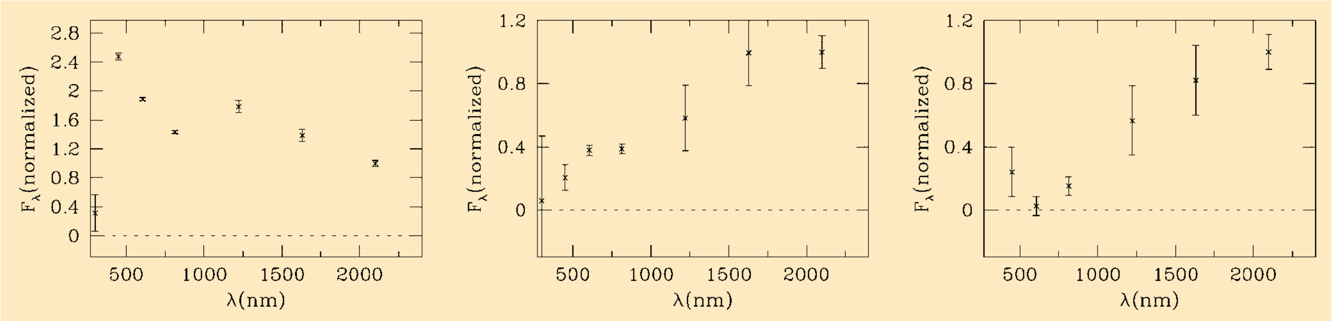

Figure 3: The normalised spectral energy distribution of 3 galaxies. From left to right we show a regular Ly-break galaxy (Fig. 2c), the "spiral" galaxy (Fig. 2d), and the very red galaxy from Figure 2e. The red continuum feature of the last two galaxies can be due to the Balmer/4000 Angstrom break or due to dust. Only one of these would be selected by the regular Ly-break selection technique, as the others are too faint in the optical (rest-frame UV).

Acknowledgement

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Optical Observations of Pulsars: the ESO Contribution

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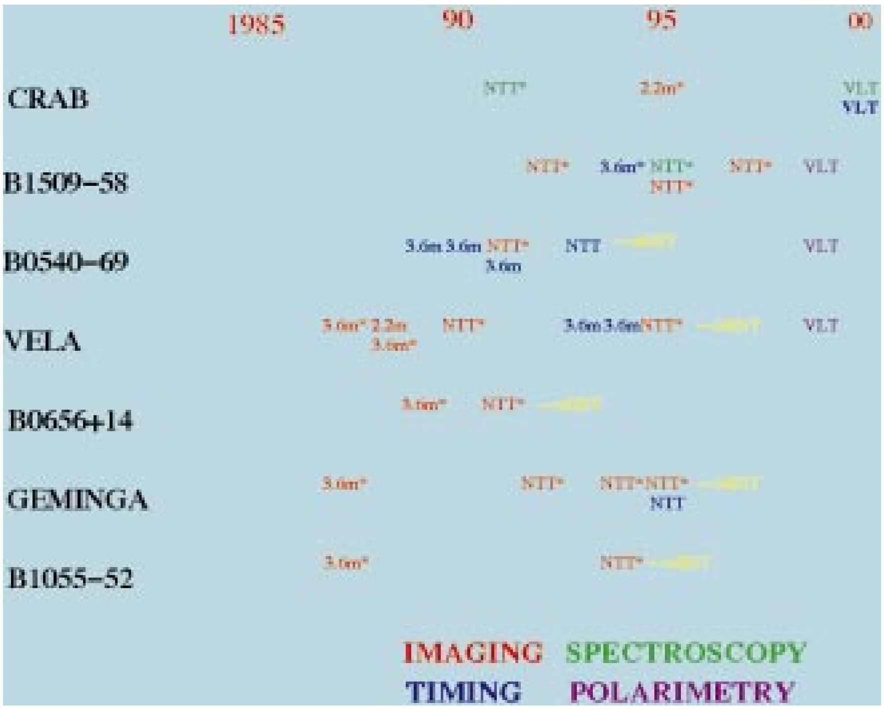
Introduction

