X-RAY OBSERVATIONS OF PARSEC-SCALE TAILS BEHIND TWO MIDDLE-AGED PULSARS

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Received 2008 February 20; accepted 2008 March 31

ABSTRACT

Chandra and XMM-Newton resolved extremely long tails behind two middle-aged pulsars, J1509—5850 and J1740+1000. The tail of PSR J1509—5850 is discernible up to 5.6' from the pulsar, which corresponds to the projected length \( l_\parallel = 6.5d_4 \) pc, where \( d = 4d_4 \) kpc is the distance to the pulsar. The observed tail flux is \( 2 \times 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) in the 0.5–8 keV band. The tail spectrum fits an absorbed power law (PL) with the photon index \( \Gamma = 2.3 \pm 0.2 \) and 0.5–8 keV luminosity of \( 1 \times 10^{33} d_4^2 \) ergs s\(^{-1}\), for \( n_H = 2.1 \times 10^{22} \) cm\(^{-2}\). The tail of PSR J1740+1000 is firmly detected up to \( S'(l_\parallel \sim 2d_4) \) pc, with a flux of \( 6 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 0.4–10 keV band. The PL fit yields \( \Gamma = 1.4\pm 1.5, n_H \approx 1 \times 10^{21} \) cm\(^{-2}\), and an 0.4–10 keV luminosity of \( \sim 2 \times 10^{31} d_4^2 \) ergs s\(^{-1}\). The large extent of the tails suggests that the bulk flow in the tails starts as mildly relativistic downstream of the termination shock and then gradually decelerates. Within the observed extent of the J1509—5850 tail, the average flow speed exceeds 5000 km s\(^{-1}\), and the equipartition magnetic field is a few \( 10^{-5} \) G. For the J1740+1000 tail, the equipartition field is a factor of a few lower. For the high-latitude PSR J1740+1000, the orientation of the tail suggests that the pulsar was born from a halo-star progenitor. The X-ray efficiencies of the ram pressure—confined pulsar wind nebulae (PWNe) correlate poorly with the pulsar spin-down luminosities or ages. The efficiencies are systematically higher than those of PWNe around slowly moving pulsars with similar spin-down parameters.

Subject headings: pulsars: individual (PSR J1509—5850, PSR J1740+1000) — stars: neutron — X-rays: stars
The pulsar’s properties are summarized in Table 1. At the DM distance of 1.4 kpc and Galactic latitude of 20.3°, J1740 belongs to a very small group of pulsars located at large distances from the Galactic plane, implying either a progenitor from the halo population or a neutron star (NS) ejected from the Galactic disk with an exceptionally high speed, ~4000 km s⁻¹. J1740 was observed with Chandra in 2001 (PI: Z. Arzoumanian). In a preliminary analysis of these data we detected the pulsar, but the exposure was too short to study possible extended emission and the pulsar’s spectrum. Therefore, we observed the field around J1740 in a much deeper imaging exposure with XMM-Newton. In this paper we report the discovery of the PWN associated with J1740 and focus on the analysis of the PWN properties, while the spectral and timing properties of the pulsar, including the detection of the thermal emission from the NS surface, will be presented in a separate publication (Z. Misanovic et al. 2008, in preparation).

Our X-ray observations of the J1509 and J1740 tails and the data analysis are described in § 2. We estimate the pulsar and flow velocities, the magnetic field strengths, and the energetics of the tails, compare these tails with the other pulsar tails currently known, and discuss the implications of our findings in § 3. Our main results are summarized in § 4.

### 2. OBSERVATIONS AND DATA ANALYSIS

J1509 was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra on 2003 February 9 (ObsID 3513). The useful scientific exposure time was 39.6 ks. The observation was carried out in Very Faint mode, and the pulsar was imaged on the S3 chip, 35° from the optical axis (CHIPX = 285, CHIPY = 503). The other chips activated during this observation were S2, I0, I1, I2, and I3. The detector was operated in Full Frame mode, which provides time resolution of 3.24 s. For the analysis, we used the data reprocessed on 2006 July 20 (ASCDS, ver. 7.6.8; CALDB, ver. 3.2.4).

J1740 was observed with the Chandra ACIS on 2001 August 19 in Timed Exposure imaging mode (ObsID 1989; useful exposure time 5.1 ks) and Continuous Clocking mode (ObsID 2426; useful exposure time 16.5 ks). Only the former observation is useful for studying faint, extended features; it was carried out in Faint mode with the pulsar imaged on the S3 chip, 35° from the optical axis.

