent an X-ray outburst detected by the Swift/BAT (January 22; Gronwall et al. 2009). A candidate counterpart (Fig. 3-right) was identified coincident with the radio error circle of 1E 1540.0−5408 (Camilo et al. 2007b) with a magnitude $K_s = 18.5$ (Israel et al. 2009a). The candidate counterpart was not detected in Magellan observations ($K_s > 20.1$) obtained just four days before the X-ray outburst (Wang et al. 2009). The candidate counterpart was also not detected in much deeper VLT images of
the same field (Fig. 3-left) acquired in July 2007 (Mignani et al. 2009c) down to a limiting magnitude of $K_s \sim 21.7$. This implies a long-term variability of about 3 magnitudes ($K_s$ band), which virtually certifies its identification with 1E 1540.0−5408.

3 UVOIR observation database of INSs

Table 1 summarizes the current UVOIR identification status for all classes of INSs, i.e. RPPs, XDINSs, and magnetars and the complete observational data base for all the listed INSs, including multi-band photometry, low-resolution spectroscopy, polarimetry and timing.

The study of the UVOIR emission properties of RPPs is complicated by the paucity of spectral information. Only four RPPs have a complete UVOIR spectral coverage, with the nUV and nIR spectral bands crucial to disentangle the contributions of thermal and non-thermal emission processes. Moreover, only for five RPPs low-resolution spectroscopy is available: the Crab pulsar (Sollerman et al. 2000), Geminga (Martin et al. 1998), PSR B0540−69 (Ser-afimovich et al. 2004), PSR B0656+14 (Zharkov et al. 2007), and the Vela pulsar (Mignani et al. 2007a), while for the others the knowledge of the spectral energy distribution (SED) still relies on, sometimes sparse, multi-band photometry, with all the implied caveats (see, e.g. discussion in Mignani et al. 2007a). Only five RPPs pulsate in the optical/UV. In addition to the Crab and Vela pulsars, these are: PSR B0540−69 (e.g., Gouiffes et al. 1992), PSR B0656+14, and Geminga (Shearer et al. 1997;1998; Kargaltsev & Pavlov 2007). They all feature double-peaked light curves, with the only exception of PSR B0540−69. Moreover, robust optical polarisation measurements exist only for the Crab pulsar (see, e.g. Slowikowska et al. 2009 and references therein), for which a $\sim 10\%$ phase-averaged polarisation degree has been measured, reducing the impact of these important diagnostic tools.

XDINSs are only detected at optical wavelengths. Although they have been repeatedly observed in the nIR with the VLT, none of them was detected so far (Mignani et al. 2007b, 2008b; Lo Curto et al. 2007; Posselt et al. 2009). No observation of XDINSs in the nUV was reported yet. Like for the RPPs, the knowledge of the SED mainly relies on multi-band photometry, with low-resolution spectroscopy only performed for RX J1856.5−3754 (van Kerkwijk & Kulkarni 2001). No search for optical pulsations or polarisation measurements have been carried out so far.