Our knowledge of the optical emission properties of neutron stars has been remarkably improved by the results obtained during the last 15 years. At the beginning of the 80s, only two of the about 500 isolated neutron stars at that time detected as radio pulsars had been identified also at optical wavelengths. These were the two young (2000–10,000 years) optical pulsars in the Crab (Cocke et al. 1969), the first and for about 10 years the only one, and Vela (Wallace 1977) supernova remnants. Soon after the identification of the Crab, a model to explain the optical emission of young pulsars was developed by Pacini (1971) in terms of synchrotron radiation emitted by charged particles injected in the pulsar's magnetosphere. According to this model, the optical luminosity of a pulsar is predicted to scale proportionally to B^4P^{-10}, where B and P are its magnetic field at the light cylinder and its period, respectively. This relation, known as the "Pacini's Law", proved correct for both the Crab and the Vela pulsars and was thereon assumed as a reference.

The panorama of neutron stars' optical astronomy changed rapidly when few more pulsars started to be identified (or discovered) in the X-ray data of the EINSTEIN satellite (see Seward and Wang 1988 for a review) and a possible X-ray counterpart for the enigmatic gamma-rays source Geminga, not yet recognised as an X/gamma-ray pulsar, was proposed. This triggered the search for their optical counterparts, and ESO telescopes gave to the European astronomers the chance to boost a virtually new field of investigation (see Table 1 for a summary of the



	1985	90	95	00
CRAB		NTT*	2.2m*	VLT VLT
B1509−58		NTT*	3.6m* NTT* NTT* NTT*	VLT
B0540−69		3.6m 3.6m NTT* 3.6m	NTT →	VLT
VELA	3.6m* 2.2m 3.6m*	NTT*	3.6m 3.6m NTT* →	VLT
B0656+14		3.6m* NTT* →		
GEMINGA	3.6m*	NTT*	NTT* NTT* → NTT	
B1055−52	3.0m*		NTT* →	

IMAGING SPECTROSCOPY
TIMING POLARIMETRY

Table 1: Summary of (published) ESO observations of the pulsars with an optical counterpart. For each pulsar the observing epochs and the telescopes are listed. Observations performed by the authors are marked by an asterisk. The observing modes are specified by the colour code. Arrows indicate HST follow-ups. The results are summarised in Table 2 and described in the text.

IDENTIFIED FROM ESO 🟥

MEASUREMENTS FIRST OBTAINED FROM ESO 🟦

Pulsar	*Age*	*Id.*	*PM*	*Tim*	*Spec*	*Pol*	*I*	*R*	*V*	*B*	*U*
Crab	3.10	Tim	Y	P	**Y**	Y	15.63	16.21	16.65	17.16	16.69
B1509-58	3.19	**Pos**		**UP**	**-**	**u.l.**	**19.8**	**20.8**	**22.1**	**23.8**	
		Pol				**Y**		**25.7**			
B0540-69	3.22	**Pos,Tim**		P	Y	**Y**	21.5	21.8	22.5	22.7	22.05
Vela	4.05	Tim	**Y**	P		**Y**		**23.9**	23.6	23.9	23.8
B0656+14	5.05	**Pos**,Tim	**Y**	P			23.8	24.5	**25**	24.8	24.1
Geminga	5.53	**PM,Tim**	**Y**	**P**	Y		**<26.4**	25.5	**25.5**	**25.7**	24.9
B1055-52	5.73	Pos									24.9
B1929+10	6.49	Pos								>26.2	25.7
B0950+08	7.24	Pos									27.1

Table 2: Summary of the existing optical database for all the pulsars identified so far. The objects (first column) are sorted according to their spin-down age in years (second column, in logarithmic units). For PSR B1509-58 both the original and the most recent candidate counterparts are reported. The row colour identifies (in increasing intensity) young, middle-aged and old pulsars. The 3rd column gives the identification evidence either from positional coincidence (Pos), timing (Tim), proper motion (PM) or polarimetry (Pol). Proper-motion measurement, timing – either resulting in the detection (P) or non-detection (UP) – of optical pulsations, spectroscopy and polarimetry observations are flagged in columns 4–7. Null results (–) and upper limits (u.l.) are also noted. The remaining columns list the available (time integrated) UBVRI photometry.

