A Radio Study of the Mouse, G359.23–0.82

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Abstract

The recent detection of a young pulsar powering “the Mouse”, G359.23–0.82, as well as detailed imaging of surrounding nebular X-ray emission, have motivated us to investigate the structural details and polarization characteristics of the radio emission from this axisymmetric source with a supersonic bow shock. Using polarization data at 3.6 and 6cm, we find that the magnetic field wraps around the bow shock structure near the apex of the system, but downstream runs parallel to the inferred direction of the pulsar's motion. The rotation measure (RM) distribution of the Mouse also suggests that the low degree of polarization combined with a high RM ahead of the pulsar result from internal plasma within the bowshock region. In addition, using sub-arcsecond radio image of the Mouse, we identify modulations in the brightness distribution of the Mouse that may be associated with the unshocked pulsar wind behind the pulsar. Lastly, we discuss the relationship between the Mouse and its neighboring shell-type supernova remnant G359.1–0.5 and argue that these two sources could potentially have the same origin.

Key words: ISM: individual: (G359.23–0.82), pulsars: individual (J1747–2958), stars: neutron, stars: winds, outflows

1 Background

G359.23–0.82 (“the Mouse”), with its long axisymmetric nonthermal nebula extending for 12 arcminutes, was first discovered as part of a Very Large Array (VLA) radio continuum survey of the Galactic center at 20cm (Yusef-Zadeh and Bally 1987). A bow-shock structure was noted along the eastern edge of the nebula (Yusef-Zadeh and Bally 1989). In addition, radio continuum data show
linearly polarized emission from the full extent of the nebula and the spectral index distribution between 2, 6 and 20cm remains flat at the head of the nebula but steepens in the direction away from the head of the Mouse (Yusef-Zadeh and Bally 1989). The detection of X-ray emission from this source and the identification of a young radio pulsar G359.23–0.82 at the head of the nebula resulted in a breakthrough in our understanding of what powers this source (Predehl and Kulkarni 1995; Sidoli et al. 1999; Camilo et al. 2002). More recently, Chandra observations show detailed structural and spectral characteristics of this bow-shock pulsar wind nebula (PWN) associated with the Mouse (Gaensler et al. 2004). Modeling of the X-ray emission suggests a high space velocity \( \approx 600 \text{ km s}^{-1} \) in a relatively warm phase of the ISM in order to explain the cometary morphology of this source.

The region where the Mouse is found contains a number of other nonthermal radio continuum sources. Figure 1 shows a large-scale 20cm view of this region where two shell-type supernova remnants (SNRs) G359.1–0.5 and G359.1–0.2, and a southern segment of a nonthermal radio filament G359.1–0.2, known as the “Snake”, are distributed (Reich & Fürst 1984; Gray et al. 1991; Yusef-Zadeh, Hewitt and Cotton 2004). The shell-like SNR G359.1-0.5 has a diameter of about 20' and the extension of the tail of the Mouse appears to be pointed toward the center of this remnant. Here, we present high-resolution radio images showing new structural details of the Mouse. Using polarization data, we present the distribution of the magnetic field and the rotation measure of the bow-shock region of the nebula. We also argue that the Mouse and SNR G359.1–0.5 are potentially associated with each other.

2 Observations and Results

Using the VLA in its BnA array configuration, we reduced the archival data taken in 1999 October at 3.6cm wavelength. Standard calibrations were carried out using 3C 286 and IERS B1741–312 as amplitude and phase calibrators, respectively. We also calibrated and combined the 6 and 2cm data taken in 1987 November and 1988 February in the BnA and CnB array configurations, respectively. 3C 286 and NRAO 530 were selected as the phase and amplitude calibrators for the 6 and 2cm data. Using different robust weighting to the \( uv \) data, the final images were constructed after phase self-calibration was applied to all 6, 3.6cm and 2cm data. The spectral index distribution of the Mouse based on these measurements will be given elsewhere. We believe that the scale lengths of the features that are described here are well-sampled in the \( uv \) plane. In particular, the best well-sampled baselines range between 10 and 550 k\( \lambda \) at 3.6cm and and 5 and 250 k\( \lambda \) at 6cm, respectively.