Historically, optical/nIR observations of SGRs and AXPs were fundamental to provide crucial supporting evidence for the INS scenario and for the magnetar model. In the IR, magnetars are characterised by a flux excess with respect to the extrapolation of the X-ray spectrum (see, e.g. Israel et al. 2005). Although this has been often referred in the literature to be a distinctive character of
| Name      | Age   | mag | d(kpc) | $A_V$ | IP       | S  | P  | T |
|-----------|-------|-----|--------|-------|----------|----|----|---|
| Crab      | 3.10  | 16.6| 1.73   | 1.6   | nUV,O,nIR| Y  | Y  | Y |
| B1509−58  | 3.19  | 25.7| 4.18   | 5.2   | O        |    |    | Y |
| B0540-69  | 3.22  | 22.0| 49.4   | 0.6   | O        | Y  | Y  | Y |
| Vela      | 4.05  | 23.6| 0.23   | 0.2   | nUV,O,nIR| Y  | Y  | Y |
| Geminga   | 5.53  | 25.5| 0.07   | 0.07  | nUV,O,nIR| Y  | Y  | Y |
| B0656+14  | 5.05  | 25.0| 0.29   | 0.09  | nUV,O,nIR| Y  | Y  | Y |
| B1055−52  | 5.73  | 24.9| 0.72   | 0.22  | nUV,O    |    |    |   |
| B1929+10  | 6.49  | 25.6| 0.33   | 0.15  | nUV      |    |    |   |
| B1133+16  | 6.69  | 28   | 0.35   | 0.12  | O        |    |    |   |
| B0950+08  | 7.24  | 27.1| 0.26   | 0.03  | nUV,O    |    |    |   |
| J0108−1431| 8.3   | 26.4| 0.2    | 0.03  | O        |    |    |   |
| J0437−4715| 9.20  | 0.14| 0.11   |       |          |    |    |   |
| J1308.6+2127| 6.11 | 28.6| <1     | 0.14  | O        |    |    |   |
| J0720.4−3125| 6.27 | 26.7| 0.30   | 0.3   | nUV,O    |    |    |   |
| J214303.7+065419| 6.56 | 27.2| 0.34   | 0.18  | O        |    |    |   |
| J1856.5−3754| 6.60 | 25.7| 0.14   | 0.12  | nUV,O    | Y  |    |   |
| J1605.3+3249| 26.8| 26.8<1| 0.06  | O        |    |    |   |
| J0420.0−5022| 27.5| 27.5| 0.35   | 0.07  | O        |    |    |   |
| 1E 1547.0-5408| 3.14| 18.5| 9      | 17    | nIR      |    |    |   |
| SGR 1806−20| 3.14| 20.1| 15.1   | 29    | nIR      |    |    |   |
| 1E 1048.1−5937| 3.63| 21.3| 3.0    | 6.10  | O,nIR    | Y  | Y  |   |
| XTE J1810−197| 3.75| 20.8| 4.0    | 5.1   | nIR      |    |    |   |
| SGR 0501+451| 4.10| 19.1| 5      | 5     | O,nIR    |    |    |   |
| 4U 0142+61 | 4.84| 20.1| 1.73   | 1.62  | O,nIR,mIR| Y  |    |   |
| 1E 2259+586| 5.34| 21.7| 3.0    | 5.7   | nIR,mIR  |    |    |   |

Table 1

UVOIR identifications of INSs: RPPs (first group), XDINSs (second), and magnetars (third). Each group is sorted according to the inferred spin down age. Column 1 gives the INS name, while columns 2 to 5 give the spin down age (in logarithmic units), magnitude, distance, and interstellar extinction $A_V$. For RPPs and XDINSs, magnitudes refer to the V band, unless otherwise indicated by the superscript, while for magnetars they refer to the K$_s$ band. For the latter, only magnitudes in quiescence are listed, with the variability range typically spanning $\approx 1-2$ magnitudes. Column 6 to 8 give the broadband imaging photometry (IP) coverage in the near-ultraviolet (nUV), optical (O), and near/mid-infrared (nIR/mIR) spectral bands, and a flag (Y) for spectroscopy (S), polarisation (P), and timing (T) measurements.
magnetars, many RPPs indeed feature a similar excess (see, e.g., Mignani et al. 2007a) and it can be interpreted in terms of either a spectral break or of the onset of a new spectral component. The magnetar optical/nIR SED is not fully characterised yet. Indeed, in most cases the accessible spectral coverage is limited to the near-IR, while mid-IR observations are hampered by their lower spatial resolutions. In the optical, only the AXPs 4U 0142+61 and 1E 1048.1−5937, and now SGR 0501+4516, were detected, but only the former at wavelengths bluer than the $I$ band. In all cases, the source of spectral information still relies on multi-band photometry. This comes with an important caveat since magnetars are known to be variable in the optical/nIR and thus the available multi-band photometry observations, which are often taken at different epochs, are not directly comparable. Due to their faintness, no optical/nIR spectroscopy observations have been performed for any magnetar, so far. The only exception is 1E 1540.0−5408 for which both spectroscopy and polarimetry observations were recently performed to follow-up the identification of the nIR counterpart (Israel et al. 2009a). However, at the time of writing of this manuscript, the data analysis is still under way. Like for the RPPs, useful information come from timing and polarimetry observations. So far, pulsations at the X-ray period were detected in the optical only for the AXPs 4U 0142+61 (Kern & Martin 2002; Dhillon et al. 2005) and 1E 1048.1−5937 (Dhillon et al. 2009). No pulsation was detected in the nIR for 4U 0142+61 down to a pulsed fraction of 17% (Morii et al. 2009). Phase-averaged polarimetry observations have been performed in the $K_s$ band with the VLT only for 1E 1048.1−5937 and XTE J1810−197 (Israel et al. 2009b, in preparation).