published ESO observations). Also taking advantage of the improved performances of the NTT and its new detectors, more optical identifications of X-ray pulsars were achieved in few years, some brand new, some the confirmation of previous detections obtained with the 3.6-m. In particular, middle-aged (≥ 100,000 years) pulsars were observed for the first time. This opened the way to the study of their optical emission properties, which turned out to be very different from the ones of young Crab-like pulsars, thus changing a well-established scenario. In parallel, fast photometry observations were pursued at the 3.6-m, also experimenting the new technology of the MAMA detectors, to monitor the light-curve evolution of the known optical pulsars and to search for new ones (a case for all: the long quest for a pulsar in SN 1987A). Last, but not least, precise proper-motion measurements of pulsars, so far obtained only in the radio band, were started at ESO using classical optical astrometry techniques, yielding results of comparable (or even higher) accuracy.

Thereafter, the stage was taken by the HST, which, exploiting its higher sensitivity in B/UV, obtained three new likely identifications and complemented the explorative work done with ESO telescopes for the pulsars already identified. Indeed, one can go as far as saying that almost all the HST time so far allocated for the study of isolated neutron stars has been a follow-up of ESO programmes (see Table 1).

Observations Review

The total number of pulsars with an optical counterpart, either secured or tentative, amounts now to nine. The available optical database (consisting of timing, spectroscopy, polarimetry and photometry) is summarised in Table 2, where the objects have been sorted according to their spin-down age (P/[2dP/dt]). From the table, it can be immediately appreciated how the observations with the ESO telescopes played an important role in the optical studies of pulsars, claiming a number of absolute firsts. For each pulsar, the major results achieved so far by ESO observations are discussed in the following sections.

The Crab Pulsar

The bright pulsar (33 ms) in the Crab Nebula (PSR B0531+21) was the first one to be identified in the optical (Cocke et al. 1969). Although the Crab is relatively bright (V = 16.6), the first good spectrum was taken only 20 years after the pulsar discovery with EMMI at the NTT (Nasuti et al. 1996a,b). The pulsar spectrum appears flat (see Fig. 1 of Nasuti et al. 1996a), as expected from a synchrotron origin of the optical radiation, apart from an unidentified broad absorption feature observed around 5900 Å, which could be originated in the pulsar magnetosphere. Photometry of the Crab pulsar, performed at different epochs from ESO, was used to critically investigate the reality of the so-called secular decrease of the pulsar's optical luminosity. This effect, predicted by the Pacini's Law as a consequence of the pulsar's spin-down, was never convincingly measured. By comparing the V flux measurements of the Crab taken over 15 years, a decrease of 0.008 ± 0.004 mag/yr was indeed found (Nasuti et al. 1996a,b), consistent with the theoretical prediction (0.005 mag/yr), but still too uncertain to prove the reality of the effect.

PSR B1509-58

With a spin-down age close to 1500 years, the pulsar PSR B1509-58 is the youngest after the Crab. Its period (P = 150 ms) is relatively long with respect to the Crab one, but it spins down much faster than almost any other pulsar (Kaspi et al. 2000). A candidate counterpart to PSR B1509-58 (V = 22.1) was first detected by the NTT (Caraveo et al. 1994b), with a corresponding optical luminosity much higher than the one expected from the Pacini's Law. The proposed identification was investigated in the following years through multicolour imaging, spectroscopy and timing performed at the NTT (EMMI and SUSI1/2) and at the 3.6-m, which, however, lead to inconclusive results (see Mignani et al. 1998a for a summary). In particular, the non-detection of optical pulsations raised doubts on the proposed identification. Recently, the pulsar field was observed in polarimetry mode with the FORS1 instrument at the VLT/UT1. Exploiting excellent seeing conditions (0.46″), the proposed counterpart of Caraveo et al. (1994b) was resolved in a triplet of objects. Of these, only one (R = 25.7) showed evidence of a significant polarisation (Wagner and Seifert 2000), as expected from pure magnetospheric optical emission from a young pulsar. Although its luminosity would still exceed the predicted one, the polarisation signature makes this new candidate a viable counterpart to PSR B1509-58.

