Neutron Star Astronomy at ESO: The VLT Decade

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In this review I summarise some of the most important results obtained in ten years of VLT observations of isolated neutron stars. More general reviews are presented in Shearer (2008) and in Mignani (2009), to which the reader is referred for a complete reference list.

Forty years have gone by since the optical identification of the Crab pulsar (PSR B0531+21), and 25 isolated neutron stars (INSs) of different types have now been identified, including the classical rotation-powered pulsars[1]. ESO observations historically played a pivotal role in the optical studies of INSs (Mignani et al., 2000). Indeed, one can go as far as saying that neutron star optical astronomy developed thanks to the seminal work carried out with ESO telescopes. The ESO contribution naturally continued with the advent of the Very Large Telescope (VLT) in 1998. At that time, in response to a Call to the Community, my collaborators and I proposed ESO optical observations of INSs as a possible test case for the Science Verification of the VLT Unit Telescope 1 (UT1). Our proposal was accepted and the first INS in the VLT record was observed with the Test Camera on 17 August 1998. Our results were promptly published (Mignani et al., 1999) in a special issue of *Astronomy & Astrophysics Letters* dedicated to the UT1 Science Verification. Remarkably, ours was historically the first *submitted* publication based on a VLT observation. Thereafter, the VLT began to make its own contribution to the optical studies of INSs, very much as its predecessor, the New Technology Telescope (NTT), had in the previous decade, marking a new era in neutron star astronomy.

VLT observations of rotation-powered pulsars

As the first class of INSs detected in the optical, and the most numerous (Lorimer, 2009), rotation-powered pulsars (simply pulsars throughout this section) were the most natural targets for the VLT. In particular, thanks to its unprecedented collecting power, the VLT has allowed the first polarimetric and spectroscopic observations of pulsars fainter than $V \sim 22$ to be carried out.

Phase-averaged polarimetry of young pulsars (< 10 000 years old) was performed in 1999, as a part of the commissioning for the first FOcal Reducer and low dispersion Spectrograph (FORS1). These observations yielded the optical identification of PSR B1509-58 from the measurement of a ~ 5 % polarisation of its counterpart. Moreover, these observations allowed the phase-averaged polarisation of the Vela pulsar to be measured, the first measurement for this object, and PSR B0540-69 in the Large Magellanic Cloud (LMC). In particular, by comparing the VLT polarimetry data with high resolution optical and X-ray observations from the Hubble Space Telescope (HST) and Chandra, respectively, it was possible to correlate the map of the synchrotron emission from the supernova remnant (SNR) with its polarisation structure. Thus, polarisation measurements provide deep insights into the highly magnetised relativistic environment around pulsars and offer a unique test bed for neutron star magnetosphere models. Interestingly, the phase-averaged polarisation of the Vela and Crab pulsars are much lower than predicted by different models. Moreover, the FORS1 observations showed, for the first time, the existence of an apparent alignment between polarisation direction in the Vela pulsar, the axis of symmetry of the X-ray arcs and jets observed by Chandra, the pulsar proper motion, and its rotation axis (Figure 1). This alignment, also observed in the Crab pulsar, suggests a connection between the pulsar's magnetospheric activity and its dynamical interaction with the synchrotron nebula.

Spectroscopy of the Vela pulsar was performed for the first time with FORS1. Spectroscopy is crucial for the characterisation of pulsar optical spectra, which, in most cases, are from multiband photometry, often compiled from the literature, and thus highly inhomogeneous. The FORS1 observations showed that the Vela optical spectrum is characterised by a featureless power-law continuum, as expected from pure synchrotron radiation (e.g., Pacini & Salvati, 1983), confirming that the optical spectra of young pulsars are dominated by magnetospheric emission. FORS1 spectroscopy was also performed for PSR B0540-69, but the background from the surround-

