Hubble Space Telescope Observations of the Old Pulsar PSR J0108–1431*

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Abstract

We present results of optical-UV observations of the 200 Myr old rotation-powered radio pulsar J0108–1431 with the Hubble Space Telescope. We found a putative candidate for the far-UV (FUV) pulsar counterpart, with the flux density $f_{\text{UV}} = 9.0 \pm 3.2$ nJy at $\lambda = 1528$ Å. The pulsar was not detected, however, at longer wavelengths, with $3\sigma$ upper limits of 52, 37, and 87 nJy at $\lambda = 4326$, 3355, and 2366 Å, respectively. Assumption that the pulsar counterpart was indeed detected in FUV, and the previously reported marginal $U$ and $B$ detections with the Very Large Telescope were real, the optical-UV spectrum of the pulsar can be described by a power-law model with a nearby flat $f_{\nu}$ spectrum. Similar to younger pulsars detected in the optical, the slope of the nonthermal spectrum steepens in the X-ray range. The pulsar’s luminosity in the 1500–6000 Å wavelength range, $L \sim 1.2 \times 10^{27} (d/210 \text{pc})^2 \text{erg s}^{-1}$, corresponds to a high efficiency of conversion of pulsar rotation energy-loss rate $\dot{E}$ to the optical-UV radiation, $\eta = L/\dot{E} \sim (1-6) \times 10^{-4}$, depending on somewhat uncertain values of distance and spectral slope. The brightness temperature of the bulk neutron star surface does not exceed 59,000 K ($3\sigma$ upper bound), as seen by a distant observer. If we assume that the FUV flux is dominated by a thermal component, then the surface temperature can be in the range of 27,000–55,000 K. Requiring a heating mechanism to operate in old neutron stars.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Pulsars (1306)

1. Introduction

Optical and ultraviolet (UV) observations of old rotation-powered pulsars (ages $\gtrsim 1$ Myr), supplemented by X-ray observations, are important to understand advanced stages of the thermal evolution of neutron stars (NSs) and study nonthermal emission processes in their magnetospheres. So far, only a handful of such pulsars have been detected in both X-rays and optical-UV. These are the 3 Myr old PSR B1929+10 (Pavlov et al. 1996; Mignani et al. 2002) and the 17 Myr old PSR B0950+08 (Pavlov et al. 1996, 2017), and two a-few-Gyr-old recycled millisecond pulsars, PSR J2124–3358 (Rangelov et al. 2017) and PSR J0437–4715 (Kargaltsev et al. 2004; Durant et al. 2012); all are identified in the UV-optical with the Hubble Space Telescope (HST). For both PSR B1929+10 and PSR J2124–3358, the spectral data are insufficient to determine the nature of the optical-UV emission, whereas the others show a Rayleigh–Jeans (R-J) continuum, with an additional power-law (PL) component in PSR B0950+08. In both cases, the inferred temperatures of $\sim 10^5$ K, higher than predicted by NS cooling models (e.g., Yakovlev & Pethick 2004), suggest that some reheating mechanisms operate in the NS interior. A candidate optical counterpart to the 3 Myr old PSR B1133+16 was found with the Very Large Telescope (VLT), but the identification is still uncertain (Zharikov et al. 2008; Zharikov & Mignani 2013).

Another old pulsar with a yet unconfirmed optical counterpart is PSR J0108–1431. This pulsar was discovered by Tauris et al. (1994) in the Parkes Southern Pulsar Survey (Manchester et al. 1996). Its spin period $P = 0.808$ s and period derivative $\dot{P} = 6.51 \times 10^{-17}$ s s$^{-1}$ (corrected for the Shklovskii effect) imply a rotational energy-loss rate $\dot{E} = 5.1 \times 10^{30}$ erg s$^{-1}$ and surface magnetic field $B_s = 2.3 \times 10^{11}$ G. With the characteristic age of 196 Myr, PSR J0108–1431 is one of the oldest nonrecycled isolated radio pulsars known to date. It lies close to the so-called “graveyard” region in the pulsar $P–P'$ diagram, and it is among the faintest radio pulsars, with a 400 MHz luminosity of 0.391 mJy kpc$^2$ for a distance of 210$^{+30}_{-50}$ pc, obtained from the Very Large Baseline Interferometer (VLBI) radio parallax (Deller et al. 2009), corrected for the Lutz–Kelker bias (Verbist et al. 2012).

In the first deep optical observation of the field of PSR J0108–1431 with the VLT, Mignani et al. (2003) noticed a faint brightness enhancement in the $U$ image within the error ellipse of the Australian Telescope Compact Array radio position, projected near the edge of an elongated background galaxy. However, they concluded that most likely it was not a real detection and reported only upper limits in the $V$, $B$, and $U$ filters.

The pulsar position measured by the Chandra X-ray Observatory by Pavlov et al. (2009) implied a significant proper motion, which, extrapolated to the epoch of the VLT observations, matched the position of the enhancement noticed by Mignani et al. (2003). It prompted Mignani et al. (2008) to propose that the pulsar counterpart had probably been detected with the VLT, with magnitudes $U = 26.4 \pm 0.3$, $B = 27.9 \pm 0.5$, $V > 27.8$. The improved VLBI proper motion, $170.0 \pm 1.7$ mas yr$^{-1}$ (Deller et al. 2009), made the proposed identification more robust, with a chance positional coincidence probability of $\sim 3 \times 10^{-4}$ (Mignani et al. 2011). The optical spectrum of the PSR J0108–1431 candidate counterpart is poorly defined, although the $U$ and $B$ fluxes are compatible with a $\sim 2.3 \times 10^{4}$ K R-J spectrum, for the NS radius of 13 km and 210 pc distance.

The PSR J0108–1431 X-ray identification with Chandra by Pavlov et al. (2009) has been confirmed by the detection of X-ray pulsations with XMM-Newton (Posselt et al. 2012). The
X-ray spectrum is best fitted by a PL with a (fixed) photon index $\Gamma = 2$ and a blackbody (BB) with temperature $1.28^{+0.32}_{-0.12} \times 10^6$ K and effective radius $R = 43^{+16}_{-9} d_{210}$ m, where $d_{210}$ is the pulsar distance in units of 210 pc, with a hydrogen column density $N_H = 2.3^{+2.4}_{-2.2} \times 10^{20}$ cm$^{-2}$.

