B1951+32 pulsar bow shock proper motion measurements based on Gemini North 8-m telescope and HST optical observations

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Abstract. Using deep optical images of the core of the CTB 80 supernova remnant, obtained with 8-m Gemini-North telescope in 2016, and archival HST images of 1997, we measured the proper motion shift of a bright [OIII] structure ahead of the fast moving pulsar B1951+32 associated with the remnant. An arc shape of the structure suggests that it is a bow shock created by the supersonic motion of the pulsar in the ambient matter, while no direct evidence of that have been presented. The measured arc shift of \(\approx 0.53'\) is compatible with the pulsar proper motion shift of \(\approx 0.6'\) based on the radio interferometry measurements. This strongly supports the bow-shock nature of the structure.

1. Introduction

The 39.5 ms radio and \(\gamma\)-ray pulsar B1951+32 is associated with the supernova remnant (SNR) CTB 80 and powers a complex pulsar wind nebula (PWN) detected in the radio, optical and X-rays [1]. An arc-like feature near the pulsar, particularly clearly visible in the radio [2] and in the optical [OIII] emission line [3], is interpreted as a bow shock created by this pulsar moving in the ambient matter with a supersonic velocity whose transverse component \(v_\perp \approx 225 \text{ km s}^{-1}\) (for the distance \(d = 1.5 \text{ kpc}\)) was measured in the radio [4]. The arc is consistent with the shape of the PWN in X-rays and can be barely resolved among irregularly shaped structures of SNR filaments and knots in H\(\alpha\) and [SII] images [1, 5]. If the arc is indeed the bow shock, it should move together with the pulsar. However, no direct measurements of its motion were reported. Optical spectroscopy reveals radial velocities in the range from \(-200\) to \(+200\) km s\(^{-1}\) for bright SNR filaments and up to 450 km s\(^{-1}\) for faint ones [5]. They reflect the overall kinematic structure of the expanding remnant and PWN but not the specific motion of the presumed bow-shock. Here we present first measurements of the arc motion which give evidence of its bow-shock nature based on Gemini-North and HST direct images obtained at a 19 yr time span.

2. HST and Gemini-North observations

HST. The CTB 80 core field containing the pulsar and its PWN was observed on October 1997 with the HST (Proposal 6858, PI J. Trauger) using the Wide Field and Planetary Camera 2
The observations were carried out using the narrow width filters F502N (centered on the [OIII] line), F656N (centered on the Hα line) and F673N (centered on the [SII] line) and a medium width filter F547M that contains no bright emission lines (table 1). The data were downloaded from the Mikulski Archive for Space Telescopes (MAST). We used drz images (calibrated and corrected for geometric distortion). Two exposures were taken for each filter which were combined to produce resulting images. The F502N image shown in the left panel of figure 1 represents the PWN structure in [OIII]. Its bright south-west arc was assumed to be the pulsar bow-shock [3]. Therefore, we use this image to determine the arc position in 1997.

### Table 1. HST observations of CTB 80

| Start time       | Instrument | Filter | Central wavelength, Å | $T_{exp}$ (s) |
|------------------|------------|--------|-----------------------|----------------|
| 1997-10-02 11:14:13 | WFPC2      | F502N  | 5012.0                | 2700           |
| 1997-10-02 12:51:13 | WFPC2      | F502N  | 5012.0                | 2700           |
| 1997-10-02 09:38:13 | WFPC2      | F547M  | 5483.0                | 1300           |
| 1997-10-02 10:02:13 | WFPC2      | F547M  | 5483.0                | 1300           |
| 1997-10-02 06:26:13 | WFPC2      | F656N  | 6564.0                | 2600           |
| 1997-10-02 08:01:13 | WFPC2      | F656N  | 6564.0                | 2700           |
| 1997-10-02 14:28:13 | WFPC2      | F673N  | 6732.0                | 2700           |
| 1997-10-02 16:05:13 | WFPC2      | F673N  | 6732.0                | 2700           |

**Gemini-North.** Our observations of the CTB 80 core were made in June-July 2016 with the Gemini Multi-Object Spectrograph (GMOS) mounted on the Gemini-North 8-m telescope. The observations were carried out in the $g'$ and $r'$ bands (table 2). We used only 2016.07.14 data, because of their highest quality. Standard data reduction was performed using GMOS IRAF utilities. As seen from the right panel of figure 1, the $g'$ image reproduce well the main features of the HST [OIII] image, including the bright arc structure. This is because this band includes the bright [OIII] line which dominates the arc emission. Much weaker Hβ emission is also captured by the band. It is responsible for fainter structures ahead and inside the arc which are not seen in the HST narrow band image. We can determine the arc position at the Gemini-North observation epoch and compare it with the HST one to measure the possible shift between the epochs.