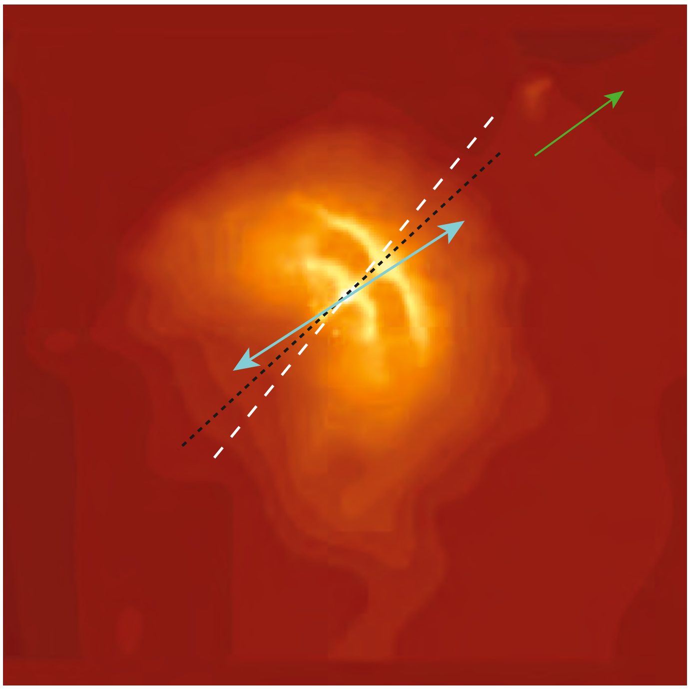

Figure 1. Chandra X-ray image of the Vela pulsar (centre) and its nebula. The white dashed and black dotted lines are the axis of symmetry of the nebula and the computed pulsar spin axis, while the green and light blue arrows are the pulsar proper motion and the polarisation direction, respectively (Mignani, 2009).

ing, compact (4 arcseconds diameter) SNR did not allow a clean measurement to be obtained. The optical spectrum is more complex for middle-aged pulsars, like the ~ 100 000 year old PSR B0656+14. Indeed, the FORS1 optical spectrum shows the signatures of two different components: a power law, ascribed to synchrotron radiation, as in younger pulsars, and a blackbody, ascribed to cooling radiation from a fraction of the neutron star surface. Similar two-component spectra are observed in soft X-ray emission, which allows the study of spectral breaks in the synchrotron emission and the mapping of regions at different temperatures on the neutron star surface, offering a unique opportunity to investigate the neutron cooling process and the structure of the neutron star interior.

On the other hand, timing observations of pulsars have rarely been performed. Although the FORS2 high time resolution (HIT) mode allows timing observations, its time resolution (2.3–600 ms) is too low to sample the light curve of fast-spinning pulsars like the Crab (33 ms) adequately, which still remains the only pulsar observed (see ESO Press Release 40/99). Indeed, in most cases, timing observations of INSs have been performed with guest instruments like ULTRACAM.

Observations with the Infrared Spectrometer And Array Camera (ISAAC) have been important in the study of pulsar emission in the near-infrared (NIR). *JHK*-band photometry of the Vela pulsar clearly showed that the IR emission is also of synchrotron origin, as in the optical, with the spectral fluxes nicely fitting the extrapolation of the FORS1 optical spectrum. This is at variance with the younger Crab pulsar, for which ISAAC multiband photometry showed evidence of a unique spectral break in its optical-to-IR synchrotron emission, possibly attributed to synchrotron self-absorption. ISAAC and NAOS–CONICA (NACO) observations allowed the IR spectrum of the mysterious emission knot ~ 0.4 arcseconds southeast of the Crab pulsar, whose connection with the pulsar is unclear, to be studied for the first time. The anti-correlation between the power-law spectra of the two objects, however, suggests that the knot is not produced by the pulsar.

One of the most interesting VLT contributions in neutron star astronomy has been in the study of the long-term evolution of their optical luminosity. According to the magnetic dipole model, the luminosity of pulsars is expected to decrease due to the neutron star spin down, an effect originally predicted by Pacini & Salvati (1983) in the optical band, but never convincingly measured so far. A first tentative measurement of this "secular decrease" was obtained with the NTT (8 ± 4 thousandths of magnitude per year). More recently, a new measurement performed with FORS1 data (2.9 ± 1.6 thousandths of magnitude per year) narrowed the magnitude of the effect by 60 %, thus imposing tighter constraints on theoretical models.

Apart from studying optically identified pulsars, the VLT competed with the HST to obtain new identifications, performing deep observations for several of them with both FORS1 and FORS2. In addition to PSR B1509-58, the VLT identified the optical counterparts of two much older pulsars: PSR B1133+16 (5 million years old) and PSR J0108-1431 (166 million years old) and confirmed the proposed identification of PSR B0950+08 (17.3 million years old) through multiband photometry. The optical counterpart to PSR B1133+16 was discovered from FORS2 observations performed in 2003, which detected a dim source (B = 28.1 mag) at the pulsar radio position. A possible counterpart (U = 26.4 mag) to PSR J0108-1431 was indeed spotted in 2001 by FORS1 observations, barely detected against the halo of a nearby elliptical galaxy (see Figure 2), but it was not recognised as such until its proper motion was measured by Chandra. These observations showed that the position of the candidate was consistent with the backward proper motion extrapolation of the pulsar and, thus confirmed its identification *a posteriori*. Optical/UV studies of old pulsars (> 100 million years) are crucial to understanding the latest stages of neutron star thermal evolution. Indeed, these old neutron stars are expected to have cooled to temperatures of ~ 10 000–100 000 K, making their surfaces too cold for thermal emission to be detectable in the X-ray band, but still hot enough to be detectable in the optical/UV. The detection of such radiation is thus the only way