The proposed optical identification of PSR J0108–1431, however, has never been confirmed. Follow-up VLT observations in 2009 with about two times larger total exposures were not conclusive because of an almost twice worse seeing of $0''.8-1''.0$ (Mignani et al. 2011), as compared to $\approx 0''.5$ in previous observations in 2000 (Mignani et al. 2003). The counterpart was not detected at the expected new position of the pulsar accounting for its proper motion, while its brightness limits, $U \gtrsim 26.5$, $B \gtrsim 27.2$, were consistent with the tentative detection reported by Mignani et al. (2008). To verify the putative VLT identification, measure the optical-UV spectrum of this pulsar, and constrain the surface temperature of the very old NS, we carried out new observations with the HST. We describe the HST observations in Section 2 and astrometry of the HST images in Section 3. Photometry of the candidate pulsar counterpart in the HST and VLT data is reported in Section 4. In Section 5, we discuss spectral fits of the optical-UV data, compare them with the X-ray spectrum, and discuss constraints on the NS surface temperature. Conclusions from our analysis are presented in Section 6.

### 2. Observations

The PSR J0108–1431 field was observed with the HST in 2016 August (program #14249, PI Mignani) using the Ultraviolet-Visible (UVIS) of the Wide Field Camera 3 (WFC3; six HST orbits) and the Solar Blind Camera (SBC) of the Advanced Camera for Surveys (ACS; two HST orbits). The WFC3/UVIS imaging was carried out with the F438W, F336W, and F225W broadband filters, while the F140LP long-pass filter was used with the ACS/SBC. The log of the observations and the pivot wavelengths of the filters are presented in Table 1. For each filter, the total integration time was split into shorter exposures distributed over two HST orbits. The WFC3/UVIS exposures were taken in the ACCUM mode, applying a four-point box dither pattern in each orbit. The UVIS2-C1K1C-CTE aperture was used to place the pulsar close to a readout amplifier and minimize the CCD charge transfer efficiency (CTE) losses, as advised in the WFC3 Instrument Handbook.\(^5\) The data were reduced and flux calibrated through the CALWF3 pipeline, which also applies the image dithering, geometric distortion and CTE corrections, cosmic-ray filtering, and stacking. For the ACS/SBC, a single exposure was taken in the ACCUM mode during each orbit. The data were processed through the CALACS pipeline including the flux calibration and geometric distortion correction. The SBC images are not affected by cosmic rays and CTE. The data for two HST orbits obtained for each filter (see Table 1) were combined to produce the resulting images. However, the aperture door was closed during the second ACS/SBC orbit (2900 s) because the Fine Guidance Sensors failed to acquire the guide stars. Because this orbit provided no science data, only the first ASC/SBC orbit is included in Table 1.

### 3. Astrometry

Precise astrometric referencing is crucial for searching the pulsar counterpart by its positional coincidence with the radio pulsar. We used the Gaia DR2 Catalog (Lindegren et al. 2018) and the IRAF tasks imcentroid and cccmap to obtain astrometric solutions. Five cataloged objects fall within the UVIS field of view (FoV) of about $162'' \times 162''$ (pixel scale of 39.6 mas was chosen in drizzling). These objects are best detected in the F438W image, which we use as a primary reference image for SBC astrometry (SBC FoV $\approx 31'' \times 34''$; pixel scale 25 mas after drizzling).\(^6\) The Gaia objects are marked and numbered in this image shown in Figure 1; their coordinates and proper motion (p.m.) components $\mu_\alpha$ and $\mu_\delta$ are listed in Table 2. Object 2 looks like an elliptical galaxy and shows no p.m.

We used the coordinates and p.m. values for the four stars in Table 2 to calculate their coordinates at the epoch of the UVIS observations, MJD 57608, for further astrometry. To increase the number of reference objects, we also used the galaxy (object 2). Thanks to its regular (elliptical) shape, the uncertainty of its position in the F438W image is reasonably small, about 2.4 mas. The total (stars plus galaxy) rms centroid radial uncertainty is 1.9 mas. According to Table 2, the rms of the Gaia radial uncertainty of the reference objects is 1.3 mas. The p.m. corrections lead to an additional radial uncertainty of 1.3 mas. Performing the astrometric fit with the cccmap, we obtained formal rms residuals of 0.7 mas for the right ascension.

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\(^5\) See https://hst-docs.stsci.edu/display/WFC3IH.

\(^6\) For the UVIS and SBC, the original pixel scales are about $40 \times 40$ and $31 \times 34$ mas, respectively.
To find an optimal source aperture for the SBC/F140LP photometry of the pulsar counterpart candidate, we calculated the S/N as a function of the radius of the circular aperture centered at the brightest source pixel in the unbinned image using the background extracted from the annulus around the same center with inner and outer radii of 20 and 50 pixels (area estimate of the shifts between the F140LP and F438W images, and found offsets of $1\sigma$ in R.A. and $0\sigma$ in decl. Their uncertainties are dominated by the position error of $\approx30$ mas of star 3 in the F140LP image. It was conservatively estimated (see, e.g., Neuschaefer & Windhorst 1995) as the FWHM of the SBC point-spread function of $\approx0\prime/2$ (Avila & Chiaberge 2016) divided by the signal-to-noise ratio, $S/N \approx 3$, of the star in the image times $\sqrt{8 \ln 2} = 2.35$. The imcentroid task yields a similar value. Then we corrected the WCS values in the header of the SBC fits file by applying the measured offsets and used the extended objects, particularly the nearby spiral galaxy seen edge on that shows a similar structure in both images, to check the shifts and reveal possible signatures of rotation between the two frames. A similar approach was applied by Zharkov et al. (2002) to align the UV and optical frames for PSR B0950+08. Overlaying the frames (see Figure 2), we found no signs of additional shifts or rotation within the uncertainty of $0\sigma/2$ and concluded that the SBC astrometric referencing is confident within this uncertainty.

