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VLT observations of the candidate counterpart to PSR J0108−1431★ (Research Note)

R. P. Mignani[1,2], G. G. Pavlov[3], and O. Kargaltsev[4]

[1] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
e-mail: rm2@mssl.ucl.ac.uk
[2] Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265 Zielona Góra, Poland
[3] Department of Astronomy and Astrophysics, Pennsylvania State University, PA 16802, USA
[4] Department of Astronomy, University of Florida, FL 32611, USA

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ABSTRACT

Context. Optical-ultraviolet (UV) observations of >100 Myr pulsars are crucial to understand the long-term evolution of neutron stars, including the late stages of the neutron star cooling. The 166 Myr old pulsar PSR J0108−1431 is one of the best targets since it is the oldest non-recycled pulsar with a candidate counterpart, detected with the Very Large Telescope (VLT).
Aims. Aim of our observations is to obtain a firm detection of its candidate counterpart, only detected with marginal significance and to measure anew its flux in the U and B bands, for which we obtained only uncertain values.
Methods. We observed the PSR J0108−1431 field with the FOcal Reducer/low dispersion Spectrograph (FORS2) at the VLT, exploiting the updated pulsar radio coordinates obtained from recent VLBI observations.
Results. Due to non-optimal seeing conditions, we only reached 3σ detection limits of $U \sim 26.5$ and $B \sim 27.2$, i.e. not incompatible with the fluxes of the candidate counterpart ($U = 26.4 \pm 0.3$; $B = 27.9 \pm 0.5$) that we measured in our previous VLT observations.
Conclusions. We can not rule out that the proposed counterpart, detected at the edge of an elliptical galaxy, is real and that we could not detect it just because its flux is close to the detection limit of our new VLT observations. Due to its blue spectrum and proximity to the galaxy, UV observations with the *Hubble* Space Telescope are more suited to confirm the pulsar identification.

Key words. stars: neutron – pulsars: individual: PSR J0108−1431

1. Introduction

The pulsar PSR J0108−1431 (Tauris et al. 1994) is one of the closest to Earth, with a distance $d = 240^{+124}_{-61}$ pc, determined from its VLBI radio parallax (Deller et al. 2009). The pulsar period, $P = 0.808$ s, and period derivative, $\dot{P} = 7.44 \times 10^{-17}$ s s^{-1}, correspond to spin-down age $\tau = P/2\dot{P} = 166$ Myr, rotational energy loss $\dot{E} = 5.8 \times 10^{30}$ erg s^{-1}, and surface magnetic field $B = 2.5 \times 10^{11}$ G. PSR J0108−1431 is one of the oldest non-recycled radio pulsars known to date, and in the P-$\dot{P}$ diagram it falls close to the "death line". Indeed, PSR J0108−1431 is a very faint radio pulsar, with a 400 MHz luminosity of 0.511 mJy kpc^2 (at 240 pc), among the faintest known so far. PSR J0108−1431 has been for a long time undetected outside the radio band until its X-ray counterpart was identified by *Chandra* (Pavlov et al. 2009), which also yielded its first proper motion measurement (199 ± 65 mas yr^{-1}). By backward-extrapolating the *Chandra* proper motion, Mignani et al. (2008) identified a candidate counterpart ($U = 26.4 \pm 0.3$; $B = 27.9 \pm 0.5$; $V > 27.8$), tentatively detected in their previous VLT observations (Mignani et al. 2003). The VLBI proper motion (170 ± 1.7 mas yr^{-1}; Deller et al. 2009), now implies a chance coincidence probability $\sim 3 \times 10^{-4}$, i.e. a factor of ~ 4 smaller than that derived by Mignani et al. (2008) on the basis of the *Chandra* proper motion, thus strengthening the association. Thus, PSR J0108−1431 might be the oldest pulsar identified in the optical (e.g., Mignani 2011). The countepart's fluxes are consistent with a $T \sim 3 \times 10^5\ (d_{240}/R_{13})^2$ K Rayleigh-Jeans spectrum from the bulk of the neutron star surface (see also Deller et al. 2009), where R_{13} is the emission radius as seen from infinity in units of 13 km and d_{240} is the pulsar distance in units of 240 pc, which is above all model predictions for such an old neutron star. Here, we present new VLT observations of PSR J0108−1431 aimed at confirming its identification. Observations and data analysis are described in Sect. 2 while results are presented and discussed in Sect. 3.

2. Observation description and data reduction

We observed PSR J0108−1431 with the VLT on 2009 August 24 and 25 with FOcal Reducer/low dispersion Spectrograph (FORS2; Appenzeller et al. 1998) using the blue-sensitive E2V detector ($8'.3 \times 8'.3$ field-of-view; $0''.25$ per pixel) and the $u_{\rm HIGH}$ ($\lambda = 3610$ Å; $\Delta\lambda = 505.1$ Å) and $b_{\rm HIGH}$ ($\lambda = 4400$ Å; $\Delta\lambda = 1035.1$ Å) filters, for a total integration time of 18 000 and 14 400 s, respectively. We observed in dark time, with mostly clear sky conditions, airmass of ∼1.05–1.14, and image quality of $\sim 0''.8$–$1''$. We obtained images of the Landolt fields (Landolt 1992), bias, and morning twilight flat-field frames. We reduced the the data using the FORS2 pipeline and we stacked the best