Figures 2a,b shows the combined polarized and total intensity images of the
Mouse with a resolution of $2.1'' \times 1.9''$ (PA = $-34^\circ$) at 6cm. The total intensity image of the head of the Mouse shows a cone-shape structure within which a bright linear feature with an extent of $\sim 45''$ appears to run along the axis of the symmetry. With the exception of depolarizing features, which are displayed as dark patches in Figure 2a, similar morphology is seen in both the total and polarized intensity images. The overall degree of polarization at 6cm ranges between 10 and 25%. Detailed 6cm images of the head of the nebula show that the peak polarized and total intensity images are offset from each other suggesting that the emission is depolarized at the outermost portion of the bow shock. This offset is best shown in Figure 3a,b where a slice is cut along the axis of the symmetry of the distribution of the polarized and total intensity, respectively. A sharp rise in the total intensity of the emission having a 6–7% degree of polarization is followed by a peak emission which coincides with a drop in the polarized emission; the degree of polarized emission is less than 1% at this position. In the region where the total intensity falls gradually, the degree of the polarization rises to values ranging between 5–10%. It is clear that either the magnetic field is highly tangled-up or that there is a high degree of thermal plasma mixed in with nonthermal gas at the head of the nebula where no polarized emission is detected. A more dramatic picture of this depolarization feature at 3.6cm is shown in Figure 6a, as discussed below.

Figure 4a,b show grayscale and contour images of the head of the Mouse immediately to the west of the bright bowshock. The bright compact source that is suspected to be coincident with the pulsar is clearly resolved in these images. The sharp distribution of the emission ahead of the pulsar when compared with a more gradual distribution of emission behind the pulsar supports for the compression of gas and magnetic field in the bowshock region resulting from the supersonic motion of the pulsar. We note a 4''"hole" in the 3.6cm brightness distribution within which the emission is three times fainter than the features surrounding it. The center of the "hole" lies near $\alpha, \delta(2000) = 17^h47^m15^s.35, -29^\circ58^\prime01^\prime\prime.5$. The non-uniform distribution of emission behind the bow-shock can be seen throughout the Mouse at 6 and 3.6cm. Additional 2 and 6cm images presented in Figures 5a,b also support the evidence for the modulation of the total intensity along the axis of the symmetry. The morphology of the emission is complicated but Figures 2 – 5 show that the overall brightness temperature along the axis of the symmetry decreases at about 5'', 12'', 20'' and 45'' west of the bowshock.

The grayscale distribution of the polarized emission superimposed on contours of total intensity at 6 and 3.6cm are shown in Figures 6a,b, respectively. The length and the position angle of the line segments represent the distributions of the polarized emission and the polarization vectors rotated by 90 degrees. The distribution of the polarization vectors at these wavelengths, including our 2cm data that are not shown here, are similar to each other. The striking feature in these images is the recognition of a depolarizing feature separating
the distribution of the polarized emission in the bowshock region from the region behind the pulsar. The position angle of the polarization angle vectors changes by $90^0$ between these two regions. The slice representations of the total and polarized intensity at 6cm, as shown in Figure 3a,b, are consistent with a picture that the scale of the magnetic field within the beam must have changed in order to produce the depolarizing feature. The distributions of the polarization vectors at 3.6 and 6cm are used to determine the rotation measure (RM) distribution of the polarized emission ahead of the Mouse.