The most accurate radio position and p.m. of the pulsar were obtained for the reference epoch of MJD 54100 with the Very Long Baseline Interferometry observations using the Australian Long Baseline Array (Deller et al. 2009). Using them, we calculated the pulsar coordinates for the epochs of the HST and VLT observations (Table 3). The uncertainties on the calculated position in the HST images (third and fourth lines in Table 3) include the uncertainties of the F438W and F140LP astrometry and the uncertainties due to propagation of the pulsar p.m. errors.

### 4. Possible Pulsar Counterpart

In the SBC/F140LP image (Figure 2), we found a faint point-like source with coordinates R.A. = $01^h08^m08^s403(14)$ and decl. = $-14^d31^m51^s66(20)$, consistent with the expected radio pulsar coordinates (see 4th row in Table 3). A zoomed-in region around this source is shown in Figure 3, which clearly demonstrates that the source is located within the circle with the radius of $0\sigma/2$ corresponding to the $1\sigma$ uncertainty of the pulsar radio position in this image.

### 4.1. Photometry of the Far-UV (FUV) Counterpart Candidate

To find an optimal source aperture for the SBC/F140LP photometry of the pulsar counterpart candidate, we calculated the S/N as a function of the radius of the circular aperture centered at the brightest source pixel in the unbinned image using the background extracted from the annulus around the same center with inner and outer radii of 20 and 50 pixels (area

![Figure 1](image-url)
The coordinates and proper motions of the radio pulsar in the second line are taken from Deller et al. (2009). They are used to calculate the coordinates at the epochs of the HST UVIS and SBC observations (third and fourth lines, respectively) and VLT FORS1 observations (first line). Hereafter, the numbers in brackets are uncertainties related to the last significant digits quoted. The uncertainties in the first, third, and fourth lines include the pulsar p.m. propagation errors and the astrometric reference uncertainties of the corresponding images.

\[ \mu_\alpha = \pm 0.63 \text{ of the total number of point-source counts.} \]

\[ A_0 = 4.12 \text{ arcsec}^2 \]

\[ \phi_E \approx 0.63 \text{ of the total number of point-source counts.} \]

\[ \text{Following Guillot et al. (2019), we estimated the mean background } C_{\text{bgd}} \text{ and its standard deviation } \sigma_{\text{bgd}} \text{ for a set of } 1000 \text{ circular background regions of size } r_{\text{extr}} = 0^\prime 62 (8 \text{ pixels, the same as of the source aperture), randomly placed in the annulus. To convert the count rate to the flux density, we took into account the recent correction of the SBC sensitivity, such that the flux density at a given count rate is about 0.77 of the previously adopted value (Avila et al. 2019). The results are presented in Table 4.} \]

As the putative pulsar counterpart is detected at only about the 3σ level, we cannot rule out that the count-rate excess at the pulsar position is caused by some fluctuation. In this case, one can estimate the flux density upper bound following

\[ C_{\text{ub}} = C_{\text{pos}} - C_{\text{bgd}} + n\sigma_{\text{bgd}}, \]

\[ \text{where } C_{\text{ub}} \text{ is applicable at } C_{\text{pos}} \geq C_{\text{bgd}}, \text{ which is fulfilled in our case.} \]

\[ 4.2. \text{UVIS Upper Bounds and VLT Observations of PSR J0108–1431} \]

The counterpart candidate is not detected in the UVIS images. Therefore, we calculated the upper bounds on the pulsar count rate and flux density for each of the UVIS filters using the same approach as for the F140LP filter. The sizes of the extraction regions used to measure \( C_{\text{pos}} \) were chosen by identifying in each image the extraction radius that maximizes the S/N for a point source (star). For each of the filters, we estimated \( C_{\text{bgd}} \) and \( \sigma_{\text{bgd}} \) from a set of 1000 circular background regions of size \( r_{\text{extr}} \).
randomly selected in the annulus of 10 pixels and 30 pixels inner and outer radii around the pulsar position. These quantities, together with $C_{\text{bgd}}$ and the corresponding flux densities corrected for the finite extraction aperture, $f_{\nu}^{\text{ub}} = C_{\text{bgd}}P_{\nu}/\phi_{\nu}$, are presented in Table 5, where we also show the 1σ flux density upper bounds used in spectral fits (Section 5.2).

We also do not detect any object in any of the HST bands at the position where Mignani et al. (2008) found a possible pulsar counterpart in the VLT $U$ and $B$ bands near the northern edge of the spiral galaxy. For the HST–VLT consistency check, we re-reduced the HST $UBV$ data using the recent version of the ESO recipe execution tool EsoRex 3.13.2.8 To maximize the spatial resolution and better resolve the putative counterpart from the galaxy, we selected six best-seeing 900 s exposures of eight available in $B$, three 1800 s exposures of five available in $U$, and all twelve 600 s exposures in $V$.9 This resulted in extremely good seeing on the stacked images of $0.\!^{\prime\prime}56$ in the $U$ and $B$ bands and $0.\!^{\prime\prime}54$ in the $V$ band.

The VLT astrometric solution was also revised using 11 relatively bright unsaturated Gaia stars, accounting for their p.m. shifts for the epoch of the VLT observations. This resulted in a 30 mas uncertainty of the WCS referencing of all images in both coordinates, which is significantly better than the previous astrometric precision of 190 mas based on the GSC-II catalog (Mignani et al. 2008). The more precise astrometry supports the assumption that the object detected with the VLT at a 2σ significance in the $U$ and $B$ bands is the counterpart candidate. Stacking the $U$ and $B$ images increases the detection significance to 3σ. The region of this image containing the pulsar is shown in the left panel of Figure 4. For comparison, we also merged the HST/UVIS images in the F336W and F438W bands. The respective region is presented in the right panel of Figure 4. Not only is the VLT source proposed as the pulsar counterpart not seen in the F336W+F438W image but some other faint VLT objects, such as sources 3 and 8–11 in Mignani et al. (2003), are also either resolved only marginally or not visible. At the same time, bright structures of the spiral galaxy are better resolved with the HST.