4 Multi-band emission properties of INSs

4.1 RPP nUV, optical, and IR emission properties

The SED of the RPPs grows in complexity with the spin-down age (see Fig. 4). It evolves from a single power-law (PL) spectrum ($F_\nu \propto \nu^{-\alpha}; \alpha \sim 0$) for young RPPs (age $< 10^4$ years) to a composite one featuring both a PL ($\alpha \geq 0$) and blackbody (BB) component ($T \sim 2 - 8 \times 10^5$ K) for the middle-aged ones (age $10^5 - 10^6$ years), the former dominating in the IR, the latter in the UV. A similar composite SED was measured also for the middle-aged PSR B1055−52 (Mignani et al. 2009a). Surprisingly, older RPPs (age $> 10^6$ years) seem to feature single PL spectra. For the very old ($10^9$ years) PSR J0437−4715, the nUV spectrum is consistent with a pure BB (Kargaltsev et al. 2004). The PL component is ascribed to non-thermal radiation produced by relativistic particles accelerated in the neutron star magnetosphere (e.g., Pacini & Salvati 1983). Breaks in the PL spectrum have been observed for the Crab pulsar only, where the spectrum features a clear turn-over in the
| Log Flux [µJy] | Log ν [Hz] | Vela | PSR B0656+14 |
|--------------|----------|-----|-------------|
| -0.3         | 1.1×10⁴  | 1.1×10⁵ |
| 0            | -0.9     | 3.4×10⁵ |
| -0.6         | -0.6     | 1.1×10⁵ |
| -0.3         | -0.3     | 3.1×10⁶ |
| 0            | -0.9     | 1.7×10⁷ |

Fig. 4. Spectral flux distribution of all rotation-powered pulsars for which either medium-resolution spectroscopy or multi-band photometry is available (From Mignani et al. 2007a). From top to bottom, objects are sorted according to increasing spin-down age.

