Neutron Star Astronomy with the HST

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Abstract. Since its launch in 1990, HST has played a leading role in optical studies of isolated neutron stars, both radio-loud pulsars and radio-silent ones, paving the way to follow-up observations performed with 8m-class telescopes, like the VLT, the Gemini, and Subaru. Here, I present the last results obtained mostly by the WFPC2, before its de-commissioning during the last refurbishment mission in May 2009, from the observations of the rotation-powered pulsars PSR B0540−69, PSR B1055−52 and of the CCO 1E 1207.4−5209 in the PKS 1209−52 SNR.

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INTRODUCTION

In its 20 years of activity, HST has observed almost all isolated neutron stars (INSs) with an optical counterpart, 24 to date including possible candidates (see, e.g. Mignani 2010a), and has carried out deep searches for several others. In particular, HST has discovered the optical counterpart to seven INSs. Four of them are classical rotation-powered pulsars, one of which is the first ms-pulsar identified in the optical, the others are X-ray Dim INSs (XDINSs). Among the major HST achievement in optical studies of INSs (see, e.g. Mignani 2010b), one should note the many detections in the near-IR and in the near-UV, high spatial resolution phase-averaged polarimetry observations of pulsars and their associated pulsar-wind nebulae (PWNe), proper motion and, in some cases, parallax measurements for several rotation-powered pulsars and XDINSs. Here, I present the results of the last observations of INSs performed by the WFPC2.

PSR B0540−69

PSR B0540−69 is a young (~1600 yr old) pulsar (P = 50 ms) in the LMC, discovered in the X-rays, and soon after observed in the optical with a V ~ 22.5 counterpart (Caraveo et al. 1992), and only later in radio. Because of its similar energetic (E ~ 1.5 × 10^{38} erg s^{-1}) and magnetic field (B ~ 5 × 10^{12} G) is also referred as the “Crab twin”. We observed PSR B0540−69 for six HST orbits: four were devoted to polarimetry observations (1800 s each) through the 606W+POLQ filter and two to multi-band photometry in the 336W (780 s), 450W (780 s), 555W (300 s), 675W (420 s), 814W (420 s) filters, to provide, for the first time, an homogeneous spectral coverage from ~ 3000 to 8000 Å. First of all, we used our imaging observations to set new constraints on the pulsar proper motion. Using a sample of WFPC2 observations spanning 4 years, Serafimovich et al. (2004) claimed a marginally significant proper motion of 4.9 ± 2.3 mas yr^{-1}, possibly parallel to the nebula symmetry axis, as in the case of the Crab and Vela pulsar/PWNe.
However, more recent $WFPC2$ observations spanning 10 years (De Luca et al. 2007), did not confirm this claim and yielded a proper motion upper limit of 1.2 mas yr$^{-1}$ (3$\sigma$). Our new $WFPC2$ observations, extending the time baseline to 12 years, allowed to refine the upper limit to 1 mas yr$^{-1}$ (3$\sigma$), implying a transverse velocity $v_t < 250$ km s$^{-1}$ (Mignani et al. 2010a). At the same time, we used the available multi-epoch image database to compute the pulsar coordinates through absolute optical astrometry. From the average of different measurements, we determined the pulsar position with an accuracy of 5 mas per coordinate ($1\sigma$), which supersedes in accuracy previously reported values (see Mignani et al. 2010a) and has been used by Gradari et al. (2010) as a reference for the pulsar optical timing observations. We used our multi-band imaging observations, together with archival $WFPC2$ broad band images, to accurately characterise the pulsar’s optical spectrum. Middleditch et al. (1987) showed a possible evidence of a flux excess in the U-band with respect to the underlying power-law (PL) continuum, not confirmed by Nasuti et al. (1997). More recently, using a small set of broad/medium-band $WFPC2$ images, Serafimovich et al. (2004) measured a PL with spectral index $\alpha = 1.07 \pm 0.2$. Using our extended $WFPC2$ database, we measured $\alpha = 0.70 \pm 0.07$, more consistent with the values measured in other rotation-powered pulsars, with no evidence of a flux excess in the U-band. Interestingly enough, the optical PL lies well below the extrapolation of the X-ray one, which implies a double break in the optical–to–X-ray spectrum, never observed so far in other rotation-powered pulsars. For PSR B0540$-$69, only a VLT measurement of a phase-averaged polarisation degree (PD) of $\sim 5\%$ (quoted without errors) existed prior to our observations (Wagner & Seifert 2000), probably polluted by the contribution of the SNR and by the difficulties in resolving the pulsar in the low-spatial resolution VLT images. After subtracting the contribution of the foreground polarisation and of the SNR, we measured a pulsar polarisation $PD = 16\% \pm 4\%$, with a position angle (PA) of $22 \pm 12^\circ$. This is closely aligned with the possible proper motion direction of the knot observed southwest of the pulsar (De Luca et al. 2007), which is also polarised ($PD \sim 10\%$), with its PA approximately aligned with that of the pulsar.