The other activated chips were S2, I0, I1, I2, and I3, and the time resolution was 3.24 s. For the analysis, we used the data reprocessed on 2006 December 21 (ASCDS, ver. 7.6.9; CALDB, ver. 3.2.4).

J1740 was also observed with the European Photon Imaging Camera (EPIC) on board XMM-Newton on 2006 September 28 and 30 (observations 0403570101 and 0403570201). The EPIC PN camera was operated in Small Window mode with a reduced field of view (FOV) of 4′ × 4′ and time resolution of 6 ms, to analyze pulsations and perform phase-resolved spectroscopy of the pulsar. To obtain a large-scale image of the PWN, the EPIC MOS1 and MOS2 cameras were operated in Full Window mode, which provides a larger FOV at the expense of lower time resolution (2.6 s). The Thin filter was in front of the PN and MOS cameras during both observations. The total exposures were 40.4 and 25.6 ks for the first and second observations, respectively. However, because of the reduced efficiency of the PN detector in the Small Window mode, the effective PN exposures were 28.6 and 17.8 ks in the first and second observations, respectively. We did not find significant flaring events in both observations (the background count rate varied by ≲20%). Thus, the useful scientific exposures were 66 ks for MOS1 and MOS2, and 46.4 ks for PN in the two observations combined.

The Chandra data were reduced using the Chandra Interactive Analysis of Observations (CIAO) software (ver. 3.4; CALDB, ver. 3.4.0). The data obtained by XMM-Newton were reduced with the Scientific Analysis Software (SAS, ver. 7.0).

#### 2.1. Images

The X-ray images of the J1509 and J1740 fields reveal point sources at the radio pulsar positions. The best-fit centroid positions obtained from the Chandra ACIS images are R.A. = 15°09'27.163", decl. = −58°50'56.12", and R.A. = 17°40'25.939", decl. = +10°00'05.78", for J1509 and J1740, respectively. These positions differ from the corresponding radio positions by 0.3" and 0.6", respectively. The differences are comparable to the uncertainty of the absolute Chandra astrometry.²

² See http://cxc.harvard.edu/cal/docs/cal_present_status.html#abs_spat_pos.

| Parameter                | J1509−5850 | J1740+1000 |
|--------------------------|------------|-----------|
| R.A. (J2000.0)           | 15 09 27.13(3) | 17 40 25.950(5) |
| Decl. (J2000.0)          | −58 50 56.1(5) | +10 00 06.3(2) |
| Epoch of position (MJD) | 51,463     | 51,662     |
| Galactic longitude (deg) | 319.97     | 34.01      |
| Galactic latitude (deg)  | −0.62      | 20.27      |
| Spin period, $P$ (ms)   | 88.9       | 154.1      |
| Period derivative, $\dot{P}$ (10⁻¹⁵) | 0.92      | 2.15      |
| Dispersion measure, DM (cm⁻³ pc) | 137.7  | 23.85      |
| Distance, $d$ (kpc)     | 3.8        | 1.4        |
| Distance from the Galactic plane, $z$ (kpc) | 0.04      | 0.48      |
| Surface magnetic field, $B_s$ (10¹² G) | 0.91      | 1.84      |
| Spin-down power, $E$ (10³² ergs s⁻¹) | 5.1       | 2.3       |
| Spin-down age, $\tau$ = $P/(2\dot{P})$ (kyr) | 154       | 114       |

Notes.—Based on the data from Kramer et al. (2003) and McLaughlin et al. (2002). Figures in parentheses represent 1σ uncertainties in least significant digits quoted. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

The distances are based on the dispersion measure and the Galactic electron density distribution model by Taylor & Cordes (1993). The Cordes & Lazio (2002) model gives $d = 2.6$ and 1.2 kpc for J1509 and J1740, respectively.
The most striking features exposed in the binned Chandra and XMM-Newton images (see Figs. 1–3) are long linear structures (hereafter we call them “tails”) attached to J1509 and J1740. The tails have similar orientations on the sky, with position angles of $\approx 203^\circ$ for J1509 and $\approx 215^\circ$ for J1740 (counted east of north). Assuming that the tails are caused by the pulsar motion, the corresponding position angles of the pulsars’ proper motion can be estimated as $\approx 23^\circ$ and $\approx 35^\circ$.