nIR (Sollerman 2003), while for the Vela pulsar (Mignani et al. 2007a) a single PL fits the entire UVOIR spectrum. The BB component is ascribed to thermal emission produced from a part of the cooling neutron star surface. In general, there is a correlation between the optical luminosity and the neutron star rotational energy loss (Zharikov et al. 2006), suggesting that the magnetospheric emission is powered by the star rotation and contributes most to the optical luminosity. As a consequence, the optical luminosity of RPPs is expected to decrease due to the neutron star spin down (see, e.g. Pacini & Salvati 1983). This "secular decrease" has been tentatively measured so far for the Crab pulsar only (Sandberg & Sollerman 2009). Optical emission efficiencies $L_{opt}/\dot{E} \approx 10^{-6} - 10^{-7}$ are derived for most RPPs, with a little dependence
It is interesting to note that the BB/PL components which fit the RPP optical spectra are not always consistent with the extrapolation of the analogue BB/PL components which fit the X-ray spectra. The presence of two PL components clearly indicates a break in the magnetospheric spectrum. No evident correlation is found between the optical PL spectral index and the neutron star age (Mignani et al. 2007a), like none is found in the X-rays (Becker et al. 2009). On the other hand, the presence of distinct optical and X-ray BB components suggests that the temperature distribution on the neutron star surface is not homogeneous. Interestingly, Kargaltsev et al. (2004) noted that the BB temperature \( T \sim 2 \times 10^5 \) K derived for PSR J0437–4715 is larger than expected from standard cooling models. This suggests that either the neutron star surface temperature was raised through the effect of re-heating processes occurring in its interior (e.g., Page 2009; Tsuruta 2009) or it was raised by accretion from its companion star during a past pulsar spin-up phase. Like for the old ms-pulsar PSR J0437–4715, re-heating might have occurred also for the 200 million year old PSR J0108–1431 (Mignani et al. 2008a). The accurate measurement of its distance (240 pc), obtained through radio parallax measurements (Deller et al. 2009), implies that the optical fluxes could be compatible with thermal emission from the bulk of the neutron star surface at a BB temperature of \( \approx 3 \times 10^5 \) K. Again, this temperature is larger than the values expected from standard cooling models.

## 4.2 XDINS optical emission properties

The XDINS optical fluxes usually exceed by a factor of \( \sim 5 \) (or more) the extrapolation of the X-ray blackbody (see, e.g. Kaplan 2008). For the XDINSs with an inferred rotational energy loss, i.e. RX J0720.4–3125, RX J1308.6+2127, RX J1856.5–3754, 1RXS J214303.7+065419 (Kaplan & van Kerkwijk 2005a,b; van Kerkwijk & Kaplan 2008; Kaplan & van Kerkwijk 2009) this turns out to be too low (\( \approx 10^{30} \) erg s\(^{-1}\)) to sustain magnetospheric emission powered by the star rotation, unless the emission efficiency is a few orders of magnitude higher than in RPPs. In at least in the best-studied cases of RX J1856.5–3754 (van Kerkwijk & Kulkarni 2001) and RX J0720.4–3125 (Motch et al. 2003), the optical spectra is found to closely follow a Rayleigh-Jeans, which suggests that the optical emission is predominantly thermal \( T \sim 2 - 4 \times 10^5 \) K. The XDINS optical emission has been thus interpreted either in terms of a non homogeneous surface temperature distribution, with the larger and cooler part emitting the optical (e.g., Pons et al. 2002), or of reprocessing of the surface radiation by a thin H atmosphere around a bare neutron star (Zane et al. 2004; Ho 2007). For RX J1605.3+3249, multi-band photometry measurements do exist (Motch et al. 2005) but they are likely affected by instrument cross-calibration problems which hamper the
SED characterisation (Zane et al. 2006). For RXJ 1308.6+2127 (Kaplan et al. 2002), 1RXS J214303.7+065419 (Zane et al. 2008; Schwope et al. 2009), and RX J0420.0−5022 (Mignani et al. 2009b) only one band measurement is available.

Interestingly, 1RXS J214303.7+065419 is characterised by an anomalously large optical excess of ≈ 35 (Zane et al. 2008). This is unlikely produced from the cooling neutron star surface unless, to explain the low observed pulsed fraction of the X-ray light curve, one invokes a peculiar alignment between the magnetic field, the rotations axis, and the line of sight (Zane et al. 2008). The 1RXS J214303.7+065419 emission may thus be of magnetospheric origin, perhaps related to its large magnetic field (∼ 10^{14} G), inferred from the observations of an absorption feature in the X-ray spectrum (Zane et al. 2005).

