Part 9

Optical, X-ray and Gamma-ray Observations

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HST and VLT Observations of Pulsars and Their Environments

R. P. Mignani

ESO, Karl Schwarzschild Str. 2, D85749 Garching, Germany

A. De Luca, P. A. Caraveo

IASF, v. Bassini 15, I-20133 Milan, Italy

Abstract. The state of the art of optical studies of isolated neutron stars (INSs) and their pulsar wind nebulae (PWNe) is reviewed. In addition, results obtained from recent *HST* and VLT observations are presented and discussed.

1. Introduction

The Crab pulsar (PSR B0531+21) was the first isolated neutron star (INS) identified at optical wavelengths (Cocke, Disney & Taylor 1969). Almost a decade went by until another INS, the Vela pulsar (PSR B0833–45), was detected (Lasker 1976) and confirmed (Wallace et al. 1977). The Vela pulsar, among the faintest objects known at that time ($V \sim 23.6$), was also the last INS detected by photographic plates. A decade later came the first CCD detection of the optical counterpart of another INS, Geminga (Bignami et al. 1987). Spurred by this result and by the advent of the new generation telescopes (e.g., the ESO NTT), optical observations of INSs were carried on with revived enthusiasm and at the beginning of the 1990s yielded to the detections of the counterparts of PSR B0540–69 (Caraveo et al. 1992), readily confirmed by Shearer et al. (1994); PSR B0656+14 (Caraveo, Bignami & Mereghetti 1994a); PSR B1509–58 (Caraveo, Mereghetti & Bignami 1994b), this one later revised by Wagner & Seifert (2000). In the meantime, the identification of Geminga was confirmed through the proper motion measurement of its counterpart (Bignami, Caraveo & Mereghetti 1993). The launch of *HST* in 1990 increased the chances of detecting new INSs by providing access to the near-UV window through the short-wavelength sensitivity of the Faint Object Camera (FOC). Indeed, soon came the detections of PSRs B0950+08, B1929+10 (Pavlov, Stringfellow & Córdova 1996) and B1055–52 (Mignani, Caraveo & Bignami 1997). Likely optical counterparts were also detected for some of the INSs singled out in *ROSAT* data (a.k.a. X-ray Dim INSs, or XDINSs), namely RX J1856.5–3754 (Walter & Matthews 1997) and RX J0720.4–3125 (Kulkarni & van Kerkwijk 1998). Thus, the number of INSs observed in the optical/UV increased by a factor of four in just a decade.

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2. The Identification Status

In recent years, much effort had been concentrated on confirming most of the proposed counterparts. Of course, pursuing the identification by searching for optical pulsations at the radio/X-ray period, although ideally the best way, turned out to be extremely difficult due to the intrinsic object faintness. Furthermore, almost none of the middle-size/large ground-based telescopes offered devices for high-resolution timing and very few of them were easily adaptable to suited guest instruments. Such problems prompted observes to devise alternative identification strategies. The use of proper motion measurements of the candidate counterpart, successfully experimented in the case of Geminga (Bignami et al. 1993), proved to be a powerful tool. Indeed, proper motion yielded the confirmation of the optical counterparts of PSR B0656+14 (Mignani, De Luca & Caraveo 2000a), although a marginal detection of optical pulsations did exist (Shearer et al. 1998), of RX J1856.5–3754 (Walter 2001), of PSR B1929+10 (Mignani et al. 2002) and of RX J0720.4–3125 (Motch, Zavlin, & Haberl 2003), all but the last one achieved through high-resolution *HST* imaging. In the meantime, the Space Telescope Imaging Spectrometer (STIS) on *HST*, equipped with a UV-sensitive MAMA device, took up the pathfinder task of the dismissed FOC. In addition, with a timing resolution of 125 μs, the STIS made it possible to perform timing observations of pulsars in this spectral region. Apart from the Crab pulsar (Gull et al., these proceedings), four other pulsars have been observed to date by the STIS. While the timing of PSR B1929+10 has not provided so far conclusive results (Mignani, private communication), pulsations at the known period have been clearly detected from the Vela pulsar and from Geminga (Romani & Pavlov 2004), as well as from PSR B0656+14 (Gull et al., these proceedings). While for the Vela pulsar the STIS data have provided the first measure of its light curve in the UV, for PSR B0656+14 and Geminga detected pulsations provided further confirmation of the identifications, improving on the earlier timing results of Shearer et al. (1997, 1998). By exploiting the high positional accuracy provided by *Chandra*, likely candidate optical counterparts have been also detected by the STIS for two newly discovered XDINSs, RX J1308.6+2127 and RX J1605.3+3249 (Kaplan, Kulkani & van Kerkwijk 2002, 2003). The last entry is PSR J0437–4715, the first millisecond pulsar (MSP) detected at optical/UV wavelengths, recently detected with the STIS (Kargaltsev, Pavlov & Romani 2004). Table 1 summarizes the current (2003 October) optical/UV identification status of INSs. As is seen, owing to their intrinsic faintness, most INSs have been detected only thanks to their proximity and small interstellar absorption. Only the Crab pulsar, PSR B1509–58 and PSR B0540–69 have been detected at more than 1 kpc distance. Looking at Table 1 we see that thanks to the new telescopes and CCD technologies, the INS discovery rate increased from *one per decade* to almost *one per year*. In particular, we note how the *HST* contribution has been fundamental, providing nearly all of the INS detections obtained in the last 10 years, i.e. half of the total. As a matter of fact, so far *HST* has clearly detected all the INSs it has targeted. Instead, the VLT potentialities have been only partially exploited in the identification work, yielding so far only one detection. Finally, proper motion measurements, although requiring much longer time spans, have turned out to be as efficient as timing in securing optical identifications of INSs.