Photometric calibration of the VLT data was carried out using Landolt’s standards PG 1323–086, PG 0231+051, and PG 2331+055, observed at the same nights as the target; it resulted in the following magnitude zero points for the stacked images: $Z_{U}=25.08\pm0.04$, $Z_{B}=27.55\pm0.05$, and $Z_{V}=28.00\pm0.01$, calculated for the fluxes in units of the CCD electron rate. For photometry of the putative pulsar counterpart, we used apertures of 2.5 pixels in $U$ and 1.3 pixels in $B$ (the pixel scale was $0.\!^{\prime\prime}/2$), which correspond to the enclosed energy fraction of 0.67 and 0.3, respectively, measured using bright unsaturated stars. Such small apertures were used because of the proximity of the bright spiral galaxy leading to large systematic errors. We obtained flux densities of the source of $44\pm22$ nJy and $30\pm14$ nJy in the $U$ and $B$ bands, respectively, and a 3σ upper bound of $36$ nJy in the $V$ band. The fluxes are consistent, within the uncertainties, with the results obtained by Mignani et al. (2008).

To understand the nature of the putative VLT pulsar counterpart, we calculated the HST upper bounds at its position in the VLT observations epoch (Table 4). The derived flux density 3σ upper bounds of 24 nJy in the F336W band and 26 nJy in the F438W band are somewhat lower than the flux densities in the VLT $U$ and $B$ bands, respectively, presented above. This implies that the VLT object has disappeared or moved out of its place by the epoch of the HST observations, i.e., it is not a steady field object. On the other hand, our 3σ upper bounds of $37$ nJy in the F336W band and $52$ nJy in the F438W band at the pulsar position at the HST epoch (Table 5) are comparable to the $U$- and $B$-band flux densities.10 This suggests that the faint pulsar counterpart was indeed seen in the $U$, $B$, and F140LP bands, and it could be seen in the HST F336W and F438W bands if the exposures were just a factor of 1.5 longer.

Thus, we cannot rule out the possibility that both the VLT ($U$ and $B$ bands) and HST (F140LP band) detected the pulsar

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Table 4

| $N_s$ (cts) | $C_{\text{pos}}$ (cts ks$^{-1}$) | $C_{\text{bgd}}$ (cts ks$^{-1}$) | $\sigma_{\text{bgd}}$ (cts ks$^{-1}$) | $N_s$ (cts) | $C_{\text{bgd}}$ (cts ks$^{-1}$) | $f_c$ (nJy) |
|------------|------------------------|------------------------|------------------------|------------|------------------------|---------|
| 15.3       | 5.5                    | 2.0                    | 0.7                    | 9.8 ± 3.7  | 5.6 ± 2.0               | 9.0 ± 3.2 |

Note. $N_s$ is the total number of counts in the $A_s = 0.126$ arcsec$^2$ source aperture, $C_{\text{pos}} = N_s/\tau_{\text{exp}}$ is the count rate measured in the source aperture ($\tau_{\text{exp}} = 2.8$ ks is the exposure time), $C_{\text{bgd}}$ and $\sigma_{\text{bgd}}$ are the mean and standard deviation of background measurements in 1000 circles with the $0.\!^{\prime\prime}/2$ radius in the $A_s = 4.12$ arcsec$^2$ annulus, $N_s$ is the net source count number in the source aperture, its error is estimated as $[\sigma_{\text{bgd}}/\tau_{\text{exp}}]^2 + N_s/\tau_{\text{exp}}$, $C_{\text{bgd}} = N_s/\tau_{\text{exp}}/\phi_s$ is the aperture-corrected net source count rate, $\phi_s = 0.63$ (Avila & Chiaberge 2016) is a fraction of source counts in the $r = 0.\!^{\prime}/2$ aperture, $f_c = C_{\text{bgd}}/\phi_s$ is the density flux at the pivot wavelength $\lambda_{\text{ piv}} = 1528$ Å, and $\phi_s = 1.61$ nJy ks$^{-1}$ is the count-rate-to-flux conversion factor.

Table 5

| Filter | $\lambda_{\text{ piv}}$ (Å) | $\tau_{\text{exp}}$ (s) | $r_{\text{ext}}$ (″) | $\phi_s$ (%) | $C_{\text{pos}}$ (cts ks$^{-1}$) | $C_{\text{bgd}}$ (cts ks$^{-1}$) | $\sigma_{\text{bgd}}$ (cts ks$^{-1}$) | $C_{\text{bgd}}$ ± $\sigma_{\text{bgd}}$ (cts ks$^{-1}$) | $C_{\text{ub}}$ (nJy ks cts$^{-1}$) | $f_{\nu}^{\text{ub}}$ (nJy) | $f_{\nu}^{\text{ub},\text{th}}$ (nJy) | $f_{\nu}^{\text{ub},\text{th},\text{th}}$ (nJy) |
|--------|------------------------|------------------------|------------------------|-------------|------------------------|------------------------|------------------------|------------------------|------------------------|----------------|----------------|----------------|
| F438W  | 4326                   | 5160                   | 0.14                   | 81          | 47                     | 16 ± 24                | 102                    | 0.416                  | 52                     | 28             |                |                |
| F336W  | 3355                   | 5160                   | 0.12                   | 78          | 27                     | 13 ± 16                | 61                     | 0.470                  | 37                     | 20             |                |                |
| F225W  | 2366                   | 4932                   | 0.14                   | 74          | 46                     | 16 ± 17                | 82                     | 0.783                  | 87                     | 50             |                |                |

Note. $C_{\text{ub}}$ and $f_{\nu}^{\text{ub}}$ are the 3σ upper bounds; $f_{\nu}^{\text{ub},\text{th}}$ is the 1σ upper bound.

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8 https://www.eso.org/sct/software/cpl/esorex.html
9 For the VLT observation log, see Mignani et al. (2003).