2.1.1. J1509 Tail

The ACIS image of J1509 reveals the compact PWN ($\approx 10'' \times 30''$) in the vicinity of the pulsar (see Fig. 4). Because of its elongated, elliptical shape, we call it the “head” hereafter. The diffuse emission is brightest close to the pulsar, then gradually broadens and becomes fainter with increasing distance from the pulsar, forming an extended tail. The tail emission is firmly detected up to $\approx 5.6''$ (or $l_\perp \approx 6.5 d_4$ pc, where $d_4 = d/4$ kpc; see Fig. 1) and possibly even farther, at a lower significance. This is demonstrated by the linear surface brightness profiles extracted along and across the tail (see Figs. 5 and 6). Although the collected number of counts from the tail is not very large (see Table 2), the low ACIS background still allows us to detect interesting morphological changes along the tail. For instance, between $\approx 15''$ and $\approx 50''$ from the pulsar, the distribution of counts in the tail becomes asymmetric with respect to the inferred pulsar proper-motion direction, shown by the dashed straight line in Figure 7 (e.g., there are more counts southeast of the line than northwest of the line). The tail, $\sim 40''$ wide at the $\approx 1.3'$ distance from the pulsar, slightly brightens and then suddenly narrows by about a factor of 2 (as shown by the small arrows in the top panel of Fig. 7). Interestingly, very similar behavior is observed in the “Mushroom PWN” (KP08) associated with another middle-aged pulsar, B0355+50 (see Fig. 7, bottom, and the images in McGowan et al. 2006). Local tail brightenings are also seen at larger distances from the J1509 pulsar (Figs. 5 and 6); however, the decreasing surface brightness of the tail and reduced off-axis resolution do not allow one to check whether or not these brightenings are accompanied by significant morphological changes.

Fig. 1.—Large-scale ACIS view of J1509’s X-ray tail. The images show the S3 and S4 chips. The 1–7 keV energy band is chosen to maximize the S/N of the faint, extended tail. Both images are binned by a factor of 16 (pixel size is 7.8$''$). The image on the right is additionally smoothed with the 24$''$ Gaussian kernel. The label “R” marks the counterpart of the pointlike source projected onto the putative radio tail (see § 3.2 and Fig. 13). The regions marked 1, 2, and 3 in the left panel are used to extract the tail spectra (see § 2.2.1).

Fig. 2.—Combined MOS1 + MOS2 images ($18' \times 13'; 0.3-10$ keV) of the field around J1740 from two XMM-Newton observations (see text). The top panel shows a binned image (pixel size 8$''$), while the bottom image (pixel size 4$''$) is adaptively smoothed with a Gaussian kernel. The top panel shows the regions from which the linear brightness profiles (shown in Fig. 9) were extracted. The overlaid contours in the bottom image show optical and radio sources from the DSS2-blue (cyan contours), DSS2-red (magenta contours), and NVSS 1.4 GHz (green contours) images.

2.1.2. J1740 Tail

Even in the short 5 ks ACIS imaging exposure of J1740 we can see traces of faint extended emission southwest of the pulsar in the heavily binned ACIS-S image (Fig. 8), and the unbinned image of the immediate vicinity of the pulsar shows an excess of counts in the same direction and perhaps some emission in front of the pulsar (see the inset in Fig. 8). The long ($\sim 5.5'$, or $l_\perp \approx 2d_{1.4}$ pc, where $d_{1.4} = d/1.4$ kpc) tail is much better seen in the EPIC images (Figs. 2 and 3). Similar to J1509, the linear profile of the J1740 tail (see Fig. 9) hints at surface brightness fluctuations along the tail; however, a detailed investigation is not possible because of the high EPIC background and poor angular resolution of XMM-Newton. In addition to the long tail, the smoothed MOS1 + MOS2 image of the J1740 field (Fig. 2) and the linear profile in the east-west direction (Fig. 9) show some diffuse emission $\approx 2.5'$ east of the pulsar, whose connection to the pulsar remains unclear. Since the XMM-Newton resolution is much more coarse than that of Chandra, emission from a number...
Fig. 3.—A $9.4' \times 6.2'$ binned image (pixel size 8") of the field around J1740 combining MOS1 + MOS2 (Full Frame mode) and PN (Small Window mode) data of two XMM-Newton observations, in the 0.3–10 keV band (see text). The regions used for spectral extraction are marked by an ellipse (the source region) and a circle (the background). The Galactic coordinate grid is shown.
As the orientation of the J1740 tail on the sky indicates the proper-motion direction, it provides useful information about the pulsar’s birthplace. Being located high above the Galactic plane, at $z = 0.48d_{1.4}$ kpc, the pulsar might be a very high speed NS if it were born in the plane [e.g., $v \approx 4200d_{1.4}(114$ kyr$/t)$ km s$^{-1}$, where $t$ is the pulsar age, if it were born in the midplane of the Galaxy]. However, the X-ray image of the tail, shown together with the Galactic coordinate grid in Figure 3, suggests that the pulsar is moving at a small angle, $\approx 7^\circ$, toward the plane, which means that it was born well out of the Galactic plane, likely from a halo-star progenitor.