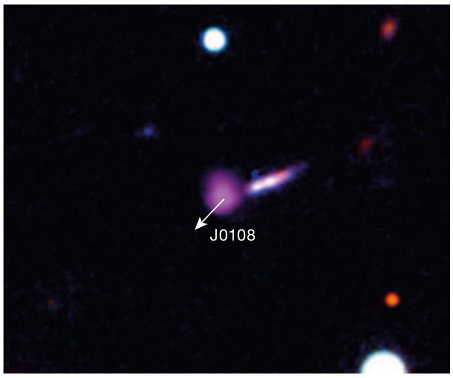

Figure 2. Composite FORS1 (red, blue and white) and Chandra (purple) image of the PSR J0108-1431 field. In the X-ray image, the pulsar is the source at the centre, in the optical it is the dim source north of the elliptical galaxy. The offset is due to the pulsar proper motion (arrow) between the FORS1 (August 2001) and Chandra (January 2007) observations (Chandra Press Release 26/02/2009).

to test the long-term predictions of cooling models and to investigate possible reheating mechanisms in the neutron star interior, which are more efficient in the optical/UV.

VLT observations of other types of INSs

Rotation-powered pulsars are only one example of the many INS types that have been observed by the VLT. Indeed, high energy observations unveiled the existence of several INS types that differ from rotation-powered pulsars in many respects. First of all, they are typically radio-silent, while the latter are radio-loud. Moreover, their multiwavelength emission is not powered by the star rotation, but by other mechanisms, not yet completely understood. VLT observations of these INSs have contributed enormously to the study of their nature and to the determination of the characteristics that distinguish them from rotation-powered pulsars.

ROSAT All Sky Survey observations in 1990 discovered seven X-ray sources, with dim (at least by the X-ray astronomy standards of the early 1990s) and purely thermal X-ray emission (blackbody temperatures kT ~ 50–100 eV) and with very high X-ray-to-optical flux ratios. These sources were associated with X-ray emitting INSs at a distance of < 500 pc, as the low X-ray absorption (hydrogen column densities N_H ~ 10^{20} cm^{-2}) suggested, and promptly nicknamed X-ray Dim INSs, or XDINSs (Haberl, 2007). The lack of magnetospheric X-ray emission and of associated SNRs suggested that the XDINSs were at least a few million years old, perhaps old enough (> 500 million years old) to be once-active radio pulsars. The origin of their thermal X-ray emission was unclear, however. Depending on the actual XDINS age, it might have originated either from a still cooling neutron star surface, or from a neutron star surface re-heated by accretion from the interstellar medium (ISM).

VLT observations were crucial in this respect. The NTT identification of the optical counterpart to the XDINS RX J0720.4-3125 (B = 26.7 mag) paved the way for the measurement of its proper motion with the VLT. This yielded the neutron star space velocity, which, for the most likely values of the distance, turned out to be too high (> 100 km/s) to be consistent with ISM accretion. A similar conclusion, inferred from the HST proper motion measurement of RX J1856.5-3754, thus made XDINSs new targets to study neutron star cooling. The measurement of X-ray pulsations (3–12 s), likely from hot polar caps, hinted at a possible non-uniform temperature distribution on the neutron star surface, with the colder and larger regions observable in the optical, as in the case of the middle-aged rotation powered-pulsars. This helped to spur on the search for the optical counterparts of XDINS, both with HST and the VLT. Recently, FORS1 and FORS2 observations identified likely counterparts to RBS 1774 and to RX J0420.0-5022. Searches for XDINS in the NIR have been performed with ISAAC and with the Multi-conjugate Adaptive optics Demonstrator (MAD), but with negative results.