### Table 2. Gemini-North GMOS observations of CTB-80

| Date      | Filter  | Effective wavelength, nm | Number of frames | $T_{exp}$ (s) | Seeing, arcsec |
|-----------|---------|--------------------------|------------------|---------------|----------------|
| 2016-06-24 | $g'$ (G0301) | 475                      | 2                | 66            | 0.61           |
| 2016-06-24 | $r'$ (G0303)  | 630                      | 6                | 180           | 0.55           |
| 2016-07-14 | $g'$ (G0301) | 475                      | 37               | 1221          | 0.54           |
| 2016-07-14 | $r'$ (G0303)  | 630                      | 17               | 510           | 0.54           |
Figure 1. 1'×1' images of the CTB 80 core obtained with the HST in the [OIII] line in 1997 (top) and with Gemini-North in the $g'$ band in 2016 (bottom). The white cross shows the pulsar position. Regions within white boxes are expanded in figure 2. Colour bars show intensity values in count rates and in counts for the HST and Gemini images, respectively.
Figure 2. Zoomed-in regions within the boxes in figure 1. The arrow shows the pulsar proper motion direction. White solid and dashed lines represent positions of the arc structure, i.e., the presumed bow-shock, in 1997 and 2016, respectively, demonstrating its shift.

3. Astrometry
We used the GAIA DR2 Catalog and the IRAF tasks *imcentroid* and *ccmap* to obtain astrometric solution for the GMOS images. We used 10 catalogued stars with proper motions
Figure 3. Structure of the eastern PWN part as it is seen with the HST and Gemini-North in Hα (top) and in the r′ band (bottom), respectively. White solid and dashed lines represent positions of two bright filaments in 1997 and 2016, respectively.

less then 5 mas yr$^{-1}$ within the GMOS field of view (FOV) and got the root-mean-square (rms) fit residuals of 0.016″ in the right ascension (RA) and 0.041″ in the declination (Dec) for the $g′$
band image. For the GMOS $r'$ image we got $0.017''$ (RA) and $0.039''$ (Dec) rms residuals. We aligned the HST images to the $g'$ image using 9 secondary standards. We got $0.023''$ (RA) and $0.043''$ (Dec) rms residuals for [OIII] and $0.019''$ (RA) and $0.042''$ (Dec) rms for H$\alpha$ images.

4. Results
We measured the $0.53'' \pm 0.11''$ shift of the bow shock structure between 1997 and 2016 epochs in the pulsar proper motion direction. The shift is demonstrated by white contours in figure 2. Based on the pulsar proper motion measurements [4], the respective pulsar shift is $0.6'' \pm 0.02''$. Within errors it is consistent with the structure shift thus confirming its bow-shock nature.

Alternatively, the arc shift could be just due to an overall PWN expansion which transverse velocity at given epoch coincides by chance with the pulsar’s transverse velocity. To check that, we measured shifts of two bright H$\alpha$ filaments in the eastern part of the PWN using our $r'$ image revealing H$\alpha$ emission and the HST H$\alpha$ image (figure 3). As a result, we found that their shifts of about $0.3''$ are significantly smaller than those of the pulsar and the arc. This makes the expansion hypothesis less plausible. Respective transverse velocities of the filaments of about $100$ km s$^{-1}$ are consistent with the radial velocity range for bright filaments obtained from spectroscopy [5].

5. Conclusions
Using HST and Gemini-North optical images obtained at the time base of 19 yr, we measured the proper motion shift of the bright arc structure ahead of the fast-moving pulsar B1951+32. The shift is compatible with the pulsar proper motion shift, which provides direct evidence on the pulsar bow-shock nature of the structure. Spectral observation of the structure in the [OIII] line would be useful to measure its radial velocity and to establish 3D structure of the bow shock.

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