PSR B0540-69

The fourth youngest pulsar (50 ms) known so far (~ 1,700 years) is PSR B0540-69 in the Large Magellanic Cloud. With the discovery of optical pulsations (Middleditch & Pennypacker

1985), it became the third optical pulsar after the Crab and Vela ones. When beaming effects were taken into account (Pacini and Salvati 1987), the optical luminosity of PSR B0540-69 was found to be consistent with the predictions of the Pacini's Law. The pulsar was monitored between 1989 and 1991 through fast-photometry observations performed at the ESO/3.6-m (Gouiffes et al. 1992). These observations allowed to measure very accurately the pulsar's timing parameters (dP/dt and d^2P/dt^2), to be used as input to derive the value of its *braking index*, i.e. a quantity of paramount importance for neutron star models (see e.g. Shapiro & Teukolsky 1983). Since the discovery of the weak radio emission from PSR B0540-69 is quite recent, optical (as well as X-ray) observations were the only way to perform a very accurate pulsar timing.

Although optical pulsations had been detected from the direction of PSR B0540-69 soon after the X-ray discovery, its counterpart remained unidentified due to the lack of a very precise positioning. The first deep search was carried on in January 1992 with SUSI at the NTT (Caraveo et al. 1992). The clue for identifying the optical counterpart of the pulsar came from an Hα image of the host supernova remnant (SNR 0540-69), which unveiled a strange spiral-like structure, somehow recalling a sort of jet-like emission activity. A point-like source (V = 22.5) was indeed observed coincident with the centre of the "spiral". The identification proposed by Caraveo et al. (1992) was later confirmed by time-resolved imaging of the field performed at the NTT with the guest TRIFFID camera equipped with a MAMA detector (Shearer et al. 1994), which allowed to determine the position of the optical pulsar. Recently, a new piece of information was added by the first measurement of the pulsar's optical polarisation, obtained by Wagner & Seifert (2000) using FORS1 at the VLT/UT1.

The Vela Pulsar

The Vela pulsar (PSR B0833-45) is the older (11,000 years) of the "young pulsar" group. Together with the Crab, it is the only one originally detected on a photographic plate (Lasker 1976). Its optical pulsations (89 ms) were extensively studied by Gouiffes (1998) through fast-photometry observations carried out at the 3.6-m thus yielding the most accurate characterisation of the pulsar's light curve.

Multi-epoch imaging with the NTT and the 3.6-m was fundamental to assess the actual value of the Vela pulsar proper motion, measured several times in radio with different instruments and techniques but with conflicting results. Indeed, optical astrometry is not affected by pulsar's timing irregularities, very frequent in the case of Vela, which hamper significantly radio proper-motion measurements. After an upper limit first obtained by Bignami & Caraveo (1988) with the 3.6-m, the measurement of the proper motion was carried out by Ogelman et al. (1989) at the 2.2-m. A few years later, the proper motion was revisited with the aid of new NTT observations by Nasuti et al. (1997a,b), who computed the angular displacement of the pulsar during 20 years and obtained a value of 52 ± 5 mas/yr, recently confirmed by DeLuca et al. (2000) using the HST.

Amongst the most recent results, imaging observations of the Vela pulsar, performed with EMMI at the NTT, allowed to improve its multicolour photometry and to add the first detection in R (Nasuti et al. 1997a). As expected from this young pulsar, the UBVR flux values are clearly indicative that the optical emission is of magnetospheric origin. This conclusion is supported by the first measurement of a significant optical polarisation from the pulsar (Wagner & Seifert 2000), obtained using FORS1 at the VLT/UT1. However, as remarked by Nasuti et al. (1997a), the broad-band spectral behaviour of Vela is significantly different from the one observed in the other young optical pulsars Crab and PSR B0540-59. While in all cases the UBV colours appear to follow the same flattish spectral distribution, the relatively lower R flux of Vela represents a clear spectral turnover in the red region of the spectrum. The origin of this turnover is unclear. We note that a similar trend was observed for the Crab in the NIR region and was interpreted as a synchrotron self-absorption taking place in the pulsar magnetosphere (see Nasuti et al. 1997a and references therein).