Table 1. INS identification status. The first four columns give the name, the publication year of the counterpart discovery and of its unambigous confirmation (italics = *HST*, bold = VLT) and the identification evidence, i.e., either pulsations (TIM) or proper motion (PM). Columns five to seven give the V-band magnitude where available (see Table 2), the distance in kpc, either obtained from the dispersion measure or from radio/optical parallaxes (see `http://rsd-www.nrl.navy.mil/7213/lazio/ne_model/`), and the interstellar absorption A_V, as measured directly or from the absorbing column derived from soft X-rays spectral fits.

Name	Proposed	Confirmed	Evidence	Mag.	d (kpc)	A_V
Crab	1968	1969	TIM	16.6	1.73	1.6
Vela	1976	1977	TIM	23.6	0.23	0.2
Geminga	1987	1993/1998,*2003*	PM/TIM	25.5	0.16	0.07
B0540–69	1992	1994	TIM	22	49.4	0.6
B0656+14	1994	1997,*2003*/*2000*	TIM/PM	25	0.29	0.09
B0950+08	*1996*			27.1	0.26	0.03
B1929+10	*1996*	*2002*	PM	25.6	0.33	0.15
B1055–52	*1997*			24.9	0.72	0.22
RX J1856.5-3754	*1997*	*2001*	PM	25.7	0.14	0.12
RX J0720.4–3125	1998	2003	PM	26.7		0.10
B1509–58	**2000**			25.7	4.18	5.2
RX J1308.6+2127	*2002*			28.6		0.14
RX J1605.3+3249	*2003*			26.8		0.06
J0437–4715	*2003*				0.14	0.11

3. New HST and VLT Observations of INSs: The Chase Goes On

Spurred by recent results, the search for new optical counterparts of INSs has been pursued both with the *HST* and the VLT. After the first-light investigation of PSR B1706–44 (Mignani, Caraveo & Bignami 1999), the VLT observed a number of pulsars and INS candidates, although with not much luck so far.

