Confirming the nature of the knot near the pulsar B1951+32

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Abstract.

The energetic and fast-moving radio and $\gamma$-ray pulsar B1951+32 is associated with the supernova remnant CTB 80. It powers a complex pulsar wind nebula detected in the radio, H$\alpha$ and X-rays (Moon et al 2004 ApJ 610 L33). A puzzling optical knot was detected about $0.5\arcsec$ from the pulsar in the optical and near-IR (Moon et al 2004 ApJ 610 L33; Hester 2000 Bulletin of the AAS 32 1542). It is reminiscent of the unique “inner optical knot” located $0.6\arcsec$ from the Crab pulsar. Until now there has been no evidence that B1951+32 knot is indeed associated with the pulsar.

We observed the pulsar field with the Gemini-North telescope in 2016 to check the association. We performed first near-IR high spatial resolution imaging in the $K_s$ band using the NIRI+Altair instrument and deep optical imaging in the $gr$ bands using the GMOS instrument.

Our observations showed that the current knot position is shifted by $\approx 0.6\arcsec$ from the position measured with the HST in 1997. This is consistent with the known pulsar proper motion and is direct evidence of the pulsar–knot connection. We compared the spectral energy distribution of the knot emission with that of the Crab knot. Possible implications of the results are discussed.

1. Introduction

Pulsar wind nebulae (PWNe) are formed as a result of interaction of a relativistic pulsar wind with ambient matter. The wind consists of particles accelerated in magnetospheres of rotation-powered pulsars. It propagates freely until it experiences a collisionless termination shock (TS). The shocked wind streams out at $\sim 0.3 - 0.5c$, producing synchrotron emission observed from the radio to X-rays [1]. The PWNe generally show two morphological types. Around young pulsars they usually appear as X-ray tori with polar jets. The classical examples are the Crab [2] and the Vela [3]. Subarcsecond optical imaging of the Crab [4] revealed puzzling knots and wisps. The so-called inner knot located at only $0.6\arcsec$ from the Crab pulsar is projected onto the free wind zone upstream of the TS, where no emission from the unshocked wind is expected [5]. More distant wisps are interpreted as Doppler-boosted emission from the equatorial zones of the shocked wind [6]. Extensive studies of the knot and wisps in the Crab revealed their temporal and spectral variability providing insight into the complex dynamics of non-stationary relativistic flows. Another type is bullet-shaped PWNe with long tails seen around pulsars moving through the ambient medium with a supersonic velocity. In this case, the overall PWN geometry is governed by the ram pressure of the oncoming medium flow, and both the TS and
Figure 1. Left: X-ray image of the PWN associated with SNR CTB 80. The pulsar position is marked by the cross. The arrow shows the pulsar proper motion direction. The X-ray spectrum of the “knot+pulsar” (figure 3) was extracted from the white ellipse. Right: g’ band image of the PWN obtained with Gemini-N. The PWN emission is dominated by the Hβ Balmer line, excited by the interaction of the pulsar wind with ambient matter. The pulsar and the knot are within the black dashed rectangle region, which is enlarged in figure 2.

the forward shock (FS) in the ambient medium acquire a bow-shock shape ahead of the moving pulsar. Intermediate types are possible for transonic motion.

An example of the latter type is the PWN around the 51 kyr old, fast-moving ($\mu = 32.3 \pm 0.9$ mas yr$^{-1}$ [7]; $v_\perp \approx 225$ km s$^{-1}$ for $d = 1.5$ kpc), energetic ($\dot{E} \approx 3.7 \times 10^{36}$ erg s$^{-1}$) PSR B1951+32, associated with the supernova remnant (SNR) CTB 80. The age is consistent with the pulsar proper motion (p.m.) shift from the SNR centre [7], and we accept the distance of 1.5 kpc recently estimated from HI studies [8]. The PWN demonstrates a bow-shock morphology in the radio, X-rays, and Hα, allowing one to determine the TS and FS positions [9]. The nebula is superimposed on the SNR limb, and the ambient medium may thus be over-pressured with respect to the general ISM. The unique feature is a compact optical knot at 0′′5 from the pulsar detected with the HST in the F547M band [10]. It has dimensions of 0′′8 × 1′′3 and, as the Crab inner knot, it is projected onto the pulsar proper-motion path. It was confirmed by ground-based observations in the r and Ks bands in 2001 and 2003 [9]. The data suggest a flat energy spectrum with $F_\nu = 40 \pm 10$ µJy, implying non-thermal nature of the knot emission. However, the fluxes in different bands were obtained at different epochs. Based on the Crab knot studies, the knot temporal variability is expected, and the spectral flatness needs a confirmation by simultaneous observations in different bands. There still is no direct evidence that the knot is not a background object. The evidence can be obtained by measuring its p.m. and comparing it with the known p.m. of the pulsar. Here we briefly report results of the new near-infrared and optical observations of the PSR B1951+32 field.