However, the recent measurement of the pulsar spin-down (Kaplan & van Kerckwijk 2009) implies a magnetic field of ∼ 2 × 10^{13} G, thus possibly arguing against this interpretation. A recent re-analysis of the XMM-Newton spectrum of 1RXS J214303.7+065419 using a different spectral model (Schwope et al. 2009), while confirming the large optical excess, does not rule out the possibility that the optical emission is indeed thermal. For RX J0420.0−5022, the flux of the putative counterpart corresponds to an optical excess of ∼ 7 with respect to the extrapolation of the XMM-Newton spectrum (Mignani et al. 2009b). From the upper limit on the RX J0420.0−5022 rotational energy loss, Ė < 8.8 × 10^{33} erg s^{-1} derived from X-ray timing (Haberl et al. 2007), the optical luminosity of the putative counterpart, L_B ∼ 1.2 × 10^{27} erg s^{-1} d_{350}^2 (where d_{350} is the distance in units of 350 pc; Posselt et al. 2007), implies an emission efficiency > 1.3 × 10^{-7} for rotation-powered emission. This value could still be compatible with the range of emission efficiencies derived for 10^6 − 10^7 years old RPPs (Zharikov et al. 2006). In case of thermal emission from the neutron star surface, the optical luminosity of the putative counterpart would be compatible with a blackbody with temperature ≤ 25 eV and an implausibly large emitting radius of ≥ 23 km. Thus, would the putative counterpart be confirmed, its optical luminosity, for a neutron star distance of ∼ 350 pc, might rather point towards a non-thermal origin for the optical emission.

4.3 AXP and SGR optical/IR emission properties

Due to the lack of a well-characterised SED, the origin of the optical/nIR emission of the magnetars is very much debated. While for both RPPs and XDINSs the UVOIR emission comes from the neutron star, for the magnetars it is still not clear yet whether the optical/nIR emission also comes from the neutron star. Interestingly, Mignani et al. (2007c) showed that, if powered by the neutron star rotation, the magnetar nIR efficiency L_{IR}/Ė would be at least two orders of magnitudes larger than that of RPPs. This larger nIR
output might be possibly related to the larger magnetar magnetic fields (Fig. 5) rather than to the neutron star rotation, or to reprocessing of the X-ray radiation in a fallback disc around the magnetar.

For the two magnetars with the broadest optical/nIR spectral coverage, 4U 0142+61 and 1E 1048.1−5937, the SED can be fitted by a PL (e.g., Wang et al. 2006; Durant & van Kerkwijk 2005), which would favour a magnetospheric origin of the optical/nIR emission. On the other hand, the detection of the AXP 4U 0142+61 in the mid-IR (Wang et al. 2006), where it features a clear spectral bump with respect to the PL which fits the optical/nIR fluxes, has been considered a possible evidence for the presence of a disc. A similar evidence was recently found also from mid-R observations of 1E 2259+585 (Kaplan et al. 2009). No other AXP/SGR has been detected in the mid-IR so far (Wang et al. 2007a). For 1E 1048.1−5937 (Wang et al. 2008), the deep Spitzer upper limits tend to rule out the presence of a disc, at least assuming the same size and geometry of the disc claimed around 4U 0142+61.

The comparison between the pulsed fractions and the relative phases of the optical and X-ray light curves provides an important diagnostic to discriminate between magnetospheric and disc emission. In the case of 4U 0142+61, Dhillon et al. (2005) found that the optical pulsed fraction (29% ± 8%) was ~5 times larger than the X-ray one and found no evidence for a significant optical-to-X-ray pulse lag, which would argue against the optical emission being due