One of the obvious targets was the ~1.7 Myrs old, nearby (~ 200 pc) pulsar J0108–1431. Although no potential counterpart was found at the revised radio position (Mignani, Manchester & Pavlov 2003a), the derived upper limits ($V \simeq 28$, $B \simeq 28.6$, $U \simeq 26.4$) allowed us to constrain the surface temperature of the neutron star to $T < 8.8\ 10^4$ K (for $d = 200$ pc and $R = 13$ km), a value in line with the expectations of standard cooling models for such an old INS (Mignani, Manchester & Pavlov 2003). The VLT also observed for the first time some MSPs, all selected according to their spin-down luminosity ($\dot{E} \approx 10^{33}$ ergs s^{-1}), X-ray emission, close distance ($d < 500$ pc) and low interstellar absorption. No counterpart was identified for PSR J2124–3358 ($U \geq 26$, $B \geq 27.7$ and $V \geq 27.8$; Mignani & Becker 2004) and PSR J0030+0451 ($B \geq 27.3$, $V \geq 27$ and $R \geq 27$; Koptsevich et al. 2003), two MSPs very similar in both their timing and X-ray emission. For PSR J0030+0451 (Koptsevich et al. 2003), and likely also for PSR J2124–3358 (Becker & Mignani 2004), the optical flux upper limits are well below the extrapolation of the non-thermal *XMM* X-ray spectrum. In case of non-thermal optical emission, this would imply a turnover in the optical/X-

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ray spectrum. The derived neutron star surface temperatures (13-km radius) for PSR J2124–3358 (Mignani & Becker 2004) and PSR J0030+0451 (Becker et al. 2004) are $\leq 4.5 \times 10^5$ K and $\leq 9 \times 10^5$ K, which are above the value measured for PSR J0437–4715 (Kargaltsev et al. 2004). Inconclusive results were reported from shallower observations of PSRs J1024–0719 and J1744–1134 (Sutaria et al. 2003) for which no spectral X-ray data are available for comparison. The VLT also observed the 424-ms pulsar 1E 1207.4–5209 in the young ($\sim$ 7 000 years) supernova remnant (SNR) G296.5+10.0, but it failed to detect any object brighter than $R \sim 27.1$ and $V \sim 27.3$ within the $\sim$2-arcsec, boresight-corrected, *XMM* error circle, thus making this apparently young object more similar to middle-aged INSs (see also De Luca et al. 2004, and in these proceedings). The 16-ms X-ray pulsar PSR J0537–6910 has been recently observed with *HST*, taking advantage of the revised and more precise ($\leq$ 1 arcsec) *Chandra* position (Wang et al. 2001). Thanks to the spatial resolution and sensitivity of the recently installed Advanced Camera for Survey (ACS), it was possible to improve on the ground-based results of Mignani et al. (2000b) and resolve faint stellar sources in the crowded core of the SNR N157B. Multicolor imaging has pinpointed few, new, potential counterparts characterized by unusual colors (Mignani et al. 2004a) which are being investigated through timing analysis with the *HST* STIS. Finally, recent *HST* and VLT observations have contributed in clarifying the nature of the puzzling compact central object (CCO) 1E 161348–5055.1 in the young ($\sim$ 2 000 years) SNR RCW 103. Originally considered as a "good" INS candidate, its real nature has been debated after the discovery of long-term variations, a $\sim$6-hour periodicity and dips in the X-ray flux (Becker & Aschenbach 2002, and references therein). Deep IR observations with the VLT have detected a potential counterpart ($J = 22.3$, $H = 19.6$, $K = 18.5$) which has been confirmed by follow-up with the *HST*. Searches for correlated long-timescale IR/X-ray variability with *Chandra* (PI G. Garmire), as well as for a 6-hour IR periodicity, have been inconclusive so far (Sanwal et al. 2004). If the object is indeed associated with the CCO, at the source distance it could only be a low-mass star or a fossil disk. It could thus be the first case of a low-mass X-ray binary identified at the center of a SNR.

4. Optical Emission Properties of INSs

The spectral database and the derived spectral properties for the INSs in Table 1 are summarized in Table 2. As can be seen, only in six cases (the Crab, PSR B0540–69, Vela, Geminga, PSR J0437–4715 and RX J1856.5–3754) does optical/UV spectroscopy add to our knowledge of the spectrum . Indeed, it is basically thanks to the advent of the 10-m class telescopes, like Keck and the VLT, that spectroscopy of the faintest INSs became possible. For most INSs, multicolor photometry is still the only source of spectral information. Only for four INSs (the Crab, Vela, PSR B0656+14 and Geminga) does the spectral coverage span all the way from the IR to the UV. For all of them, with the exception the Crab, IR detections were provided for the first time by *HST* and the VLT . This was crucial to unveiling the presence of both thermal and non-thermal spectral components, whose contributions are expected to be markedly different in the IR and in the UV. For five INSs (PSR B1509–58, PSR B1055–