2.2. PWN Spectra

2.2.1. J1509

We extracted the spectrum of the J1509 PWN from the three numbered rectangular regions shown in Figure 1 (left). Region 1 (hereafter R1) includes the PWN head, but not the pulsar (we excluded counts from the 0.9" radius circle shown in Fig. 4). We also extracted the spectrum from the combined region 1 + 2 + 3 (although it includes the PWN head, the head contribution is small compared to that of the tail, so we refer to it as the “entire tail” region). For each of the regions, the background was extracted from the two corresponding rectangular regions located on both sides of the source region (see Fig. 1, left). The measured source and background count numbers and areas are given in Table 2. The observed flux in the entire tail is $F_{\text{tail}} = (2.0 \pm 0.2) \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$ in the 0.5–8 keV band. In addition, we extracted the head spectrum from the elliptical region shown in Figure 4 (top), with the absorbed flux $F_{\text{head}} = (4.9 \pm 0.5) \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ in the 0.5–8 keV band.

First, we fit the R1 spectrum with the absorbed power-law (PL) model, allowing the hydrogen column density, $n_{\text{HI}}$, to vary. The fit gives $n_{\text{HI}} = n_{\text{HI}}/10^{22}$ cm$^{-2} = 2.1 \pm 0.2$ (the uncertainties here and below correspond to the 68% confidence level for a single interesting parameter, i.e., $\chi^2 - \chi^2_{\text{min}} = 1$). Fitting the same model to the R2 and R3 spectra results in larger uncertainties, while the best-fit $n_{\text{HI}}$-values are similar to that obtained for R1. The PL fit to the spectrum of the entire tail gives a slightly larger column density, $n_{\text{HI}} = 2.5 \pm 0.5$, while the fit to the head spectrum gives a lower $n_{\text{HI}} = 1.3 \pm 0.5$, which is still consistent with the above values (see Fig. 10). The total Galactic H column in that direction is $n_{\text{HI}} = 1.7$ (Dickey & Lockman 1990); however, this does not contradict the larger $n_{\text{HI}}$-values for the J1509 PWN because the $n_{\text{HI}}$ deduced from an X-ray spectrum under the assumption of standard element abundances generally exceeds the $n_{\text{HI}}$ measured from 21 cm observations by a factor of 1.5–3 (e.g., Baumgartner & Mushotzky 2006). Finally, the value $n_{\text{HI}} = 0.42$, estimated from the pulsar’s dispersion measure under the standard assumption of 10% ionization of the interstellar medium (ISM), is noticeably lower than the above values, which possibly means that average ISM ionization is lower than 10% in the direction to J1509. Thus, given different kinds of uncertainties, we can only conclude that the true $n_{\text{HI}}$ is somewhere between 0.4 and 3. Throughout most of the analysis below

of clustered point sources may sometimes mimic the diffuse emission in the EPIC images. Therefore, we searched for point sources at radio and optical wavelengths. The bottom panel of Figure 2 shows the contours of optical and radio sources detected in the Digitized Sky Survey (DSS2-blue and DSS2-red) and NRAO VLA Sky Survey (NVSS; 1.4 GHz) images of the region around J1740. There are a few optical sources that coincide with the X-ray pointlike sources in the EPIC images. However, the majority of optical sources in the field are faint and have no X-ray counterparts. Furthermore, the distribution of these sources shows that they cannot be responsible for the emission detected in the tail region, nor in the region $\approx 2.5'$ east of the pulsar. Yet until a high-resolution, deep ACIS image is obtained, we cannot exclude the possibility that some of the J1740 tail emission comes from faint point sources lacking obvious optical counterparts.

3 Although in most cases this is true, we note that elongated features misaligned with the pulsar motion direction were found in several cases (e.g., near PSR B2224+65; see Fig. 4 in KP08). The origin of these features is, however, unclear.

4 These values are larger than the $n_{\text{HI}}^{\text{ref}} = 0.82^{+0.09}_{-0.07}$ reported by HB07 from the same ACIS data. From the description in HB07, it appears that the lower $n_{\text{HI}}$ was a result of overcorrecting for the ACIS filter contamination. To correct for the contamination, HB07 used the XSPEC model ACISABS despite the fact that this correction is already included in the ARF files generated by CIAO (since the release of CALDB ver. 2.26 on 2004 February 2).
Fig. 5.—ACIS images (top) of the J1509 tail (binned to the pixel size of 4′ and smoothed with a 20″ Gaussian kernel) in the total (1–7 keV; left), soft (1–2.5 keV; middle), and hard (2.5–7 keV; right) bands. The total band image is color-coded, with the soft emission shown in red and hard emission shown in green. The bottom panels show the tail profiles in each energy band. The linear brightness profiles are obtained by extracting the source and background counts from the 1.6′ × 6′ rectangular regions shown in the top left panel. The original unsmoothed images were used for the extraction. The profile extracted from the source region is plotted by the solid line, while the averaged background profile extracted from the adjacent background regions is shown by the dashed line. The bin size is 15″ in the linear profile plots.
we choose to fix $n_{H,22}$ at the value obtained from the fit to the R1 spectrum since it has the highest signal-to-noise ratio (S/N) among the other PWN elements (see Table 2).5