![Figure 5](image-url)
to X-ray reprocessing in a disc. However, the optical and X-ray observations were not simultaneous and the variation of the X-ray pulsed fraction along the source state might have hampered the comparison. On the other hand, in the case of 1E 1048.1–5937 Dhillon et al. (2009) found, through simultaneous optical and X-ray observations, that the optical pulsed fraction (21% ± 7%) was actually a factor ~ 0.7 lower than the X-ray one but they also found a possibly significant evidence of an X-ray-to-optical pulse lag (0.06±0.02). All in all, timing observations tend to favour a magnetospheric origin of the pulsed optical emission. However, a disc origin of the magnetar optical/nIR emission is still considered a possibility (see, e.g. Ertan et al. 2007), at least to explain the unpulsed emission component. A magnetospheric origin of the nIR emission is supported by the erratic nIR-to-X-ray variability observed in XTE J1810–197 (Testa et al. 2008), which is hardly compatible with X-ray reprocessing in a disc. Possible evidence might also come from the nIR-to-X-ray decay rate of 1E 1048.1–5937 in the 2.5 month following the March 2007 outburst. VLT data (Israel et al. 2009c, in preparation) show evidence for a larger decay in the nIR with respect to the X-rays, which also argues against disc reprocessing. The upper limit of ~ 25% on the phase-averaged nIR polarisation of 1E 1048.1–5937 (Israel et al. 2009b), with respect to the ~10% measured in the optical for RPPs (see, e.g. Slowikowska et al. 2009 and references therein), does not provide compelling evidence for a non-thermal origin of the magnetar nIR emission, though.

5 Central Compact Objects (CCOs)

For the CCOs, deep optical/nIR observations have been performed for nearly all sources using the HST, the VLT, and the Gemini. For the CCO in PKS 1209–51, the originally proposed nIR identification with a low-mass M-star (Pavlov et al. 2004) was ruled out by an improved astrometry analysis (Mignani et al. 2007b; Wang et al. 2007b) and by the upper limit on the proper motion of the proposed candidate counterpart (De Luca et al. 2009). No viable candidate counterpart was found for the CCOs in Cas A (Fesen et al. 2006), Kesteven 79 (Gotthelf et al. 2005), G347.3–0.5 (Mignani et al. 2008c), Puppis A (Wang et al. 2007b; Mignani et al. 2009d). For all of them, the derived optical/nIR upper limits enable to rule out the presence of a binary companion other than a very low mass star (M5 type or later), although they do not exclude the presence of a debris disc as well, like in the case of the magnetars.

Only for the CCO in Vela Jr. a possible nIR counterpart (H ~ 21.6; K_s ~ 21.4) was identified by the VLT (Mignani et al. 2007d), whose nature is yet undetermined. The nIR emission of the candidate counterpart could be compatible with it being the neutron star itself, a low-mass M-star, or a fallback disc.
Interestingly, the Vela Jr. CCO features an optical nebulosity detected in the $R$ band with the VLT and also detected in the $H_\alpha$ line, which has been interpreted as either a bow-shock, produced by the neutron star motion in the ISM, or a photo-ionisation nebula (Mignani et al. 2007b,d). However, new HST observations (Mignani et al. 2009e) apparently contradict the latter scenario. For the CCO in RCW 103, often suspected to be in a binary system because of its transient X-ray emission and its 6 hours periodicity, a candidate counterpart was proposed (Pavlov et al. 2004) with an M-star identified close to the Chandra position. However, a systematic re-analysis of the astrometry of all the available Chandra observations of the CCO (De Luca et al. 2008) ruled out the association with the proposed counterpart. A search for correlated X-ray and nIR variability, both along the source 6 hours period and along a time base line of years, from all possible counterparts detected around the Chandra position was carried out by De Luca et al. (2008) using all the available HST and VLT data sets. However, no significant evidence of variability at any time scale was found, leaving the identification of the RCW 103 CCO an open issue. Following the magnetar recipe, ToO nIR observations following the source re-brightening in the X-ray could help to pinpoint the CCO counterpart.