Table 2. Spectral database for the INSs in Table 1, sorted according to their spin down age τ (column two) and grouped by age decades. Column three and four give the spectral range covered by spectroscopy and by photometry (band-coded), respectively. The spectral index α and temperature, T, of the observed power law (PL) ($F_\nu \propto \nu^{-\alpha}$) and blackbody (BB) components ("—" indicates a non-detection) are listed in columns five and six, respectively. The last column lists whether the flux of the PL/BB optical (PL_o, BB_o) components is higher, lower or comparable to the optical extrapolation of the analogous X-rays components (PL_x, BB_x).

Name	log(τ/yr)	Spec. (Å)	Phot.	α	T (10^5 K)	Comments
Crab[1]	3.1	1100–9000	UV, UBVRI, JHK	−0.11	-	$PL_o < PL_x$
B1509–58[2]	3.19		R			
B0540–69[3]	3.22	2500–5500	UBVRI	+0.2	-	$PL_o < PL_x$
Vela[4]	4.05	4500–8600	UV, UBVRI, JH	+0.12	-	$PL_o \sim PL_x$
B0656+14[5]	5.05		UV, UBVRI, JHK	+0.45	8.5	$PL_o \sim PL_x$ $BB_o \sim BB_x$
Geminga[5]	5.53	3700–8000	UV, UBVRI, JH	+0.8	4.5	$PL_o < PL_x$ $BB_o \sim BB_x$
B1055–52[6]	5.73		U			
RX J0720.4–3125[7]	6.4		UV, UBVR	−1.4	4*	$BB_o > BB_x$
B1929+10[8]	6.49		UV, U	+0.5	—	$PL_o < PL_x$
B0950+08[9]	7.24		U, BVI	+0.65	—	$PL_o \sim PL_x$
J0437–4715[10]	9.2	11500-1700		—	1.0	$BB_o > BB_x$
RX J1856.5–3754[11]	?	3600–9000	UV, UBV	—	2.3	$BB_o > BB_x$
RX J1605.3+3249[12]	?		VR			
RX J1308.6+2127[13]	?		V			

* A distance of 300 pc is assumed.
[1]Sollerman et al. 2000; [2]Wagner & Seifert 2000; [3]Nasuti et al. 1997; [4]Shibanov et al. 2003; [5]Komarova et al. 2003; [6]Mignani et al. 1997; [7]Motch et al. 2003; [8]Mignani et al. 2002; [9]Zharikov et al. 2003; [10]Kargaltsev et al. 2004; [11]van Kerkwijk & Kulkarni 2001; [12]Kaplan et al. 2003; [13]Kaplan et al. 2002.

52, PSR B1929+10, RX J1605.3+3249 and RX J1308.6+2127) only one- or two-passband photometry is available, and the characterization of the optical spectrum is only tentative.

Although the spectral database is incomplete, some patterns can be recognized in Table 2. First, the spectrum grows in complexity as a function of an INS' age, passing from a single power law (PL) to a composite one featuring both PL and blackbody (BB) components. The underlying presence of a PL component is also recognizable from the correlation between the optical luminosity, L_o, and the rotational energy loss, $\dot{E}$ (see Kramer, these proceedings). Although in some cases the optical PL/BB components do match the extrapolation of the analogous components observed in the X-ray domain, no general optical/X-ray correlation can be recognized. Thus, optical and X-ray emission mechanisms are not always related to each other. The optical emission properties of INSs can be summarized as follows for the different age class identified in Table 2:
(i) Young INSs are characterized by single PL spectra, all with spectral indices $\alpha_\nu > 0$, apart from the Crab, which shows evidence for a spectral turnover in the optical/IR (Sollerman et al. 2000).
(ii) Middle-aged INSs feature composite spectra with both PL and BB components, dominating in the IR and the UV, respectively. In general they have

