VLT observations of the middle-aged pulsar PSR B1055–52[★] (Research Note)

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ABSTRACT

Context. The 535 kyear old radio pulsar B1055–52 is the oldest of the “Three Musketeers”, the group of the middle-aged pulsars (the other two being PSR B0656+14 and Geminga) with bright soft X-ray and high-energy γ -ray emission. The identification of its optical counterpart has been only recently confirmed through observations performed with the Hubble Space Telescope (HST), which provided a first characterisation of the pulsar spectrum.

Aims. We aim at measuring the pulsar flux in the B band for which only an upper limit has been obtained with the HST.

Methods. We used the deepest ground-based observations of the PSR B1055–52 field obtained with Very Large Telescope (VLT), available in the ESO archive.

Results. Due to the non-optimal image quality of the VLT data ($\sim 1''.2$) we could not resolve the faint pulsar emission against the higher sky background induced by the presence of a bright star (Star A; $m_V = 14.6$) $\sim 4''.4$ away from the pulsar position. We determined a 3σ upper limit of $m_B \sim 25.3$ on the pulsar brightness. This corresponds to an extinction-corrected flux $\lesssim 0.391 \mu\text{Jy}$ which is consistent with the HST spectrum and comparable with the HST flux upper limit at a similar wavelength.

Conclusions. The presence of Star A makes it improbable to detect PSR B1055–52 in the optical bands through ground-based observations, unless performed under exceptional seeing conditions. The situation might be more promising through adaptive optics high-spatial resolution observations in the near-infrared, where the HST spectrum hints at a steep power-law which predicts an higher flux at longer wavelengths.

Key words. pulsars: individual: PSR B1055–52

1. Introduction

PSR B1055–52 (Vaughan & Large 1972) is a middle-aged radio pulsar with a spin-down age $\tau = 535$ kyrs, inferred from its period ($P = 197$ ms) and period derivative ($\dot{P} = 5.8 \times 10^{-15} \text{ s s}^{-1}$). These also give, assuming a pure magneto-dipolar spin-down, a rotational energy loss $\dot{E} = 3.0 \times 10^{34} \text{ erg s}^{-1}$ and a surface magnetic field $B = 1.1 \times 10^{12} \text{ G}$. The distance to PSR B1055–52 is uncertain. The ATNF radio pulsar catalogue¹ reports 1.53 kpc, based on the radio dispersion measure $DM = 30.1 \text{ pc cm}^{-3}$ and the original galactic free electron density model of Taylor & Cordes (1993), while a distance of $726^{+154}_{-156} \text{ pc}$ is derived using the updated NE2001 model of Cordes & Lazio (2002). Recently, a distance of $\approx 350 \text{ pc}$ has been determined by Mignani et al. (2010).

PSR B1055–52 is one of the radio pulsars detected in X-rays by Einstein (Cheng & Helfand 1983), although X-ray pulsations were discovered only later by ROSAT (Ögelman & Finley 1993). PSR B1055–52 is also a γ -ray pulsar, detected by the Compton Gamma-ray Observatory (CGRO) (Fierro et al. 1993). In particular, together with the slightly younger PSR B0656+14 (111 kyrs) and Geminga (340 kyrs), PSR B1055–52 is one of the

three pulsars for which ROSAT discovered thermal X-ray emission. Their similar age and their overall similarities in their X-ray emission properties promptly earned them the nickname of “The Three Musketeers” (Becker & Trümper 1997). PSR B1055–52 has been also studied with Chandra (Pavlov et al. 2002) and XMM-Newton (De Luca et al. 2005), which showed that its X-ray spectrum, like that of the other two “Musketeers”, is the combination of soft/hard blackbody (BB) and a power-law (PL) components. Recently, PSR B1055–52 has been observed by the Fermi Gamma-ray Space Telescope (Abdo et al. 2010).