10 Difference of the upper bounds at the two pulsar positions is due to different properties of the local backgrounds.
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Figure 4. $12^h50^m \times 11^d55'$ vicinity of the pulsar as seen with the VLT in the $U+B$ band (left) and with the HST/UVIS in the F438W+F336W band (right). North is up and east is left. Smoothing with the Gaussian kernel radius of 1 pixel is applied to the VLT image. The sources are numbered using the nomenclature of Mignani et al. (2003). Pulsar radio positions at the VLT epoch (2000) and the HST epoch (2016) are shown by yellow and red crosses, respectively. A faint source is marginally detected in the VLT image near the 2000 position of the pulsar, while it is absent in the HST image (for details, see Section 4.2).

Table 6
3σ Upper Bounds on Count Rate and Mean Flux Density at the Pulsar Radio Position, $\alpha = 01^h08^m08^s5314$ and $\delta = -14^\circ31'49''207$, at the VLT Observations Epoch (MJD 51752)

| Filter   | $\lambda$ (Å) | $t_{exp}$ (s) | $r_{sky}$ (″) | $\phi_r$ (%) | $C_{pos}$ (cts ks$^{-1}$) | $C_{bgd}$ ± $\sigma_{bgd}$ (cts ks$^{-1}$) | $C_{abh}$ (cts ks$^{-1}$) | $\gamma_d$ (nJy ks cts$^{-1}$) | $f_{\nu,10}$ (nJy) |
|----------|----------------|----------------|---------------|--------------|----------------|------------------------------------------|----------------|--------------------------|---------------|
| F438W    | 4326           | 5160           | 0.14          | 81           | 13             | 15 ± 17                                   | 50             | 0.416                    | 26             |
| F336W    | 3355           | 5160           | 0.12          | 78           | 6.4           | 12 ± 13                                   | 40             | 0.470                    | 24             |
| F225W    | 2366           | 4932           | 0.14          | 74           | 25            | 6 ± 13                                    | 59             | 0.783                    | 62             |
| F140LP   | 1528           | 2800           | 0.2           | 63           | 0.9           | 2.1 ± 0.6                                  | 1.8            | 1.61                     | 5              |

Note. For the F438W, F336W, and F140LP bands, $C_{pos} < C_{bgd}$, and the upper bounds are calculated as $C_{abh} = 3\sigma_{bgd}$.

counterpart, but further deep observations are needed to prove it.

5. Discussion

We likely detected the putative pulsar FUV counterpart in the F140LP band. Our photometric measurements show that its brightness is near the SBC detection threshold for the one-orbit HST observation. Three HST orbits would be needed to confirm the FUV counterpart at a 5σ significance. Nevertheless, the tentative detections with the HST ACS/SBC and VLT FORS1 U, B bands, combined with the upper bounds obtained in the UVIS (and VLT V) bands, as well as the Chandra and XMM-Newton X-ray data, can provide interesting constraints on the optical-UV-X-ray spectral energy distribution (SED) of this old pulsar.

5.1. Extinction toward PSR J0108−1431

According to the Galactic 3D extinction map by Green et al. (2018), the color excess $E(B−V)$ varies between 0.00 and 0.04 within the uncertainty of the distance to the pulsar, and $E(B−V) = 0.02^{+0.02}_{−0.01}$ for $d = 210$ pc.

The $E(B−V)$ value is correlated with the effective hydrogen column density $N_H$ for X-ray photoelectric absorption models. Applying the empirical relation $N_H = (0.7 \pm 0.1) \times 10^{22}E(B−V)$ cm$^{-2}$, obtained by Watson (2011) for the Galaxy using observations of X-ray afterglows of a large number of γ-ray bursts, we expect $N_H = 1.4^{+1.8}_{−0.8} \times 10^{20}$ cm$^{-2}$.

Alternatively, $N_H$ can be estimated using the pulsar’s dispersion measure, $DM = 2.38$ pc cm$^{-3}$, and the correlation between $DM$ and $N_H$ obtained by He et al. (2013). $N_H = 0.30^{+0.13}_{−0.09} \times 10^{23}$DM cm$^{-2}$, which yields $N_H = 0.71^{+0.31}_{−0.21} \times 10^{20}$ cm$^{-2}$, in agreement with the value derived from $E(B−V)$. This also overlaps with the $N_H$ range of $(0.3−0.8) \times 10^{20}$ cm$^{-2}$ at $d = 210$ pc obtained from the study of interstellar NaD absorption lines (Posselt et al. 2007, 2008).

Finally, the phase-integrated X-ray spectrum of the pulsar obtained with XMM-Newton is most plausibly described by the absorbed PL plus blackbody BB model with $N_H = 2.3^{+2.4}_{−2.3} \times 10^{20}$ cm$^{-2}$ (Posselt et al. 2012; Arumugasamy & Mitra 2019). The latter value is very uncertain but consistent with the above estimates.

All in all, we can accept $E(B−V) = 0.01−0.03$ as the most probable color excess range for dereddening of the optical-UV data and combining them consistently with the X-ray data.
Using this color excess range and the extinction law from Cardelli et al. (1989), we can calculate the extinction $A_V$ and the dereddened source flux density or its upper bound for all the bands where the pulsar was observed. These quantities are presented in Table 7 and Figure 5.

### 5.2. Multiwavelength Spectrum of PSR J0108–1431

Optical-UV emission from a rotation-powered pulsar generally consists of two components, thermal and nonthermal. The nonthermal component, produced by relativistic particles in the pulsar magnetosphere, is usually described by a PL model, $f_{\nu} \propto \nu^{\alpha}$, while the spectrum of the thermal component, emitted from the NS surface, is close to a blackbody spectrum (Mignani 2011). In middle-aged ($0.1\sim1$ Myr) and moderately old ($1\sim10$ Myr) pulsars, the nonthermal component dominates in the optical while the thermal component dominates in the FUV (e.g., Koptsevich et al. 2001; Zharkov et al. 2004; Shibanov et al. 2006; Kargaltsev & Pavlov 2007; Pavlov et al. 2017). However, we know too little about optical-UV emissions of pulsars as old as PSR J0108–1431; the only other very old pulsar, J2144–3933 with the age of 300 Myr, observed in the optical-UV, was not detected (Guillot et al. 2019). Therefore, we should explore various options and their connection with the results in X-rays where spectra of very old pulsars, including PSR J0108–1431, typically show only the PL component of the NS magnetosphere origin and a thermal component from small hot spots at the NS surface near magnetic pole regions heated by relativistic particles generated in its magnetosphere.