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spectral indices, $\alpha_\nu > 0$, which at least for PSR B0656+14 seem to be steeper than in young INSs. For both PSR B0656+14 and Geminga, the optical BB is consistent with the extrapolation of the X-ray one and is likely produced from the whole neutron star surface. For PSR B1055–52 nothing can be said except that the U-band flux is consistent with the extrapolation of the X-ray PL.
(iii) Old INSs: Both PSRs B1929+10 and B0950+08 feature single PL spectra with spectral indexes, $\alpha_\nu > 0$, and steeper than those of middle-aged INSs. An additional BB component might be present, but cannot be constrained by the present data.
(iv) MSPs: The UV spectrum of PSR J0437–4715 is a BB, with a temperature higher than that of the $> 20\times$ younger pulsar J0108–1431. For PSRs J2124–3358 and J0030+04651 (see §3), the available flux upper limits seem also to suggest a BB spectrum.
(v) XDINSs: For RX J1856.5–3754, the spectrum is a BB and is above the optical extrapolation of the X-ray one. On the other hand, the spectrum of RX J0720.4–3125 seems to be composite, with a dominant BB component (also above the optical extrapolation of the X-ray one) and a PL with $\alpha_\nu < 0$.

5. HST Observations of Pulsar Wind Nebulae

Although several PWNe have been detected in X-rays by *Chandra* (Gaensler, these proceedings), optical observations are still limited to a few cases. Apart from the Crab (e.g., Hester et al. 2002), *HST* has observed only three other young pulsars with PWNe.

The structure of the PWN around PSR B0540–69 has been resolved by *Chandra* HRC (Gotthelf & Wang 2000) into three different components: a point-like source coincident with the pulsar, an elongated toroidal structure around it, and a jet-like feature apparently protruding from the pulsar. In the optical, a PWN is clearly detected in the *HST* data of Caraveo et al. (2000) with a very similar elongated pattern and a shallow maximum southwest of the pulsar. Also the faint jet, marginally visible in the *Chandra* image, has an optical counterpart.

The Vela PWN features a brighter inner part ($\approx 2'$), with two arcs, a jet, and a counter-jet, symmetric around the pulsar's proper motion direction. The inner PWN is then embedded in extended emission (the outer PWN), surrounded by a bean-shaped diffuse nebula ($\sim 2' \times 2'$), with an elongated region of fainter emission and $100''$-long outer jets southwest and northwest of it, respectively (see also Kalgartzev et al., these proceedings). To investigate the reality of the previously claimed optical PWN (Ögelman, Koch-Miramond & Auriére 1989), Mignani et al. (2003b) have compared *Chandra* and very deep *HST* images of the field, but no optical counterparts of the known X-ray features could be identified with 3-σ (extinction corrected) upper limits of ≈ 27.9 mag arcsec^{-2} and $\approx 28.3 - 27.8$ mag arcsec^{-2} on the brightnesses of the inner and outer PWN, respectively. By using wider ESO NTT and 2.2-m images, Mignani et al. (2003b) also set upper limits of ≈ 27.1 mag arcsec^{-2} on the optical emission from the southwest extension of the X-ray nebula. While the derived upper limits for the inner/outer PWN are not far from the extrapolation of the available X-ray/radio data, the ones for the southwest extension are at least three orders of magnitudes above the expected value. For the PWN around PSR J0537–6910, no conclusive results have been obtained so far. A preliminary search for an optical PWN was performed by Wang et al. (2001) using archived *HST* observations but they were too shallow to set stringent constraints. Their results can now be improved thanks to recent, much deeper, *HST* ACS observations of the field (Mignani et al. 2004b).

6. Conclusions

Isolated neutron stars with either a secured or a likely optical counterpart amount now to 14, i.e., a number comparable to those detected in X-rays in the pre-*ROSAT* era. Thus, the optical branch, originally confined to a handful of representative cases, is growing in importance, occupying a larger and larger niche in multiwavelength studies of INSs. Certainly, much work remains to be done to reduce the gap, both in terms of quality and quantity, with the X-ray domain. More deep imaging observations are needed to pinpoint new candidates, to study correlations between the emission properties (luminosities, spectra) as a function of the pulsar parameters and to search for diffuse emission structures (PWNe and bow-shocks). More timing observations are required, both to secure faster identifications and to provide a broader characterization of the pulsars' lightcurves. Finally, more spectroscopy is critical to better define the emission processes. These are tasks both for the current 10-m class telescopes and for the next generation of extra-large telescopes (Becker & Mignani, these proceedings).

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