FORS1 optical spectroscopy of RX J1856.5-3754 and multiband photometry of RX J0720.4-3125 showed optical spectra closely following Rayleigh–Jeans, suggesting that their optical emission is thermal and, indeed, possibly coming from a colder and larger region on the neutron star surface. This might be true also for other XDINSs, although still unconfirmed (Mignani, 2009). Since the inferred XDINS rotational energy loss is too low (~ 10^{30} erg s^{-1}), however, it is unlikely that their optical emission is powered by the star rotation as in young radio pulsars. For RBS 1774, its relatively high optical flux may be related to the huge magnetic field (~ 10^{14} Gauss), inferred from the observation of an X-ray absorption feature. Confirmation of this interpretation, might establish a link between RBS 1774 and a family of much younger INSs: the magnetars.

Magnetars (of which about 15 are known to date) represent one of the most interesting INS families. They have spin periods of 1.5–12 s, longer than those of most rotation-powered pulsars, and period derivatives of 10^{-13}–10^{-10} s s^{-1}. For a pure magneto-dipolar spin down, this yields ages of only ~ 1000–10 000 years and magnetic fields of ~ 10^{14}–10^{15} Gauss, typically a factor of 10–100 higher than those of rotation-powered pulsars. Historically, magnetars were identified in two families of high energy sources (Mereghetti, 2008): the Soft Gamma-ray Repeaters (SGRs), first discovered in 1979 through their recurrent soft gamma-ray bursts, and the Anomalous X-ray Pulsars (AXPs), discovered in the 1980s through their persistent X-ray emission. SGRs and AXPs are likely linked by their extreme magnetic fields. According to the magnetar model, the torque from these extreme fields rapidly spins down the neutron star, while the field decay explains the persistent X-ray emission, much larger than can be accounted for by neutron star rotation; crustal fractures induced by the field drifting explain the X-/gamma-ray bursts. However, other models were developed in parallel, based on accretion from low-mass companion stars or from debris discs formed by the supernova explosion, which could at least explain the persistent X-ray emission. Depending on the accretion regime, a disc extending to the neutron star magnetosphere might contribute to its spin down, which would mean that the inferred magnetic field values would be overestimated. Thus, SGRs and AXPs would not be magnetars at all but more ordinary INSs.

Optical observations have obviously been crucial in testing different models. Unfortunately, the field crowding towards the Galactic Plane, where most magnetars reside, and the high interstellar extinction (up to A_V ~ 30) have only allowed high-resolution NIR NACO observations. Since magnetars are variable at high energies, their counterparts can be pinpointed by the detection of correlated IR variability. This was only possible through prompt, i.e. within a few hours or days, Target of Opportunity observations in response to triggers from high energy satellites. In this way, IR counterparts were identified for SGR 1806-20, and possibly SGR 1900+14, and for the AXPs 1E 1048.1-5937, XTE J1810-197, 1E 1540.0-5408 (Figure 3), and possibly also for 1E 1841-045, amounting to most of the magnetars identified in the NIR. These observations ruled out the presence of both a companion star and of

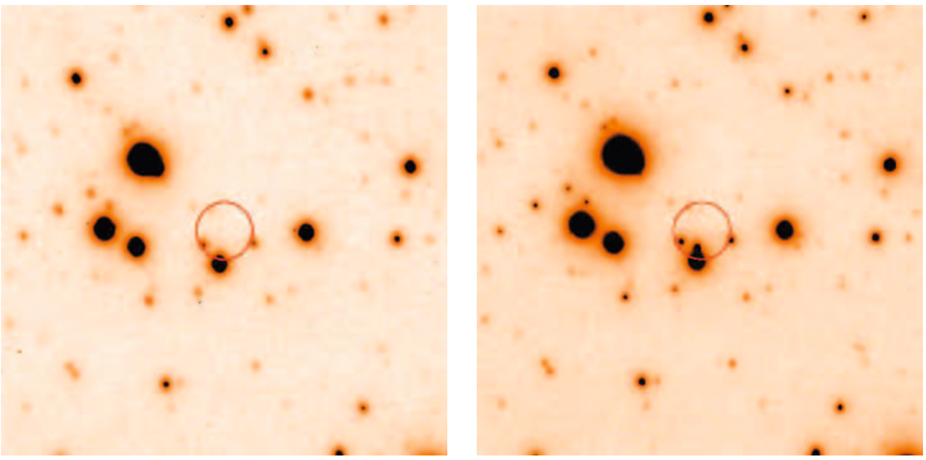

Figure 3. NACO Ks-band images (10 × 10 arcseconds) of the magnetar 1E 1540.0-5408 field taken in July 2007 (left) and in January 2009 (right). The variable object in the error circle (0.63 arcseconds) is the magnetar IR counterpart (Mignani, 2009).