#### 5.2.1. Possible Power-law Spectrum of the Tentative Pulsar Counterpart

Assuming both optical ($B$ and $U$) and FUV (F140LP) detections were real, we can fit the unabsorbed flux density points with a PL model: $f_{\nu} = f_0(\nu/\nu_0)^\alpha$, where we choose the reference frequency $\nu_0 = 1 \times 10^{15}$ Hz. Following the approach suggested by Sawicki (2012) and developed by Drouart & Falkendal (2018), in addition to the three detected SED data points, we also included in the fits the four nondetections ($1\sigma$ upper bounds) in other filters presented in Table 7. Specifically, we used the Python package Mr-Moose (Drouart & Falkendal 2018), which allows data fitting in a Bayesian framework implementing the Markov Chain Monte Carlo (MCMC) approach. To do that, we included the FWHM of the HST and VLT filters into the filters directory of the Mr-Moose distributive. For the MCMC convergence, we utilized 1000 walkers and 1000 steps. The fitting parameters were the spectral index $\alpha$ and the PL normalization $f_0$, which were allowed to vary in wide ranges between $-1.7$ and $1.1$ for $\alpha$ and between $-31.2$ and $-30.5$ for $\log f_0$ (where $f_0$ is in units of erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$). Their best-fit values with uncertainties, corresponding to the 10th and 90th percentiles of the parameter...
distribution obtained by cumulative integration of the posterior probability density function, are presented in Table 7. Large uncertainties in the data result in large uncertainties of the PL parameters, and the parameter ranges are almost insensitive to \(E(B - V)\). As an example, we show the fit results for \(E(B - V) = 0.02\) in Figure 5, where the right panel shows the 1D and 2D marginalized posterior probability distributions of the parameters reflecting the fit convergence and quality. The fit results practically do not depend on the HST/UVIS flux upper bounds, while they are critically affected by the VLT upper bound in the \(V\) band. We also tried to include into the fit the VLT \(U\)- and \(B\)-band upper bounds of 2009, which are consistent with the detections in these bands of 2000 (see Section 1). This led to a marginal flattening of the best-fit PL.

For instance, we obtained \(\alpha \approx -0.57\) instead of \(-0.63\) without these upper bounds, for \(E(B - V) = 0.02\). Such a small difference is insignificant, accounting for the large error budget (see Table 7).

The obtained constraints on the spectral index of the pulsar’s nonthermal emission are compatible with (broader than) a typical range \(-0.7 \leq \alpha \leq 0.2\) for other pulsars observed in the optical-UV range (e.g., Mignani 2011; Mignani et al. 2019). The best-fit PL parameters correspond to the optical-UV flux \(F(1500-6000\,\text{Å}) = 2.3 \times 10^{-16}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}\) and luminosity \(L(1500-6000\,\text{Å}) = 1.2 \times 10^{27}d_{210pc}^{-2}\,\text{erg}\,\text{s}^{-1}\). Comparing the latter value with the FUV luminosities of pulsars that have been detected in this range (Mignani et al. 2019), we see that J0108–1431 might be the least luminous FUV pulsar. On the other hand, the efficiency of conversion of pulsar rotation energy to optical-UV radiation is \(\eta_{\text{opt-UV}} = L(1500-6000\,\text{Å})/\dot{E} = 2.4 \times 10^{-4}d_{210pc}^{2}\). Accounting for the distance and fit uncertainties, the efficiency could be anywhere in the range \(0.7 \leq \eta_{\text{opt-UV}}/10^{-4} \leq 5.9\). Even for lower values from this range, PSR J0108–1431 is the most efficient nonthermal emitter among pulsars detected in the optical-UV. For instance, based on the data obtained by Pavlov et al. (2017), the 17 Myr old PSR B0950+08 shows about a two-order-of-magnitude lower \(\eta_{\text{opt-UV}}\) of about \(6 \times 10^{-6}\) in the same range. A typical optical efficiency range of pulsars is \(10^{-7}–10^{-5}\); only the very young and much more energetic Crab and B0540–69 pulsars have efficiencies comparable to the above estimate for J0108–1431 (Zharikov et al. 2006; Mignani et al. 2010; Kirichenko et al. 2015).

On the other hand, the pulsar is also a highly efficient nonthermal emitter in X-rays with \(\eta_X \approx 0.003–0.006\) (Posselt et al. 2012). This results in the ratio of the nonthermal-optical-UV to the X-ray luminosity \(L(1500-6000\,\text{Å})/L_X \approx 0.02–0.04\), marginally compatible with the typical range of 0.001–0.01 for pulsars observed in the optical-UV and X-rays (Zavlin & Pavlov 2004; Zharikov et al. 2006).

