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MERLIN Observations of PSR B1951+32 and its associated plerion

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Abstract. In an investigative 16 hour L-band observation using MERLIN, we have resolved both the pulsar PSR B1951+32 and structure within the flat spectral radio continuum region, believed to be the synchrotron nebula associated with the interaction of the pulsar and its 'host' supernova remnant CTB 80. The dimensions of the extended structure suggests a sharp bow shaped arc of shocked emission which correlates with similar structure seen in lower resolution radio maps and X-ray images. This is the first time such emission has been detected at ~150 mas in the radio. We present the implications of these results and the initial results from a deep follow-up MERLIN observation.

1. Introduction

Placed in a theoretical context, multi-wavelength observations of known pulsar/plerion/supernova remnant (SNR) associations are important in extending our empirical datasets with which to test evolving models. A 'young' pulsar/SNR/X-ray plerion association that provides a working laboratory with which to test our understanding of such interactions is that of the young radio, X-ray and γ-ray pulsar PSR B1951+32 associated with the CTB 80 SNR.

Early radio and X-ray observations noted a central plerion/spectrally flat region to the SW of the SNR, within which PSR B1951+32 was detected, located within a concentration of nebular emission towards one edge of the flat spectral region (Strom et al. 1984). The association is valid based on this clear interaction between pulsar and remnant, with similar pulsar canonical age (107 kyr) and dynamically derived SNR age ($9.6 \times 10^4 d_{2.5\,\mathrm{kpc}}$ yr). In contrast to other young SNR systems such as the Crab, it appears that the older PSR B1951+32 has caught up with its expanding remnant, resulting in the observed complex multi-wavelength emission.

Chandra data of the system clearly shows a cometary pulsar wind nebula which appears to be confined by a bow shock produced by the high velocity motion of the pulsar, which corresponds to Strom's previously defined radio 'hot spot' (Moon et al. 2004). Interestingly, Moon et al. indicate that there are spatial discrepancies in the boundaries of the X-ray emission, radio emission and the H_α bow shock as one moves away along the line of the pulsar's proper motion. Broadband optical/IR photometry have also indicated the presence of a synchrotron 'knot', as originally reported by

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Hester (2000) embedded within the cometary head observed by Chandra.

The key to resolving many of the outstanding aspects of the the system's multi-wavelength geometry is a rigorous astrometric reference frame. In this article we report two L-Band observations, one year apart, of the pulsar-'hot spot' system obtained with the MERLIN radio interferometer. Both objects were resolved at a resolution of 150 mas, and despite the relatively low signal to noise of the extended emission associated with the shock front in the 2002 data, we have been able to re-examine existing multi-wavelength data using the MERLIN data as the astrometric reference.

2. Observations & Data Analysis

On January 19th 2002, a 16 hour L-band MERLIN observation was performed on the central 'flat' region centred on PSR B1951+32. The pulsar is clearly evident, and its position as obtained during this observation with MERLIN is determined to be α 19:52:58.204, δ +32:52:40.53. There is also a significant ($\sim$ 4.5 σ) detection of a structure within the anticipated 'hot-spot' some 4" SW of the pulsar, of approximate dimensions 2.5" by 0.75", with the pulsar's motion approximately bisecting the observed emission.

Follow-up observations were obtained during the months of April, May, & June of 2003. With the improved dynamic range we have placed the peak of the shock at a distance of 2.3" from the pulsar.

3. The Optical Synchrotron Knot

The optical knot, identified in 2000 (Hester 2000) with HST F547M observations, can now be placed in its correct astrometric context given this MERLIN dataset. In figure 2 we indicate the central region of the HST WFPC2 field, which has been smoothed using a gaussian function with radius 0.5 units. Morphologically, the knot resembles a teardrop like structure, of dimensions 0.8" $\times$ 1.3". What of the optical knot structure in this regard? Its approximate length along the direction of the pulsar's motion is $\sim$ 1.3" - given the pulsar's