2. Observations with Gemini-North
The pulsar B1951+32 field was observed in June-July 2016 with the ALTtitude conjugate Adaptive optics for the InfraRed (ALTAIR) connected with the Near InfraRed Imager and Spectrometer (NIRI), and with the Gemini Multi-Object Spectrograph (Gmos) mounted on the Gemini-North telescope. The observations were carried out in the Ks, g’ and r’ bands.
Figure 2. *Left:* HST image of the knot region obtained in 1997 in the F547M band. The “1HST” circle within the knot extended emission marks the position of the possible pulsar optical counterpart reported in [10]. *Middle:* Gemini-N image of the same field obtained in 2016 in the g’ band. The black and white contours in this and the left panel show the knot boundaries defined at 3σ level in 1997 and 2016, respectively. The black arrow demonstrates the pulsar p.m. shift between 1997 and 2016. As seen, the knot contour shift is consistent with that of the pulsar. *Right:* Gemini-N high spatial resolution image of the field obtained in 2016 in the Ks band. The small circle demonstrates the expected position of the “1HST” source in 2016 if it would be the real pulsar counterpart. However, no point source is detected there. The large black circle labelled as “radio” is the pulsar radio position error circle in 2016. A new pulsar counterpart candidate, marked by the cross, is detected near the edge of the radio circle.

3. Results
The main results are presented in figures 1–3. The PWN shock structure in the optical is quite complex (figure 1), likely due to the interaction with the SNR limb. Comparing the images obtained in the g’ and HST/F547M bands (figure 2), whose band-passes are close to each other, we found that the knot was shifted by ≈ 0".6 between the epochs of the observations with the HST (1997) and Gemini-N (2016). The shift value and direction approximately coincide with the pulsar p.m. shift of 0".61 ± 0".02 with the position angle of 249° ± 2°. This is direct evidence of the pulsar-knot association. In Ks the knot is more extended and brighter in the north–east direction than in g’. In general, it is much less compact than the Crab inner knot. A new near-IR pulsar counterpart candidate is detected in the Ks band near the edge of the radio pulsar position error circle, while the previous candidate proposed in [10] is not detected (figure 2).

The knot optical-IR spectral energy distribution (SED) is almost flat, with the spectral index αν ≈ 0.14 (figure 3), which is different from the steep SED of the Crab inner knot [11]. This can be related to different compactness and physical nature of the knots. To compare the optical and X-ray data, we extracted the X-ray spectrum of the knot+pulsar from the ellipse in figure 1, using *Chandra* archive, fitted it with the thermal + non-thermal model, and adopted the non-thermal component of the pulsar X-ray spectrum from [12]. It is hard to distinguish the non-thermal pulsar and knot contributions in X-rays (figure 3). Nevertheless, it is obvious that the spectrum of the knot should have a break between the optical and X-rays with ∆αν ≥ 0.5. The flux of the new pulsar counterpart candidate lies significantly below the long-wavelength extrapolation of the presumed pulsar nonthermal X-ray spectrum, as is typically observed for pulsars detected in both ranges. The thermal component is negligible in the optical.

4. Conclusions
We resolved a complex structure of the PSR B1951+32 bow-shock PWN in the optical and found strong evidence that its puzzling knot is indeed associated with the pulsar. In the near-IR.
Log _{10}^{\nu}[\text{Hz}]$ 

$F_\nu[\mu\text{Jy}]$ 

$X$-rays

$\alpha_\nu=0.63\pm0.05$

$\alpha_\nu=0.63\pm0.03$

$\alpha_\nu=0$

$\alpha_\nu=0.14\pm0.09$

Av=2.48

Figure 3. Left: Near-IR–X-ray SEDs of the knot and the pulsar corrected for interstellar absorption $A_V=2.48$. Black optical–near-IR data points are taken from [9], while blue ones are obtained in this work. The knot+pulsar and the presumed pulsar X-ray spectra with their uncertainties are shown by black and red lines. The near-IR pulsar counterpart candidate flux is shown by red. Right: The closeup view of the optical–near-IR knot SED. Blue lines show the power-law fit to the fluxes obtained in this work and its uncertainties.

the knot is more extended than in the optical. Its SED is almost flat in the optical–near-IR, which together with the X-ray data implies a spectral break between these ranges. We did not detect the possible pulsar optical counterpart suggested in [10]; however, we found a new near-IR pulsar counterpart candidate near the edge of the pulsar radio position error circle.

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References

[1] Kargaltsev O and Pavlov G G 2008 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More (American Institute of Physics Conference Series vol 983) ed Bassa C, Wang Z, Cumming A and Kaspi V M pp 171–85 (Preprint 0801.2602)

[2] Weisskopf M C et al 2000 ApJ 536 L81–4 (Preprint astro-ph/0003216)

[3] Pavlov G G, Kargaltsev O Y, Sanwal D and Garmire G P 2001 ApJ 554 L189–92 (Preprint astro-ph/0104264)

[4] Hester J J et al 1995 ApJ 448 240

[5] Kennel C F and Coroniti F V 1984 ApJ 283 694–709

[6] Komissarov S S and Lyubarsky Y E 2003 MNRAS 344 L93–6 (Preprint astro-ph/0306162)

[7] Zeiger B R, Brisken W F, Chatterjee S and Goss W M 2008 ApJ 674 271–7 (Preprint 0801.0244)

[8] Leahy D A and Ranasinghe S 2012 MNRAS 423 718–24

[9] Moon D S, Lee J J, Eikenberry S S, Koo B C, Chatterjee S, Kaplan D L, Hester J J, Cordes J M, Gallant Y A and Koch-Miramond L 2004 ApJ 610 L33–6 (Preprint astro-ph/0406240)

[10] Hester J 2000 American Astronomical Society Meeting Abstracts (Bulletin of the American Astronomical Society vol 32) p 1542

[11] Sandberg A and Sollerman J 2009 A&A 504 525–30 (Preprint 0906.2065)

[12] Li X H, Lu F J and Li T P 2005 ApJ 628 931–7 (Preprint astro-ph/0504293)