6 Rotating radio transients (RRATs) and high-B radio pulsars (HBRPs)

For the RRATs, a search for bursting optical emission from J1819–1458 was carried out by Dhillon et al. (2006) but with negative results. More recently, nIR observations were performed with the VLT for all RRATs which are detected in X-rays, i.e. J1819–1458, J1317–5759, and J1913+1333. However, only for the former a candidate counterpart has been detected based on the positional coincidence with the Chandra coordinates (Rea et al. 2009), while for the others no viable candidate counterpart has been singled out so far based on colours and/or variability. Interestingly enough, the high nIR emission efficiency of J1819–1458, i.e. the RRAT with the highest inferred magnetic field ($4.9 \times 10^{13}$ G), would fit very well the magnetar characteristics (see Fig. 5), which might support the proposed identification and strengthen a possible link between the two INS classes. The only HBRP observed in the optical/nIR is PSR J1119–6127, one of the very few also detected in X-rays. In particular, nIR observations were performed with the aim of searching for a possible evidence of a fallback disc which might have exerted an extra torque on the pulsar, thus modifying its spin-down parameters and increasing the value of the inferred magnetic field. However, VLT observations failed in detecting nIR emission from the pulsar position (Mignani et al. 2007c) and could not rule out the presence of a disc with accretion rate $\dot{M} < 3 \times 10^{16}$ g s$^{-1}$, still capable of producing a substantial torque on the pulsar. Interestingly, the de-
derived upper limit on its nIR emission efficiency suggests that PSR J1119−6127 is more similar to the rotation-powered pulsars than to the magnetars.

7 Summary and Conclusions

UVOIR observations not only add a tile to complete the picture of the multi-wavelength phenomenology of different classes of INSs but they also play a major role in studying the intrinsic properties of neutron stars and in shedding light on their formation and evolution. Like it is shown in the case of RPPs and XDINSs, optical/nUV observations are important, together with the X-ray ones, to build the thermal map of the neutron star surface and to investigate the conductivity in the neutron star interior. nUV observations are especially important to study the surface thermal radiation from neutron stars much older than $10^6$ years and to determine the temperature of the bulk of the neutron star surface, which is too low to be measured in X-rays where only very small, hot polar caps are seen (e.g., Becker 2009). This is crucial to constrain the tails of neutron star cooling models and to investigate possible re-heating processes (e.g., Page 2009 and Tsuruta 2009). While timing is instrumental in securing the INS identification, the comparison of the UVOIR light curves with the radio, X-ray, and $\gamma$-ray ones is important to locate different emission regions in the neutron star magnetosphere. Moreover, the study of the giant pulses in RPPs, so far observed only in the radio and in the optical bands (Shearer et al. 2003), allows to uniquely study the relation between coherent and incoherent emission. Optical polarisation measurements represent important tests for neutron star magnetosphere models, they allow to measure the neutron star magnetic field and spin axis angles, and to unveil magneto-dynamical interactions between the neutron star and the surrounding PWNe (see Mignani et al. 2007e). IR observations proved crucial to search for fallback discs around neutron stars, to verify accretion scenarios, to test magnetars and CCO models, and to investigate the neutron star evolution in the immediate post-supernova phases. Finally, UVOIR astrometry is still the best way to measure proper motion and parallaxes of radio-silent INSs. Moreover, high-resolution UVOIR imaging allows to study the morphology and evolution of PWNe, to search for bow-shocks produced by the INS motion through the ISM and, thus, to reconstruct its spatial velocity and trace back its birth place and its parental stellar population.

As it is seen from Table 1, a total of 25 INSs have been identified so far. Although this represents a factor of 3 increase with respect to the number of identifications obtained by the end of the 1990s, it is still far from the number of INSs identified in the X-rays (e.g., Becker 2009) and from the number of INSs which are being identified in $\gamma$-rays by Fermi (Abdo et al. 2009).
Moreover, spectroscopy, polarimetry, and timing observations still represent a severe challenge for the current generation of 8m-class telescopes. This challenge can be faced with the new generation of large telescopes, like the 42m European Extremely Large Telescope (E-ELT). Observations with the E-ELT will open a new era in the UVOIR astronomy of INSs, yielding to at least a hundred of new identifications and allowing to carry out studies so far limited to a handful of objects only.

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