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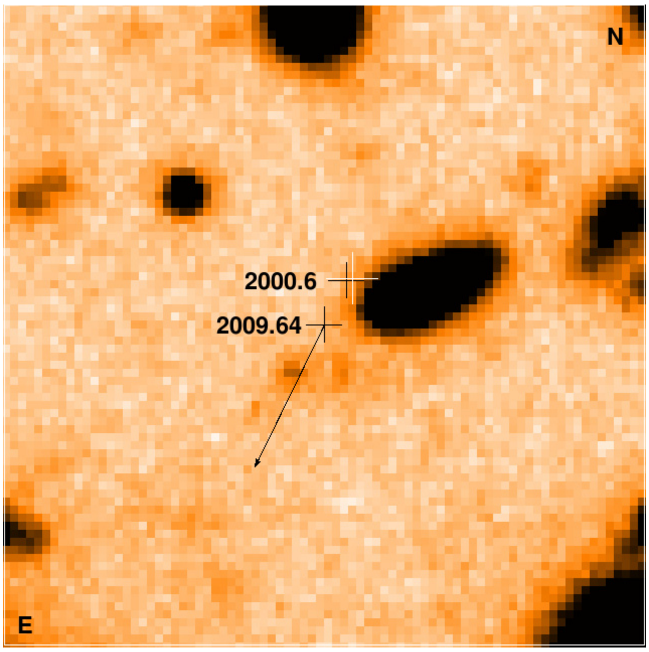

Fig. 1. VLT/FORS2 20″ × 20″ *B*-band image (7800 s) of PSR J0108−1431. The VLBI pulsar positions at the epochs of our FORS2 (2009.64) and FORS1 (2000.6) observations (Mignani et al. 2003) are marked by the black crosses, while that of the candidate counterpart is marked by the white cross. The cross arms correspond to the 3σ error on our absolute FORS2 astrometry. The arrow indicates the pulsar proper motion direction and its length (5″) the expected 30 yr displacement.

image quality science images using the `drizzle` tool in IRAF. We computed the photometric zero points by fitting the instrumental magnitudes of the Landolt stars to their catalogue values and using the most recent atmospheric extinction coefficients for the E2V detector. We estimate that the zero point error due to the uncertain extinction correction and the unknown colour term is ~0.1 mag, which we assume as the accuracy of our absolute photometry. We re-computed the astrometry of the FORS2 images by fitting the positions of Guide Star Catalogue 2 (GSC-2; Lasker et al. 2008) objects. This yielded a 0.″28 uncertainty (1σ) on our astrometry after accounting for the registration of the FORS2 image on the GSC-2 grid and the 0.″15 uncertainty on the link of the GSC-2 to the International Celestial Reference Frame (ICRF). To compute the PSR J0108−1431 position at the epoch of our observations (2009.64) we used its VLBI coordinates (Deller et al. 2009): $\alpha = 01^{h}08^{m}08^{s}.347$; $\delta = -14^{\circ}31'50''.187$ (epoch 2007.0), with an error of ≈1 mas per coordinate, and proper motion, $\mu_\alpha = +75.05 \pm 2.26$ mas yr^{-1}; $\mu_\delta = -152.54 \pm 1.65$ mas yr^{-1}.

3. Results and conclusions

The PSR J0108−1431 position (epoch 2009.64) is shown in Fig. 1, overlaid on the FORS2 $b_{\rm HIGH}$-filter image. We could not detect any object close to the pulsar position in both the $u_{\rm HIGH}$ and $b_{\rm HIGH}$-filter images. We then determined the detection limit from the standard deviation of the background sampled at the pulsar position in an aperture with diameter equal to 4 pixels, i.e. comparable with the *FWHM* of the image PSF. After applying the aperture and airmass corrections, we derived 3σ detection limits of $U \sim 26.5$ and $B \sim 27.2$. We cross-checked our U and B-band photometry by comparing the fluxes of stars matched with the FORS1 observations of Mignani et al. (2003), and we found a mean difference $\delta_U = -0.08$ with an rms $\sigma_U = 0.12$, and $\delta_B = 0.1$ ($\sigma_B = 0.1$). This is consistent with the uncertainty of our absolute photometry calibration (Sect. 2). Thus, our detection limits are compatible with the non-detection of the PSR J0108−1431 candidate counterpart, whose fluxes are $U = 26.4 \pm 0.3$ and $B = 27.9 \pm 0.5$ (Mignani et al. 2008), and do not allow to establish whether this object is real or it was just a background fluctuation, possibly produced by the halo of the close-by ellipitcal galaxy (Fig. 1). Moreover, due to the presence of this galaxy the 3σ detection limits at the epoch 2000.6 pulsar position, i.e. that of the FORS1 observations of Mignani et al. (2003), are even brighter ($U \sim 25.7$ and $B \sim 26.7$) that those computed at the 2009.64 position. This means that we cannot determine whether the candidate counterpart (if real) was a back/foreground object or it was the pulsar which now moved away from its discovery position because of its proper motion. Thus, the identification of PSR J0108−1431 is still an open issue. Due to the faintness of the candidate counterpart, and its proximity to the background galaxy, its detection from the ground requires exceptional observing conditions. Thus, more detection chances will come from observations with the *Hubble* Space Telescope in the near/far-UV where the pulsar is expected to be brighter because of its Rayleigh-Jeans spectrum. Moreover, it is imperative to carry out additional observations as soon as possible because, in a few years from now, the pulsar proper motion direction will bring it closer to the two objects detected south-east of the background galaxy (see Fig. 1), making its faint counterpart much more difficult to resolve.

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