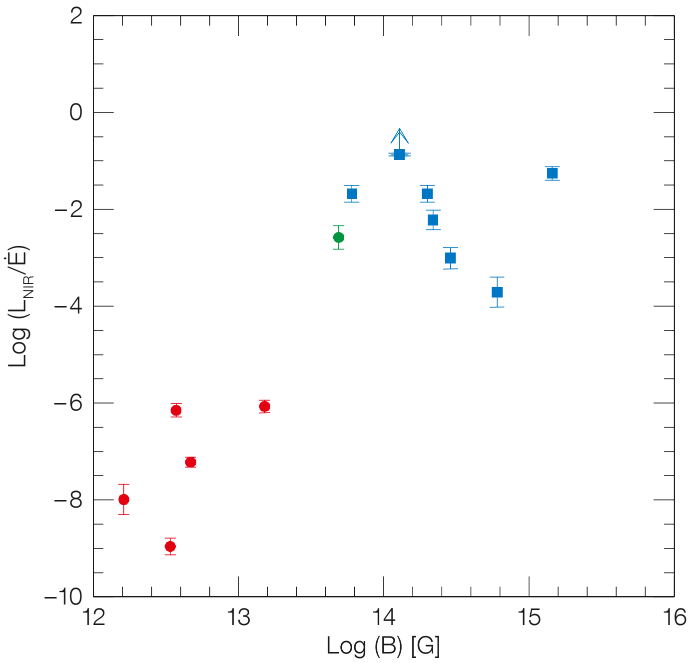

Figure 4. IR luminosity/rotational energy loss ratio (Ė) as a function of the magnetic field for rotation-powered pulsars (red), magnetars (blue), and rotating radio transients (green).

a disc extending down to the magnetospheric boundary, thus supporting the magnetar model.

The origin of magnetar NIR emission, however, is still uncertain. Interestingly, the ratio between the magnetar NIR luminosity and the rotational energy loss is a factor of > 100 larger than for radio pulsars (Mignani, 2009), suggesting that it is not powered by rotation but, rather, by their larger magnetic fields (Figure 4). Alternatively, the IR luminosity could be due to reprocessing of the X-ray radiation in a passive disc, which might have been detected in the mid-IR by Spitzer around the AXPs 4U 0142+61 and 1E 2259+585. Determining the source of the magnetar IR emission would thus represent an important test of both the magnetar and supernova models. However the NACO phase-averaged upper limit on the polarisation of the AXPs 1E 1048.1-5937 and XTE J1810-197 is inconclusive (Israel et al., in preparation). At the same time, the detection of optical pulsations from the AXP 1E 1048.1-5937, obtained with ULTRACAM at the VLT did not yield conclusive evidence either. The disc reprocessing scenario, however, is incompatible with the uncorrelated IR-to-X-ray variability of the AXP XTE J1810-197.

IR observations might also help to clarify the link between magnetars and other INS types. In particular, the detection of transient radio emission from the AXPs XTE J1810-197 and 1E 1540.0-5408 suggests that they might be related to the recently discovered class of radio-transient INSs called Rotating Radio Transients, or RRATs (McLaughlin, 2009). These sources (about 20 known to date) feature extremely bright radio bursts lasting only 2–30 ms, which tend to repeat at intervals of minutes to hours. NACO observations pinpointed a possible counterpart to the RRAT J1819-1458 (Rea et al., submitted), whose IR emission fits the magnetar characteristics very well (see Figure 4) and might strengthen a possible link between the two INS classes.

The radio-silent INSs (about ten known to date) at the centre of young (~ 2000–40 000 year old) SNRs are very much at variance with magnetars. Originally discovered by the Einstein Observatory, more of these sources were discovered by ROSAT, while Chandra made the spectacular discovery of a new source at the centre of the Cas A SNR. The nature of these sources, also known as central compact objects, or CCOs (De Luca, 2008), is puzzling. Their association with young SNRs suggests that they are young INSs, but they show no evidence of magnetospheric activity, either in the form of power-law X-ray spectra or of pulsar wind nebulae as, for example, in the Crab pulsar. X-ray pulsations have been detected (0.1–0.4 s) with period derivatives < 10^{-13} s s^{-1}, implying magnetic fields < 5×10^{11} Gauss, in just three cases for CCOs. CCOs might thus be neutron stars born spinning close to their present period and with very low magnetic fields, which might have accreted from a debris disc. Deep optical/IR observations of CCOs have been performed mainly with FORS1 and NACO, but no likely candidate counterparts have been found. NACO has identified a possible IR counterpart for the CCO in the Vela Jr. SNR, but its nature is as yet undetermined. Interestingly, the Vela Jr. CCO also features an optical nebulosity detected both in the *R*-band and at Hα which might be a possible bow-shock produced by the neutron star motion through the interstellar medium. Most puzzling of all, is the source in the RCW 103 SNR, which is very different from the other CCOs, featuring a six-hour X-ray period and spectacular long-term X-ray flux variations. It might be a magnetar, braked by a magnetic field > 10^{15} Gauss, or a very rare example of a neutron star in a binary system born in a SNR. A search for correlated periodic or long-term X-ray and IR variability, however, did not pinpoint a likely counterpart, the upper limits being consistent with both a very low-mass (later than spectral type M5) star or with a debris disc.