PSR B1055–52 is the last of the “Musketeers” to have been firmly identified at optical/near-ultraviolet (nUV) wavelengths, and one of the very few pulsars identified optically (see Mignani 2010a,b for recent reviews). Indeed, optical observations of PSR B1055–52 had been tried since its X-ray detection by Einstein, but they had been frustrated by the presence of a bright ($m_V \sim 14.6$) F-type field star (Star A; Manchester et al. 1978), positioned $4''.4$ away from the pulsar, which made all ground-based observations unsuccessful (Cheng & Helfand 1983; Bignami et al. 1988; Mignani 1994). Indeed, Mignani et al. (1997) could identify the candidate pulsar counterpart only thanks to the sharp resolution and high nUV sensitivity of the Faint Object Camera (FOC) aboard the Hubble Space Telescope (HST). The identification has been confirmed through new HST observations (Mignani et al. 2010) which also yielded

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¹ <http://www.atnf.csiro.au/research/pulsar/psrcat/>

the first measurement of the pulsar proper motion. Like for the other “Musketees”, the PSR B1055–52 spectrum in the optical/nUV is the combination of a PL, with spectral index $\alpha_O = 1.05 \pm 0.34$, and a Rayleigh-Jeans (R-J), with temperature $T_O = (0.66 \pm 0.10) d_{350}^2 R_{O,13}^{-2} 10^6$ K (Mignani et al. 2010), where d_{350} and $R_{O,13}$ are the pulsar distance in units of 350 pc and the emitting radius in units of 13 km. No detection of PSR B1055–52 was obtained in the *B* band, which is important to constrain the relative slopes of the PL and the R-J.

Here we present the results of optical observations of PSR B1055–52 performed with the Very Large Telescope (VLT). Observations and data analysis are described in Sect. 2 while results are presented in Sect. 3.

2. Observations and data analysis

VLT observations of the PSR B1055–52 field, obtained on 2002 March 21, are available in the public ESO archive² (Programme 68.D-0407A, PI. P. Lundqvist). The observations were performed with FOCAL Reducer/low dispersion Spectrograph (FORS1), a multi-mode camera for imaging and long-slit/multi-object spectroscopy. At the time of the observations, FORS1 was still equipped with the original four-port 2048×2084 CCD detector. The camera was operated in high resolution (HR) mode ($0''.1$ pixel size) but with a windowing of the CCD, which decreased the instrument field of view to $1''.6 \times 1''.6$. A sequence of 18 short (140 s) exposures to avoid the saturation of Star A were obtained through the Bessel *B* filter ($\lambda = 4290$ Å; $\Delta\lambda = 880$ Å) for a total integration time of 2520 s. Another sequence of 12 exposures of the field was obtained but, strangely enough, not centred on the PSR B1055–52 position. Single exposures were dithered by steps of $\pm 50''$ along the *X* and *Y* axis. The pulsar was observed close to its maximum altitude, with an airmass of ~ 1.2 . The average image quality during the exposures was $\sim 1''.2$, as measured directly on the frames. Observations were obtained with the Moon at $\sim 50\%$ illumination, at a distance of $\sim 100^\circ$ from our target and at $< 30^\circ$ on the horizon at the time of the observations.

We retrieved the data from the ESO archive together with the associated calibration files (bias and flat fields) and we reduced them using standard programs in MIDAS for bias subtraction, flat-fielding, cosmic-ray removal, image alignment and stacking. Unfortunately, no standard star observations in HR mode were obtained for the night of 2002 March 21. For this reason, we computed the FORS1 photometry calibration using archival images of the standard star fields PG 1323 and SA 101 (Landolt 1992), taken on 2002 March 11 and 12. Since these observations were obtained a few days before those of PSR B1055–52, we verified that in both cases the night conditions were of comparable photometric quality according to the ESO ambient conditions database³. We then fitted Landolt to instrumental magnitudes computed through aperture photometry using a fixed radius of $10''$, for comparison with values measured by the FORS1 photometric calibration pipeline. For the airmass correction we applied the average *B*-band atmospheric extinction coefficient at the Paranal Observatory measured with FORS1⁴ and closest in time to our observations ($k_B = 0.301 \pm 0.08$). The overall uncertainty of our photometric calibration corresponds

to an error of less than 0.1 mag on the value of the zero point ($ZP = 26.98$).