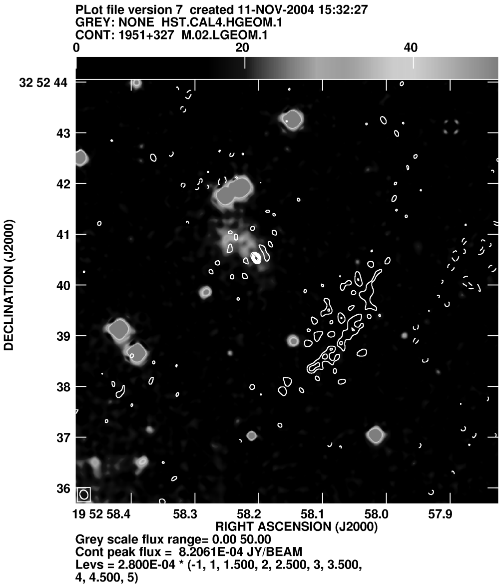


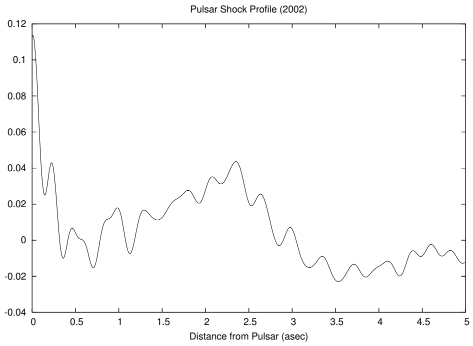
Fig. 1. MERLIN & HST images of shocked region.

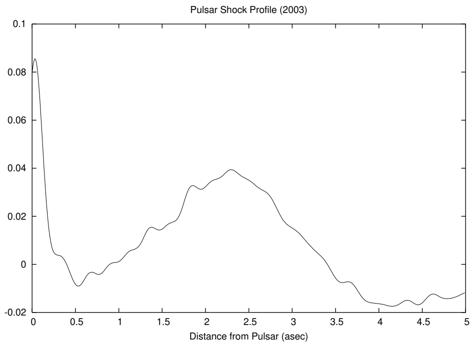
proper motion - and this suggests a timescale of $\sim$ 50 yr, assuming the knot's emission is a consequence of 'cooling' synchrotron particles. One can use this assumed cooling time, and the energy of these optical photons to constrain the previous equation to yield a value for B_{eq}, which comes to $\sim$ 600 μG. As this value is not inconsistent with the previous studies, it does appear to confirm the relatively high ambient magnetic field around the pulsar within the cometary 'cloak'.

4. Shock Profiles

Using previous proper motion measurements (Migliazzo et al. 2002) as a basis, we generated emission profiles along the direction of motion of the pulsar. Given that we have multi epoch data this lets us characterise the stand-off distance as a function of time. Understanding precisely how this pulsar interacts with its environment will provide perhaps uniquely an important insight into this stage of pulsar evolution.

From a first order analysis of the data it appears that the stand-off distance hasn't changed between the two epochs. The main difference





been that the shock appears broader on its leading edge. Given the poor signal to noise of the 2002 data it is difficult to say whether this is a real effect or simply a consequence of the low dynamic range in the 2002 data.

5. Astrometry

MERLIN's astrometric fidelity also provides us with an a reference frame of unprecedented accuracy for studying the dynamics of this object. With respect to the motion of the pulsar, the 2002 epoch measures the pulsar at:

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RA  19 52 58.20428    +/-  0.002
DEC 32 52 40.5318    +/-   0.03
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The 2003 epoch measurement is as follows:

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RA  19 52 58.20227    +/-  0.002
DEC 32 52 40.5063    +/-  0.025
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giving a movement of 36 mas over a period of 1.4 yr. This is in very good agreement with Migliazzo et al.'s measurements.

6. Conclusions

We have resolved both the pulsar and apparent fine structure within the 'hot spot' identified at lower resolution and believed to be a consequence of the pulsar wind interacting with swept up ISM/SNR material.

Astrometrically, we have used the MERLIN data to register the previously 2MASS astrometrically corrected archival HST observations of the field. Combined, these data indicate that the previously identified optical 'knot' of synchrotron emission extends behind the pulsar, along a line that bisects the shock front emission. The dimensions of the optical knot and the VLA determined proper motion argue for a synchrotron cooling time inconsistent with particle replenishment from the pulsar wind, and suggest that the knot is a consequence of quasi-stationary shock structures previously identified with the Crab pulsar. Finally, the MERLIN data rules out the putative optical counterparts (Butler et al. 2002), (Moon et al. 2004) to PSR B1951+32, and provides an unambiguous error box with which to assist future high time resolution searches.

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