It is interesting to compare the optical-UV spectrum of the pulsar candidate with the X-ray spectrum of PSR J0108–1431 obtained with XMM-Newton (Posselt et al. 2012; Arumugamasy & Mitra 2019). The latter presumably consists of a magnetospheric PL component and a thermal component emitted from hot polar caps. Using the XSPEC tool (ver. 12.11.0),\(^{11}\) we fit the time-integrated spectra obtained by the XMM-Newton EPIC-pn and MOS1 instruments in the 0.2–10 keV range with the absorbed PL+BB model at fixed \(N_{\text{H}} = 1.4 \times 10^{20}\,\text{cm}^{-2}\), corresponding to \(E(B - V) = 0.02\). We obtained the photon index \(\Gamma = 2.35^{+0.35}_{-0.40}\) (i.e., \(\alpha_X = -\Gamma + 1 = -1.35^{+0.35}_{-0.40}\)), the PL normalization \((1.4 \pm 0.4) \times 10^{-6}\,\text{ph}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}\) at \(E = 1\,\text{keV}\), the temperature \(k_B T_{\text{BB}} = 0.14^{+0.03}_{-0.02}\,\text{keV}\) (\(T_{\text{BB}} = 1.6^{+0.3}_{-0.2}\,\text{MK}\)), and the BB radius \(R_{\text{BB}} = 22^{+13}_{-10}\,\text{d}_{210\,\text{m}}\) (\(\chi^2 \approx 0.9\) for \(\nu = 20\) d.o.f.). The fit parameters are consistent, within the uncertainties (quoted above at a 1\(\sigma\) confidence level), with those obtained by Posselt et al. (2012), who fixed the photon index (at \(\Gamma = 2.0\)) instead of \(N_H\). The obtained temperature is within the range of typical BB temperatures of hot polar caps of old pulsars, while the BB radius is a factor of 10 smaller than the “canonical” cap radius \(R_{\text{can}} = R_{\text{NS}}(2\pi R_{\text{BB}}/cP)^{1/2} \approx 238\,\text{m}\) for \(P = 0.808\,\text{s}\), assuming a plausible intrinsic NS radius \(R_{\text{NS}} = 13\,\text{km}\). A similar discrepancy between \(R_{\text{BB}}\) and \(R_{\text{can}}\) is observed in other old pulsars (see Posselt et al. 2012; Szomjed & Geppert 2020, and references therein).

Figure 6 shows the fit for the absorbed and unabsorbed spectra, together with the PL fit to the optical-UV spectrum shown in Figure 5. We see that the continuation of the X-ray model spectrum dominated by the PL component into the optical-UV lies well above the optical-UV detections and upper limits. If we associate the optical-UV and X-ray PL components with the pulsar’s magnetosphere emission, we can conclude that its spectrum steepens with increasing photon energy toward X-rays and has a spectral break somewhere between the UV and soft X-rays, similar to other (younger) pulsars that were detected in both X-rays and the optical (e.g., Kargaltsev & Pavlov 2007). However, better quality data in both ranges are needed to make a convincing mult iwavelength spectral analysis.

Based on the high optical through X-ray efficiency of J0108–1431, one can speculate that for old pulsars, the highest efficiency range migrates from \(\gamma\)-rays toward lower photon energies.

### 5.2.2. Possibility of Thermal Emission in FUV and Limits on Surface Temperature

The main goal of these observations was to constrain the NS surface temperature. First of all, we note that if the optical emission allegedly detected with the VLT were thermal, then the FUV flux should be much higher than either its presumably measured value or the upper bound, at any reasonable temperature and size of the emitting NS surface. Therefore, we can rule out the temperature estimate by Mignani et al. (2008) derived from the assumption that the optical spectrum is an R-J part of thermal emission from the entire NS surface.

On the other hand, it is possible that the FUV emission is due, at least partly, to a thermal component. If the \(U\) and \(B\) detections are associated with the pulsar, then the relatively low upper limit on the \(V\) flux does not allow a steep negative slope of the PL component, which leaves little room for the thermal component in F140LP. If, however, the \(U\) and \(B\) detections are not associated with the pulsar while the F140LP detection is, then the F140LP flux could be entirely thermal. As seen from Figure 6, it cannot come from the hot polar caps of the pulsar seen in X-rays, but can only come from a cooler bulk surface of the NS. Assuming that the spectrum of the NS surface emission is described by the Planck function, \(B_\nu(T) = (2\pi\nu^3/c^2)\exp[\nu/(kT) - 1]^{-1}\), its brightness temperature can be estimated from the observed flux density,

\[
\dot{f}_\nu = (R_{\infty}/d)^2\pi B_\nu(T_{\infty})10^{-0.4A},
\]

where \(T_{\infty} = T/(1 + z)\) K and \(R_{\infty} = R(1 + z)\) km are the NS temperature and radius as measured by a distant observer, and

\(^{11}\) See https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec.
z = [1 – 2.953(M/M⊙)(1 km/R)]^{-1/2} – 1 is the gravitational redshift. For the F140LP filter (ν_{plv} = 1.96 × 10^{15} Hz, A_ν = 8.15E(B-V)), we have

\[ T_\infty = \frac{9.42 \times 10^4 K}{\ln \left[ 1 + \frac{187 nJy}{f_{140LP}} \left( \frac{R_{15}}{d_{210}} \right)^2 \right]^{-3.26E(B-V)}} \]  

(2)

where \( R_{15} = R_\infty / 15 \) km and \( d_{210} = d / 210 \) pc.

For plausible \( d = 210 \) pc, \( E(B-V) = 0.02 \), and \( R_\infty = 15.8 \) km (which corresponds to \( R = 13 \) km at \( M = 1.4M_\odot \)), the measured FUV flux density \( f_{140LP} = 9.0 \pm 3.2 \) nJy yields \( T_\infty = 3.1_{-0.3}^{+0.3} \times 10^4 \) K (\( T = 3.8_{-0.5}^{+0.5} \times 10^4 \) K). The optical-UV part of this thermal spectrum with its uncertainties is shown in the left panel of Figure 7. In the right panel of this figure, we show the dereddened thermal spectrum at the upper end of plausible distances, \( d = 300 \) pc, and the lower end of plausible radii, \( R_\infty = 13.1 \) km (corresponding to \( R = 10 \) km at \( M = 1.4M_\odot \)) (Lattimer & Prakash 2016) for the upper bound of the color index, \( E(B-V) = 0.03 \); these parameters correspond to a higher temperature, \( T_\infty = 4.8_{-0.4}^{+0.7} \times 10^4 \) K \( (T = 6.3_{-1.1}^{+0.8} \times 10^4 \) K). The spectrum is extrapolated toward X-rays, where the unabsorbed PL + BB fit of the XMM-Newton spectrum of the pulsar is also shown. We see that emission from the NS surface with such a temperature would not be detectable in the optical and X-rays. If we assume that the F140LP detection was not real, then the 3σ upper limit on the FUV flux density, \( f_{140LP} < 14 \) nJy, gives us an upper limit on the temperature—e.g., \( T_\infty < 5.9 \times 10^4 \) K \( (T < 7.7 \times 10^4 \) K) at \( d = 300 \) pc, \( R_\infty = 13.1 \) km, \( E(B-V) = 0.03 \) (the corresponding thermal spectrum is shown by the red line in the right panel of Figure 7).