Given the presence of Star A, a very accurate astrometry of the FORS1 image is crucial to precisely locate the pulsar position and to properly account for the effects of the local background enhancement produced by the wings of the star point spread function (PSF). We performed the astrometric calibration of the FORS1 image using the GSC-2.3 (Lasker et al. 2008) as a reference catalogue. We measured the pixel coordinates of the GSC-2.3 stars through Gaussian fitting with the Graphical Astronomy and Image Analysis (GAIA) tool⁵ and we computed the pixel-to-sky coordinates transformation using the code ASTROM⁶. Unfortunately, due to the windowing of the CCD, only 9 suitable stars (after sigma clipping) were available for the astrometry calibration. From the astrometric fit we then obtained an rms of $\sigma_r \approx 0''.2$ on the position residuals. To this, we added in quadrature the uncertainty in the registration of the FORS1 image on the GSC-2.3 reference frame ($0''.17$). As in Lattanzi et al. (1997), we estimated it as $\sigma_{tr} = \sqrt{3} \times \sigma_{GSC} / \sqrt{N_{GSC}}$, where $\sqrt{3}$ accounts for the free parameters in the astrometric fit, $\sigma_{GSC} = 0''.3$ is the mean positional error of the GSC-2.3 coordinates (Lasker et al. 2008), and $N_{GSC} = 9$ is the number of GSC-2.3 stars used to compute the astrometric solution. Accounting for the $0''.15$ uncertainty (Lasker et al. 2008) on the link of the GSC-2.3 to the International Celestial Reference Frame (ICRF), the overall accuracy of the FORS1 astrometry is, thus, $\delta_r = 0''.3$ (1σ). The uncertainty on the star centroids is ≤ 0.1 pixel ($\leq 0''.01$) and is negligible with respect to the overall uncertainty of our absolute astrometry calibration.

3. Results

As a reference for the PSR B1055–52 position we used the coordinates derived from HST astrometry (Mignani et al. 2010): $\alpha = 10^h 57^m 58^s.965$; $\delta = -52^\circ 26' 56''.26$ (J2000) with a position error $\delta_r = 0''.15$. Since these coordinates refer to epoch 2008.18 while the epoch of the VLT observations is 2002.21, we applied the correction for the pulsar proper motion (Mignani et al. 2010): $\mu_\alpha \cos \delta = +0''.042 \pm 0''.005$ yr⁻¹; $\mu_\delta = -0''.003 \pm 0''.005$ yr⁻¹. The computed PSR B1055–52 position overlaid on the FORS1 image is shown in Fig. 1 (left), where the size of the error circle ($0''.4$) accounts for both the uncertainty of the PSR B1055–52 coordinates at the reference epoch (2008.18), of the proper motion extrapolation, and of our astrometric calibration. Unfortunately, since the FORS1 image is affected by a non-optimal image quality ($\sim 1''.2$), the wings of the Star A PSF extend up to a radial distance of $\sim 6''$ (Fig. 1, right). This produces a ~ 15 – 20% enhancement of the sky background at the pulsar position, which obviously makes it more difficult to detect emission from a faint point source, even if the FORS1 image was taken in high-resolution mode. Using the tools available in the IRAF package daophot, we tried to subtract Star A after fitting the image PSF computed from a number of reference stars selected in the image field of view. However, probably due to its much higher brightness, the subtraction of Star A produced quite large residuals and, thus, it did not help to detect any excess of signal at the pulsar position. Thus, we concluded that PSR B1055–52 is not detected in the VLT images.

We used the VLT/FORS1 observations of the PSR B1055–52 field to derive an upper limit on its spectral

² www.eso.org/archive

³ <http://archive.eso.org/asm/ambient-server>

⁴ <http://www.eso.org/observing/dfo/quality/FORS1/qc/qc1.html>

⁵ star-www.dur.ac.uk/~pdraper/gaia/gaia.html

⁶ <http://www.starlink.rl.ac.uk/star/docs/sun5.htx/sun5.html>

Fig. 1. (Left) VLT/FORS1 $40'' \times 40''$ B -band image (2520 s integration time) of the PSR B1055–52 field (North to the top, east to the left). The computed pulsar position (Sect. 3) is marked by the circle ($0''.4$ radius). The bright star A (Manchester et al. 1978) is labelled. (Right) Radial intensity plot of the Star A PSF (each pixel is $0''.1$). The vertical solid line corresponds to the Star A centroid, while the vertical dashed line corresponds to the computed position of PSR B1055–52 with the 1σ position uncertainty marked by the vertical dot-dashed lines. The horizontal dotted line in the inset shows the average level of the background away from the wings of the Star A PSF.