PSR B0656+14

With a spin-down age of 100,000 years, PSR B0656+14 (384 ms) is one of the two middle-aged pulsars identified from ESO. A possible optical counterpart was detected by Caraveo et al. (1994a) in a faint (V ~ 25) point source detected in images obtained in 1989 (3.6-m) and 1991 (NTT) and later confirmed by an HST/WFPC2 observation (Mignani et al. 1997b). Since proper motion is a very distinctive characteristic of each pulsar, the known radio displacement of PSR B0656+14 was searched in the optical but, owing to the poorer angular resolution of the 3.6-m and NTT images, only a marginal result was obtained.

Geminga

The optical identification of the middle-aged (340,000 years) Geminga pulsar (237 ms) with a faint star named G" (V = 25.5), proposed by Bignami et al. (1987), was initially substantiated by its unusual colours (Halpern & Tytler 1987). In particular, multicolour photometry observations performed at the 3.6-m (Bignami et al. 1988) showed for the first time that its optical flux distribution could not be explained by a simple spectral model, as happens e.g. for the Crab, and that different emission mechanisms were at work. A few years later, the optical identification of Geminga was supported by the measurement of the G" proper motion, obtained thanks to a new NTT/SUSI observation (Bignami et al. 1993) and later reassessed both with the NTT/SUSI (Mignani et al. 1994) and with the HST/WFPC2 (Caraveo et al. 1996). The definitive proof of the optical identification came when the gamma-ray light curve of Geminga was found to be sensitive to the G" proper motion (Mattox et al. 1996), finally closing the loop.

NTT/SUSI observations of the Geminga field were also fundamental to tie, through a multi-step astrometric procedure, the Hipparcos reference frame to the HST/WFPC2 one and to obtain the absolute coordinates of the pulsar with an accuracy of only 40 mas (Caraveo et al. 1998). This, together with the refined measurement of the proper motion, obtained by the HST (Caraveo et al. 1996), makes it possible to compute the absolute position of Geminga at a given epoch, a critical information to phase together its gamma-ray pulsations over 20 years of observations (Mattox et al. 1998).

The last, although still weak, proof of the optical identification of Geminga came recently with the tentative detection of optical pulsations from G" (237 ms), a result partially obtained using the TRIFFID camera at the 3.6-m (Shearer et al. 1998).

The Chase Goes On

A few more pulsars were observed through the years from ESO but no new optical identification was achieved. Among the best-studied targets, we recall the middle-aged (540,000 years) pulsar (197 ms) PSR B1055-52, observed for the first time from the 3.6-m (Bignami et al. 1988) and later also from the NTT. With a flux comparable to the one of Geminga (see Table 2), this pulsar would probably have been detected if it were not buried in the PSF's wings of a very close and bright star (see Fig. 1 of Mignani et al. 1997a), which made mandatory the use of the HST. The more recent (and deeper) optical investigations are those of two young pulsars: the Crab-like PSR J0537-6910 (5,000 years) and the Vela-like PSR B1706-44 (17,000 years), observed respectively with the NTT and the VLT.

The X-ray pulsar PSR J0537-6910 in the Large Magellanic Clouds supernova remnant N157B is the fastest (16