Figure 7a,b show slice representations of the distribution of the RM and its error between 3.6 and 6cm cut along the symmetry axis of the Mouse. The RM value is on order of $500\pm40$ rad m$^{-2}$ near the bow shock to $-400\pm20$ rad m$^{-2}$ at the position of the depolarizing feature before it increases to a value $0\pm60$ rad m$^{-2}$ away from the bow shock. The low value of the RM and its error in the region behind the pulsar suggests the intrinsic magnetic field traces the direction of the inferred motion. We believe that the Faraday rotation toward the Mouse due to interstellar material along the line of sight is well represented in the RM distribution behind the pulsar and along the tail of the Mouse. However, the high RM values as well as the evidence in field reversal and the low degree of polarization ahead of the pulsar are distinctly different than the region behind the pulsar. These effects, in particular, the increase in RM toward the head of the Mouse by two orders of magnitude imply that Faraday rotation along the line of sight can not explain the unusual characteristics of polarization ahead of the pulsar. We suggest a picture in which there is a mixture of thermal and nonthermal plasma coexisting in the bowshock region. Although, it is expected that the magnetic field gets compressed and becomes more uniform in the bowshock region of a pulsar wind nebula, internal thermal plasma can produce a high degree of Faraday rotation and depolarization (Burn 1966). Future detailed polarization observations using multiple bands in order to determine the true distribution of Faraday rotation should be able to test this interpretation.

Using the dispersion measure of $\approx100$ cm$^{-3}$ pc (Camilo et al. 2002) and an upper limit of RM$\approx100$ rad m$^{-2}$, the parallel component of the magnetic field along the line of sight is estimated to be $\approx1.2\mu$G. This unusually low value of the magnetic field along the line of sight is likely to be underestimated since the sign of the RM could change between the head and the tail of the Mouse. The fluctuation of electron density and magnetic field of a turbulent medium along the line of sight, as well as from the region within the nebula, can severely affect the correct estimate of the magnetic field along the line of sight (Beck et al. 2003). In spite of this difficulty, the RM estimate made here is at least an order of magnitude less than the estimate made toward objects lying within a few hundred pcs of the Galactic center (e.g., Yusef-Zadeh, Wardle and Parastaran 1997). The RM value estimated from this study is consistent with a source lying less than 5 kpc from us.
3 Discussion

One of the most puzzling aspects of radio observations reported here is the distribution of synchrotron emission near the apex of the pulsar wind where the intensity is modulated at 3 cm. The drop in synchrotron emissivity may be accounted for in terms of the unshocked wind arising from the pulsar or an inhomogeneous distribution of synchrotron emission. The numerical simulations carried out by Gaensler et al. (2004) have in fact predicted a closed elongated structure associated with the termination shock behind a supersonically moving pulsar. A more detailed comparison of radio and X-ray data is needed to determine the nature of the intensity distribution and how it may be related to the termination shock behind the pulsar.

Radio and X-ray observations suggest the the Mouse could lie at distance ranging between 2 and 5 kpc and that this object is not associated with SNR G359.1–0.5. Uchida et al. (1992) considered that G359.1–0.5 is associated with a molecular ring lying near the Galactic center requiring multiple supernova explosions to account for an energy of $6 \times 10^{52}$ ergs. However, a subsequent detection of maser emission at $-5$ km s$^{-1}$ surrounding this large-scale source (Yusef-Zadeh et al. 1995), as well as the detection of low value of rotation measure toward the remnant (Yusef-Zadeh et al. 2005, in preparation), suggest that SNR G359.1–0.5 is unlikely to be located within a few parsec of the Galactic center at the distance of 8.5 kpc. One possibility is that the Mouse and SNR G359.1–0.5 are associated with each other. The support for this suggestion may come from the absorption column measured ranging between $3 \times 10^{22}$ cm$^{-2}$ and $(6 \pm 2) \times 10^{22}$ cm$^{-2}$ toward the remnant (Bamba et al. 2000; Egger and Sun 1998) and $(2.7 \pm 0.1) \times 10^{22}$ cm$^{-2}$ toward the Mouse (Gaensler et al. 2004). Depending on how one fits the X-ray spectrum, these estimates could be consistent with each other. If SNR G359.1–0.5 and the Mouse lie at the distance of 5 kpc, the time that it takes for the pulsar to travel 34 pc, the distance between the center of the remnant and the pulsar, is $\approx 5.7 \times 10^4$ years. This is more than twice the characteristic age of the pulsar $2.5 \times 10^4$ yr. Recent studies suggest that the true age of young pulsars can be longer than their characteristic age, so it is possible that the Mouse and SNR G359.1–0.5 could have the same origin.