flux in the B band, to be compared with that derived in the HST $F450W$ filter by Mignani et al. (2010), which has a similar wavelength and band pass ($\lambda = 4557 \text{ \AA}$; $\Delta\lambda = 951 \text{ \AA}$). Following, e.g., Newberry (1991), we determined the number of counts corresponding to a 3σ detection limit in a photometry aperture with diameter equal to the full-width at half maximum ($FWHM$) of the image PSF ($1''.2$) assuming the standard deviation of the background (σ_B) sampled within a $0''.4$ radius around the computed pulsar position. We note that, thanks to the small uncertainty of our astrometry, the value of σ_B does not vary more than $\sim 30\%$ in the region of interest. To the number of counts thus determined and normalised to the average frame exposure time of 140 s, we then applied the aperture correction computed using the growth curve from a number of unsaturated field stars. After applying the photometric zero point and correcting for the air mass we thus derived a 3σ upper limit of $m_B \sim 25.3$ on the flux of PSR B1055–52, which conservatively accounts for both the <0.1 mag uncertainty on our photometry calibration (see Sect. 2) and for the ± 0.3 magnitude upper limit uncertainty due the fluctuations of σ_B around the pulsar position (see Fig. 1-right). Our value is slightly above the 3σ upper limit of $m_{450W} = 24.97$ obtained by Mignani et al. (2010), once the difference between the Johnson and the STMAG photometric systems is taken into account. According to the simulations performed with the *synphot* tool⁷ using a set of suitable templates for the pulsar spectrum we estimated that this difference corresponds to a $m_B - m_{450W} \approx 0.4$. By using the magnitude-to-flux conversion tool available on the STScI web site⁸, we obtained an observed spectral flux upper limit $F_\nu^{\text{obs}} = 0.299 \mu\text{Jy}$ from our FORS1 B -band measurement. In order to compare the observed flux with the pulsar optical/nUV spectrum, we corrected this value for the estimated interstellar reddening towards the pulsar. As done in Mignani et al. (2010),

Fig. 2. Optical/nUV spectrum of PSR B1055–52 (updated from Mignani et al. 2010). HST flux measurements are marked with filter numbers. The solid and dashed lines are the best fit to the data points and their Rayleigh-Jeans (RJ; red) and power-law (PL_0 ; blue) components, respectively with spectral index $\alpha_0 = 1.05$ and temperature $T_0 = 0.66 d_{350}^2 R_{0.13}^{-2} 10^6 \text{ K}$. The green/orange areas correspond to the 1σ uncertainty on the best fit PL and R-J components, respectively.

we assumed as a reference $E(B - V) = 0.07$. We derived the extinction coefficient in the B band from the extinction curves of Fitzpatrick (1999), which yield $A_B = 0.29$. We finally derived an extinction-corrected B -band flux upper limit $F_\nu^{\text{der}} = 0.391 \mu\text{Jy}$.

The FORS1 B -band flux upper limit is shown in Fig. 2, together with the HST flux measurements and their computed best

⁷ stdas.stsci.edu

⁸ http://www.stsci.edu/hst/nicmos/tools/conversion_form.html

fit (Mignani et al. 2010). We note that our *B*-band upper limit is comparable with the value obtained in the *F450W* filter, which is $0.340 \mu\text{Jy}$. This is consistent with the estimated ≈ 0.4 mag difference between the Johnson and the STMAG photometric systems. In particular, the FORS1 *B*-band upper limit is still above the best fit to the HST fluxes (solid line in Fig. 2). Thus, it can not be used to constrain the spectrum of PSR B1055–52 in the optical band and, hence, to weight the contribution of the thermal and non-thermal components. Observations deeper by at least 0.7 mag would be needed to detect PSR B1055–52 in the *B* band, which are possible with 8 m-class telescopes, although dependent on the seeing conditions, and with the refurbished HST.

4. Summary

We used archival FORS1 observations at the VLT to measure the PSR B1055–52 *B*-band flux for which only an upper limit is available from HST observations (Mignani et al. 2010). Unfortunately, due to the non-optimal image quality ($\sim 1''2$), the pulsar is not detected in the FORS1 data down to a 3σ limit of $m_B \sim 25.3$. This limit, the deepest so far reported from ground-based observations, is comparable to that obtained with the HST in the *F450W* filter and, thus, it is still above the optical/nUV best-fit spectrum. Due to the presence of the bright and nearby Star A, ground-based optical imaging of PSR B1055–52 is obviously seeing-limited and, perhaps, challenging even under sub-arcsecond seeing conditions. While the study of the pulsar in the optical/nUV band can be better pursued with the HST, more detections chances with 8 m-class telescopes, however, might come from high spatial resolution observations in the near-infrared (NIR) with adaptive optics devices like NAOS-CONICA (NACO) at the VLT. Indeed, the contribution of star A PSF

(spectral type F) should be lower in the nIR, while the PSR B1055–52 flux should be higher, as suggested by its power-law tail hinted in the HST spectrum (Fig. 2). These observations would be critical to constrain the slope of the power-law continuum and, thus, to characterise the pulsar multi-band spectrum.

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