Prospects

VLT observations (see Table 1 for a qualitative summary) have played a major role in the study of the many INS types, the emission processes in their hypermagnetised magnetospheres and of neutron star cooling. While in the years to come the VLT will still be a leading facility in neutron star optical astronomy in its own right, it will also be a pathfinder for E-ELT observations. Following on from the VLT, the E-ELT should be able to yield about a hundred new INS identifications, reducing the current gap between optical and high energy observations (Becker, 2009; Abdo et al., 2009). Many identifications will likely come from follow-ups of observations with the new megastructure facilities, like the Square Kilometre Array (SKA) in the radio band. Moreover, the E-ELT will allow those observations that still represent a challenge for the VLT to be carried out easily for the faintest INSs, enabling more in-depth investigations to complete the seminal work of the VLT. Forty years after the identification of the Crab pulsar, the optical study of INSs is still a very active field, where ESO has marked important milestones in the last 20 years, first with the NTT (Mignani et al., 2000) and now with the VLT. The E-ELT will be able to take up this legacy, opening a third era in neutron star astronomy.

Name	Age	Mag	D (kpc)	A_V	Instruments	Modes
Crab	3.10	16.6 (*V*)	1.73	1.6	FORS1/ISAAC/NACO	IMG, HITI
B1509-58	3.19	25.7 (*R*)	4.18	5.2	FORS1	IPOL
B0540-69	3.22	22.0 (*V*)	49.4	0.6	FORS1	LSS
Vela	4.05	23.6 (*V*)	0.23	0.2	FORS1/ISAAC	IMG, IPOL, LSS
B0656+14	5.05	25.0 (*V*)	0.29	0.09	FORS1	LSS
B1133+16	8.89	28.0 (*B*)	0.35	0.12	FORS1	IMG
B0950+08	7.24	27.1 (*V*)	0.26	0.03	FORS1	IMG
J0108-1431	8.3	26.4 (*U*)	0.2	0.03	FORS1	IMG
RX J0720.4-3125	6.27	26.7 (*V*)	0.30	0.3	FORS1/FORS2/ISAAC	IMG
RBS 1774	6.57	27.2 (*B*)	0.34	0.18	FORS1/FORS2	IMG
RX J1856.5-3754	6.60	25.7 (*V*)	0.30	0.12	FORS1/ISAAC/MAD	IMG, LSS
RX J0420-5022	–	27.5 (*B*)	0.35	0.07	FORS1/FORS2/MAD	IMG
1E 1547.0-5408	3.14	18.2 (*K*)	9	17	NACO	IMG, IPOL, LSS
SGR1806-20	3.14	20.1 (*K*)	15.1	29	ISAAC/NACO	IMG
1E 1048.1-5937	3.63	21.3 (*K*)	3.0	6.10	NACO, ULTRACAM	IMG, IPOL
XTE J1810-197	3.75	20.8 (*K*)	4.0	5.1	NACO	IMG, IPOL

Table 1. VLT detections of INSs with optical counterparts (identifications in bold). INSs (blue: radio pulsars; red: XDINSs; green: magnetars) are sorted according to the logarithm of the spin-down age.

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Notes

[1] According to the magnetic dipole model (Pacini, 1968; Gold, 1968) radio pulsars are powered by the neutron star rotation. Hence, the measurement of the pulsar period and period derivative yield an indirect estimate of the neutron star age, rotational energy loss and dipolar magnetic field.

Colour image of a rim of the supernova remnant RCW 86 showing the numerous shock-ionised filaments. This is a composite of a broadband kev Chandra image (blue) and a FORS2 Hα filter image (red). More details can be found in the ESO Science Release 23/09.