It is interesting to compare the obtained constraints on the surface temperature of the 196 Myr old PSR J0108–1431 with those for other old pulsars. Based on the upper limit, \( T_\infty < 6 \times 10^4 \) K, we can conclude that PSR J0108–1431 is colder than the 17 Myr old PSR B0950+08, the only old
ordinary pulsar whose thermal emission has been detected, with $T_{\infty}$ in the range of $(1-3) \times 10^4$ K (Pavlov et al. 2017).

If the F140LP detection of thermal emission from PSR J0108–1431 was real, then the plausible temperature range, $T_{\infty} \approx (2.7-5.5) \times 10^4$ K, is just slightly above the conservative upper limit, $T_{\infty} \lesssim 3.2 \times 10^4$ K, for the 330 Myr old PSR J2144–3933 (Guillot et al. 2019). The highest temperature of this range is lower than the surface temperature, $T_s \approx (1.2-3.5) \times 10^5$ K, of the 7 Gyr old nearest millisecond (recycled) pulsar (MSP) J0437–4715 (Kargaltsev et al. 2004; Durant et al. 2012; González-Caniulef et al. 2019). It means that either thermal evolution of NSs is not monotonic or it proceeded differently for J0108–1431 and J0437–4715, e.g., because old ordinary and recycled pulsars have some different properties, including periods and their derivatives, magnetic field strengths and masses (González-Jiménez et al. 2015).

Confirmation of the possible detection of thermal emission from J0108–1431 would mean that it is the coldest NS whose thermal emission has been detected, but its temperature is still high enough to support the idea that NSs do not just cool passively but that some heating mechanisms strongly affect their thermal evolution. According to passive cooling scenarios, cooling of isolated NSs becomes exponentially fast at ages of a few Myr after which thermal emission from their surfaces becomes undetectable (e.g., Yakovlev & Pethick 2004). However, this rapid cooling can be partly compensated by a number of heating mechanisms. One of them is the so-called rotochemical heating due to composition changes (such as the neutron beta decay) forced by density increase as the centrifugal force decreases in the course of NS spindown (Reisenegger 1995; Fernández & Reisenegger 2005). This heating mechanism has a minor effect on the surface temperatures of young NSs but its contribution can dominate at ages $\gtrsim 10$ Myr. Another important mechanism is “frictional heating” caused by the interaction of vortex lines of the faster-rotating neutron superfluid with the slower rotating normal matter in the inner NS crust (Alpar et al. 1984; Larson & Link 1999).

According to the top panel of Figure 5 of Guillot et al. (2019), the upper bound on the (unredshifted) surface temperature of PSR J0108–1431, $T \lesssim 8 \times 10^4$ K, is consistent with the values predicted by the models of rotochemical heating by González & Reisenegger (2010) for a 200 Myr old pulsar with the surface magnetic field of $2.4 \times 10^{13}$ G and initial period at birth of 1 ms, assuming either modified Urca reactions or direct Urca reactions with additional frictional heating with excess angular momentum $J = 1 \times 10^{46}$ erg s (the predicted temperatures are very close to each other at these parameters). This is similar to the younger PSR B0950+08. However, if the FUV thermal emission was actually detected, then the observed temperature range $T \sim (3-7) \times 10^4$ K lies between these predictions and the low-temperature boundary provided by the direct Urca models without frictional heating. This would mean that frictional heating is less efficient in PSR J0108–1431 than in PSR B0950+08. To obtain tighter constraints on heating mechanisms, one should re-observe PSR J0108–1431 with deeper exposures as well as observe more old pulsars in the optical-UV.

6. Conclusions

We observed the field of the nearby 196 Myr old PSR J0108–1431 with the HST in four optical-UV bands. We detected a point-like FUV source in the F140LP band at about $3\sigma$ significance level with coordinates coinciding with the position of the pulsar within the 1$\sigma$ uncertainty of 0''.2. We consider this source as a possible FUV counterpart of PSR J0108–1431. Also, we placed upper limits on the flux densities of the pulsar in the F225W, F336W, and F438W bands. Using more accurate astrometry, we confirmed the $3\sigma$ detection of the optical source at the pulsar position in the year 2000 in the VLT U+B filters and its upper limit in the V filter, reported earlier by Mignani et al. (2008).

Assuming that the possibly detected F140LP, $U$, and $B$ emission come from the pulsar counterpart, we analyzed its multiwavelength spectral energy distribution, including the archival X-ray data obtained with XMM-Newton. We found that the spectral flux density distribution can be described by a PL model in the optical-UV part, suggesting its magnetospheric origin. The spectrum becomes steeper in X-rays, implying a spectral break between the UV and X-ray ranges. Such behavior is typical for pulsars observed in both ranges. The pulsar has a record high efficiency, $\eta \sim 10^{-2}$, of transformation of the spin-down power to nonthermal (magnetospheric) radiation in the optical-UV through X-rays.

In the FUV band, the pulsar emission might be dominated by thermal emission from the bulk of the NS surface. If this is the case, the NS surface temperature is in the range of $(3-6) \times 10^4$ K, as seen by a distant observer—the lowest NS temperature ever measured. At the same time, it is much higher than predicted by scenarios of passive NS cooling at this NS age, which could be due to heating mechanisms operating in the NS interiors. A conservative consideration of the FUV data point as an upper bound yields the $3\sigma$ upper limit on the NS brightness temperature, $T_{\infty} < 6 \times 10^4$ K.

Detection of PSR J0108–1431 in the optical and UV bands at higher significance levels is needed to confirm the counterpart and study its properties.

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