**PSR B1055−52**

PSR B1055−52 is a middle-aged ($\sim 535$ kyr old) radio, X and $\gamma$-ray pulsar ($\dot{E} \sim 3 \times 10^{34}$ erg s$^{-1}$; $B \sim 1.1 \times 10^{12}$ G) and, together with PSR B0656+14 and Geminga, one of the so-called “Three Musketeers”. In the optical, the detection of PSR B1055−52 has been troublesome due to a bright star ($V \sim 14$), located at $\sim 4.4$ arcsec from the pulsar, which hampered all ground-based observations (e.g., Mignani et al. 2010b). Indeed, the pulsar counterpart was only detected thanks to the high spatial resolution and near-UV sensitivity of the $HST/FOC$ (Mignani et al. 1997). We observed PSR B1055−52 with the $HST$ both in the near-UV (140 LP filter; 5600 s) with the $ACS/SBC$ and in the optical with the $WFPC2$ in the 450W (1800 s), 555W (1800s) and 702W (3600 s) filters. The pulsar identification was complicated by the uncertainty on its coordinates (epoch 1978 in the ATNF catalogue) which could be up to $\sim 4$ arcseconds due to its unknown proper motion. We detected a source positionally coincident, within the uncertainty of the $HST$ astrometry, with the pulsar candidate counterpart both in the $SBC$ ($m_{140LP} \sim 22.6$), and in the $WFPC2$ images ($m_{555W} \sim 25.4; m_{702W} \sim 26.08; m_{450W} > 24.97$). Thus, its
blue colours certified its identification with the pulsar (Mignani et al. 2010c). Using our high-spatial resolution WFPC2 images, we obtained an updated measurement of the pulsar coordinates (epoch 2008.18) through absolute optical astrometry ($\sim 0.15$ arcsec positional accuracy), consistent with the new radio timing position (Manchester, R.N., private communication). From the comparison with the ATNF radio coordinates we also obtained the first measurement of the pulsar absolute proper motion which is consistent with the relative one measured from the comparison of the pulsar position measured in the SBC and FOC images, taken 12 years apart: $\mu_\alpha = 43 \pm 6$ mas yr$^{-1}$ and $\mu_\delta = -5 \pm 6$ mas yr$^{-1}$. This implies a transverse velocity $v_t \sim (70 \pm 8)$ km s$^{-1}$, for a pulsar distance of 350 pc (see below). We then computed the backward extrapolation of the pulsar galactic orbit to locate its birth place and indentify its parental open cluster, after backward-extrapolating the orbits of selected candidate clusters. Unfortunately, both the unknown pulsar radial velocity and the uncertain distance did not allow us to determine an unambiguous association. A more accurate determination of the pulsar distance, e.g. from the measurement of the radio parallax, will be important to narrow the list of candidate parental clusters. We used our multi-band images to characterise, for the first time, the pulsar optical-UV spectrum. This can be described by the combination of a power-law ($PL_O$; $\alpha_O = 1.05 \pm 0.34$) and a Rayleigh-Jeans (RJ). Interestingly enough, the RJ is above the extrapolation of the cold blackbody ($BB_C$) component used to fit the XMM-Newton spectrum (De Luca et al. 2005), together with a hot blackbody ($BB_H$) and a power-law ($PL_X$). This suggests a three-component thermal map for the neutron star surface, unlike the other “Musketeers”. The temperature of the RJ component, however, is parametrised by the ratio $(d/R)^2$, where $d$ and $R$ are the neutron star distance and the radius of the optical emitting region, respectively. To solve the degeneracy, we imposed that $R < R_{NS,13}$, where $R_{NS,13}$ is the neutron star radius in units of 13 km (as seen from infinity) and that the BB extrapolation of the RJ yields an X-ray flux much smaller than that of $BB_C$. From the limit case $R \sim R_{NS,13}$ we then derive a distance estimate of $d \sim 350$ pc, i.e. lower than the 750 pc value estimated from the dispersion measure (DM). The new distance yields a factor of 4 smaller radius (5.7 km) for $BB_C$, which has important implications for comparisons with neutron star cooling model, and implies a downward rescaling for the different multi-wavelength emission efficiencies, with the $\gamma$-ray one being $\sim 0.13\%$. The best fit $PL_O$ is below the extrapolation in the optical domain of $PL_X$ ($\alpha_X = 0.7 \pm 0.1$), as seen in many other rotation-powered pulsars. This suggests a spectral break between the X-ray and optical-UV regions. However, the extrapolation of the $\gamma$-ray $PL$ ($\alpha_\gamma \sim 0.5$) possibly matches the optical one, as seen, e.g in the Vela pulsar, although it is not a common feature of all rotation-powered pulsars.