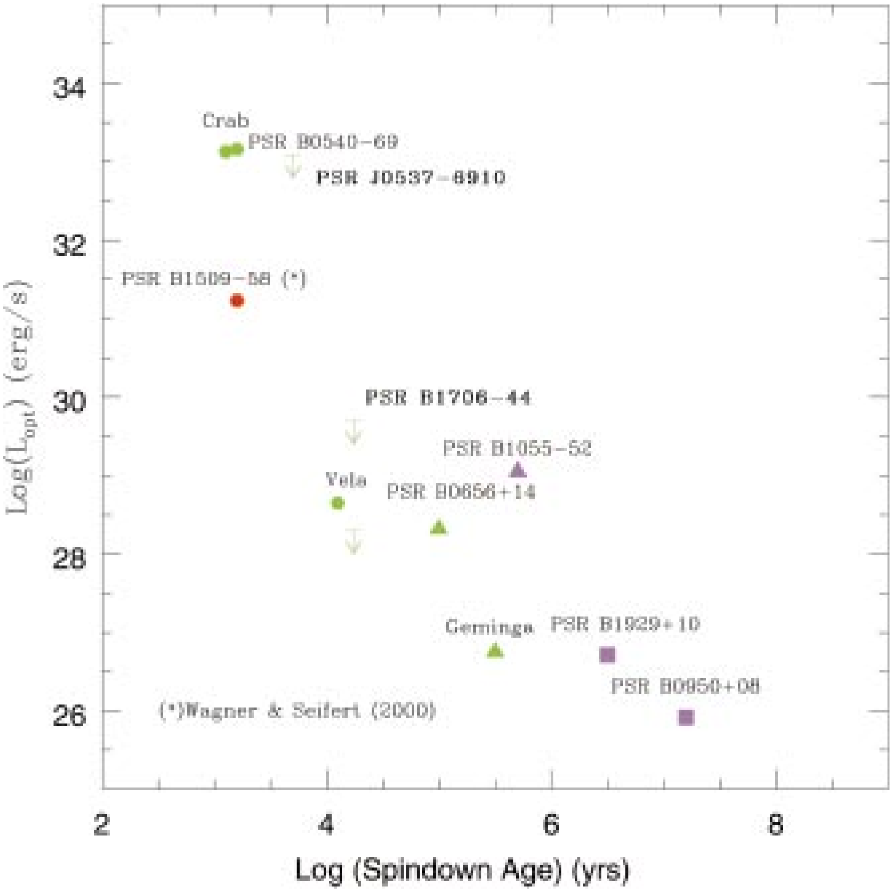


Figure 1: Extinction-corrected optical luminosities of identified pulsars plotted vs. their spin-down ages. In all cases but Geminga, for which an optical parallax measurement exists (Caraveo et al. 1996), the luminosities have been calculated assuming the nominal radio distances. Available upper limits are reported for PSR J0537-6910 and PSR B1706-44 (in this case for the extreme values of the interstellar extinction). The different symbols indicates young (hexagons), middle-aged (triangles) and old (squares) pulsars, with luminosities computed in the V (green), R (red) and U (magenta) bands.

ms) known isolated (non-recycled) pulsar and the most energetic (together with the Crab). Although the X-ray detection has been confirmed by all operating X-ray satellites, PSR J0537-6910 is still undetected in radio (see Mignani et al. 2000 and references therein). In the optical, the field was observed in 1998 in the BVI bands with the SUSI2 camera at the NTT. Few objects were detected close/inside the X-ray error circle but none of them could be convincingly associated to the pulsar, which appears undetected down to V ~ 23.4 (Mignani et al. 2000). This result has been independently confirmed by the upper limits on the pulsed optical flux obtained by Gouiffes & Ogelman (2000) from the reanalysis of fast-photometry observations of the field performed with the ESO fast photometer at the 3.6-m.

PSR B1706-44 is a radio/gamma-ray pulsar (P = 102 ms) and a weak soft X-ray source (see Mignani et al. 1999 and references therein), very similar to the Vela pulsar both in its dynamical parameters and in its multiwavelength phenomenology. After a few (unpublished) trials with the NTT, deep optical observations of PSR B1706-44 were obtained in August 1998 during the Science Verification programme of the VLT/UT1 using the Test Camera (Mignani et al. 1999; Lundquist et al. 1999). Unfortunately, no candidate optical counterpart to the pulsar has been detected down to V ~ 25–27, depending on the computed image astrometry.

The General Picture

Although still incomplete, the information obtained so far is sufficient to draw a first, general, picture of the optical emission properties of pulsars (see Mignani 1998 for a review). To summarise, two different processes can contribute to the optical emission: (i) synchrotron radiation from the magnetosphere, fuelled by the neutron star's rotational energy loss dE/dt, and (ii) thermal ($T \approx 10^5$–10^6 °K) radiation from the cooling neutron star's surface, which peaks in the soft X-ray band.