In conclusion, we have presented new high-resolution radio continuum images of the Mouse, showing a modulation of the intensity behind the pulsar. A polarization image of the Mouse at 3.6 cm shows that the overall distribution of the inferred magnetic field is parallel to the axis of symmetry away from the bow shock. However, a high degree of depolarization, field reversal and high RM are detected ahead of the pulsar near the interface where the polarization angle changes by 90°. These images indicate that the direction of the magnetic field in the bow shock is likely to be tangent to the shock normal, though
more detailed radio observations are required to correct for Faraday effects. We have also argued that the Mouse and an adjacent SNR G359.1–0.5, may be associated. Future radio and X-ray observations should be able to shed light on the nature of the Mouse and SNR G359.1–0.5 as well as their physical relationship.

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Fig. 1. A complete shell-type SNR, G359.1–0.5, an incomplete shell-type SNR G359.0–0.9, and the Mouse, G359.23–0.82, are shown at 20cm with a resolution of 12.8′′ × 8.4′′ (PA = 56°). The southern extension of the Snake filament, G359.1–0.2, is also noted (Yusef-Zadeh et al. 2004).

Fig. 2. The top (a) and bottom (b) panels show grayscale polarized and total intensity images of the Mouse at 6cm, respectively, based on combined BnA and CnB-array configurations with a resolution of 2.1′′ × 1.9′′ (PA = −34°) and uniform uv weighting.

Fig. 3. The top (a) and bottom (b) panels show a slice cut along the axis of the symmetry of the respective polarized and total intensity images that are shown in Figure 2. The position angle of slice is −90°.

Fig. 4. (The top (a) and bottom (b) panels show a grayscale total intensity image and contours of total intensity at (2, 3, 4, 5, 7, 9, 11, 13, 20, 30 and 40) × 90 μJy beam⁻¹ with a robust weighting of -7 and a convolved spatial resolution of 0.82″ × 0.82″ at 3.6cm, respectively.

Fig. 5. The top (a) and bottom (b) panels show contours of total intensity at 0.5, 1, 2, 3, 5, 7, 10, 15 and 20 mJy beam⁻¹ and 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7 and 8 mJy beam⁻¹ at 2 and 6cm, respectively. The spatial resolutions of 2 and 6cm images are 3″ × 1.75″ and 1.1″ × 1.1″, respectively. The 6cm data are based only on the BnA array configuration data with a robust weighting -7 whereas the 2cm data have used the data combined from BnA and CnB array configuration observations using a uv taper 100 kλ and a robust weighting 4.

Fig. 6. [Top] The distribution of the inferred magnetic field orientation at 3.6cm with no Faraday correction. The length of the vectors correspond to the strength of polarized emission. The grayscale image shows the distribution of the total intensity with contours set at 0.1, 0.3, 0.5, 0.7, 1, 3 and 5 mJy beam⁻¹ and resolution of 1.4″ × 0.7″ (PA = 18°) with a robust weighting 5. [bottom] Similar to the top panel except that this image is based only on BnA array at 6cm with a resolution of 1.6″ × 1.4″ (PA = −18°) with uniform uv weighting and contour levels 1, 2 and 8 mJy beam⁻¹.

Fig. 7. [Top] A slice cut along the symmetry axis of the distribution of the rotation measure based on 6 and 3.6cm polarization measurements. [Bottom] Similar to the top panel except that the slice is made through the error map of the RM distribution.
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