**THE CCO IN PKS 1209−52**

The X-ray source 1E 1207.4−5209 in the PKS 1209−52 SNR is one of the three CCOs found to feature X-ray pulsations so far, with a period $P = 424$ ms. Optical/IR observations with the HST/ACS and with the VLT/ISAAC spotted a possible counterpart from a claimed coincidence with the source Chandra position (Pavlov et al. 2004). However, more recent astrometry recalibration of the HST images suggested that the proposed counterpart was off the Chandra error circle. This has been confirmed also
by updated Chandra astrometry of the source (see De Luca et al. 2011 and references therein). While this is already a strong argument against the association of the object with the CCO, the final evidence comes from the measurement of its proper motion with respect to the centre of the SNR. Indeed, if associated with the CCO, the counterpart should feature a proper motion $\mu \sim 70$ mas yr$^{-1}$, given the SNR age of $\sim 7000$ years and the offset of the CCO with respect to the SNR centre ($\sim 8$ arcmin). We observed the CCO field with the WFPC2 in the 814W filter (2000 s) and we performed relative astrometry with respect to archival ACS observations performed in 2003 through the same filter. We obtained a $3\sigma$ limit on the proper motion of $\mu = 7$ mas yr$^{-1}$, which would imply a SNR age larger than 70 000 years. Thus, such a measurement firmly establishes that the proposed counterpart is not associated with the CCO. From the available HST and VLT photometry, complemented by public Spitzer data, we could set a limit of $\sim 0.1$ solar masses on a stellar mass companion. The upper limits on the optical/IR spectrum are also compatible with the presence of a debris disc. Using disc emission models (Perna et al. 2000) and the derived CCO X-ray luminosity $L_X \sim 2.2 \times 10^{33}$ erg s$^{-1}$ at a 2.2 kpc distance we determined, for the assumed disc parameters (inclination, albedo, inner radius) and for the constraint on the magnetic field ($B < 8 \times 10^{10}$ G), an upper limit of $8 \times 10^{11}$ g s$^{-1}$ on the disc $\dot{M}$. This is too small for a putative disc to significantly contribute to the polar cap re-heating, as it has been proposed in some CCO scenarios.

**CONCLUSIONS**

INS astronomy with the refurbished HST (up to 2015) has still many potentials, thanks to its instrument suite, covering the near-UV (COS, ACS/SBC, STIS), near-IR (NICMOS, WFC3) and optical (ACS/WFC, WFC3), as well as timing (COS, STIS), polarimetry (ACS, NICMOS), and spectroscopy capabilities. This allows to study the NS magnetosphere, the NS interior, to search for debris discs, and to pursue new INS identifications.

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