The first process is dominant in young and bright objects but its efficiency seems to decay rapidly (Fig. 1), to wit, the case of the Vela pulsar, which is only 5 times older than the Crab but channels in the optical approximately a 1,000 times smaller fraction of its global energy budget. For the middle-aged and fainter pulsars, the scenario is less clear. First, the optical luminosity falls well below the value predicted by the Pacini's Law and its dependence on the spin-down age is smoother. Second, the available multicolour flux measurements are clearly inconsistent with a single spectral model, thus implying that both the emission processes described above probably contribute to the optical luminosity. In the case of PSR B0656+14, the optical flux distribution can be fit by the combination of both a magnetospheric and a thermal component (Pavlov et al. 1997). On the other hand, for the slightly older Geminga, the optical continuum seems to be thermal with a broad emission feature at 6,000 Å (Mignani et al. 1998b), which, following the original idea of Bignami et al. (1988), has been interpreted as a possible Hydrogen cyclotron emission line originated in the neutron star's atmosphere (Jacchia et al. 1999). For older pulsars (>1,000,000 years), thermal emission is thought to become finally dominant over the magnetospheric one (Pavlov et al. 1996).

The Future

Although the last years marked a big step forward in the optical astronomy of pulsars, much work remains to be done to understand the emission properties of these objects. While the above picture seems substantially correct, the question of when and how the optical emission of young pulsars starts to fade away and switches from a pure magnetospheric to a thermal regime is still an open issue. Optical observations of more pulsars, especially in the age interval 5000–100,000 years, are thus crucial to find an answer. Starting from the updated pulsar database, now counting ≈ 500 additional detections (e.g. Camilo et al. 2000), future Chandra and XMM observations should pinpoint targets worth of optical follow-ups.

The knowledge of the pulsars spectra in the optical domain is also rather poor. Up to now, it was based on spectral information gathered through multicolour photometry and hidden in timing and polarimetry data. Only for the bright Crab pulsar (Nasuti et al. 1996a,b) and PSR B0540-69 (Hill et al. 1997) a rather accurate spectroscopy is available. Future observations of pulsars should certainly be more focussed on spectroscopy. Amongst young optical pulsars, Vela is certainly the one that could benefit more from a comprehensive spectral study. An accurate determination of its spectral shape would be crucial both to unveil emission/absorption mechanisms in the pulsar's magnetosphere and to trace the transition in the emission physics between young and middle-aged pulsars. Spectroscopic observations are also needed to resolve the different components (magnetospheric and thermal) so far only hinted in the multicolour flux distribution of the middle-aged PSR B0656+14 and Geminga, including possible atmospheric cyclotron lines. A joint fit of the optical/X-ray thermal components would provide a better measurement of the observed neutron star surface temperature, important to investigate both its internal structure and the physical/chemical properties of its atmosphere. On the other hand, fitting well-resolved cyclotron lines would allow to obtain the first direct measurements of the neutron star magnetic field (Bignami 1998). For Geminga, a spectrum was recently obtained from the ground (Martin et al. 1998) but with a very low S/N, while no spectroscopy observation has yet been tried for the slightly brighter PSR B0656+14.

To pursue all the above goals, deep imaging, timing and spectroscopic observations, as feasible with 8-m-class telescopes, are required. Needless to say, in all cases the VLT could offer an invaluable contribution. In particular, with FORS1 and FORS2, both Antu and Kueyen fulfil the imaging/spectroscopy requirements. On the other hand, timing observations can be performed either by using FORS2 in trailer mode (see e.g. ESO/PR 17/99) or by using MAMA detectors attached to the visitor focus of Yepun. Thus, we can certainly say that the VLT has all the potentialities to open a new era in the optical astronomy of pulsars, giving back to ESO the leadership achieved before the advent of the HST.

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The ROSAT Deep Cluster Survey: Probing the Galaxy Cluster Population out to *z* = 1.3

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1. Introduction

The redshift evolution of the space density of galaxy clusters has long served as a valuable tool with which to test models of structure formation and to set constraints on fundamental cosmological parameters. Being recognisable out to large redshifts, clusters are also ideal laboratories to study the evolutionary history of old stellar systems, such as E/S0s, back to early cosmic look-back times. It is therefore not surprising that a considerable observational effort has been devoted over the last decade to the construction of homogeneous samples of clusters over a large redshift baseline. Until a few years ago, however, the difficulty of finding high-redshift clusters in deep optical images and the limited sensitivity of early X-ray surveys had resulted in only a handful of spectroscopically confirmed clusters at $z > 0.5$. The ROSAT satellite, with its improved sensitivity and spatial resolution, made clusters high-contrast, extended objects in the X-ray sky and has thus allowed for a significant leap forward. About a thousand clusters have now been selected from the ROSAT