With the fixed $n_{H,22} = 2.1$, the absorbed PL fits to the R1 spectrum and the entire tail spectrum result in the photon indices $\Gamma_{R1} = 2.1 \pm 0.2$ and $\Gamma_{tail} = 2.4 \pm 0.15$, with the unabsorbed $0.5–8$ keV fluxes $F_{unabs}^{R1} = 2.33^{+0.27}_{-0.22} \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ and $F_{unabs}^{tail} = (5.9 \pm 0.5) \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (see also Fig. 11 and Table 3). The unabsorbed $0.5–8$ keV luminosity of the entire tail is $L_{tail} \approx 1.1 \times 10^{33} d_s^2$ ergs s$^{-1}$, while the luminosity of the head is a factor of 10 lower (see Table 3 for other details).

The pulsar’s spectrum will be analyzed in detail elsewhere. For the purposes of this paper, it suffices to say that the spectrum fits the absorbed PL model with $\Gamma_{psr} \approx 2.2$ and an unabsorbed $0.5–8$ keV flux $F_{psr}^{unabs} \approx 7.8 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ (for $n_{H,22} = 2.1$), corresponding to the isotropic luminosity $L_{psr} = 1.5 \times 10^{32} d_s^2$ ergs s$^{-1}$.

2.2.2. J1740

Since the ACIS imaging exposure of J1740 was very short, we have to rely on the XMM-Newton data to infer the spectral properties of the extended tail. We excluded events with energies below 0.4 keV and above 10 keV from the analysis because of the large particle background contribution at these energies. We then extracted the spectrum of the bright part of the tail (within the PN FOV) from the elliptical region shown in Figure 3. The choice of the background region was limited by the size of the PN FOV in the Small Window mode, so we extracted it from the largest possible circular region, also shown in Figure 3. In the first observation we collected 1459, 471, and 492 counts (of which 25.6%, 38.0%, and 27.9% come from the source) in PN, MOS1, and MOS2, respectively. A slightly smaller number of counts were collected from the second observation: 986 (28.4% from the source) in PN, 342 (46.1%) in MOS1, and 353 (44.9%) in MOS2.

We fit the PN and MOS spectra of both observations simultaneously in the 0.4–10 keV band using an absorbed PL model. First, we fit the data with all parameters allowed to vary. The hydrogen column density obtained from this fit is poorly constrained:

5 Although the spectrum extracted from the entire tail region has even higher S/N and formally fits with a PL model, the actual spectrum of the entire tail can deviate from a simple PL because of synchrotron cooling. (Evidence of synchrotron cooling is seen in the energy-resolved images shown in Fig. 5.)

### TABLE 2

**Count Statistics for PWN Regions**

| Region                   | $A$ (arcmin$^2$) | $N_{tot}$ | $N_{bg}$ | $N_{src}$ | $S$   | $S/N$   |
|--------------------------|------------------|----------|----------|-----------|-------|---------|
| J1509                    |                  |          |          |           |       |         |
| Head                     | 0.073            | 118 ± 11 | 18 ± 1   | 100 ± 11  | 9.1   | 34.6 ± 3.8 |
| R1                       | 1.16             | 542 ± 23 | 249 ± 11 | 293 ± 26  | 11.3  | 6.38 ± 0.57 |
| R2                       | 1.26             | 453 ± 21 | 280 ± 12 | 173 ± 24  | 7.2   | 3.45 ± 0.48 |
| R3                       | 2.24             | 691 ± 26 | 530 ± 16 | 161 ± 31  | 5.2   | 1.80 ± 0.35 |
| Entire tail              | 4.68             | 1686 ± 41| 1059 ± 23| 627 ± 47  | 13.3  | 3.38 ± 0.25 |
| J1740                    |                  |          |          |           |       |         |
| Bright portion (MOS1 + MOS2) | 2.10         | 1658 ± 41| 1026 ± 32| 632 ± 56  | 11.4  | 6.48 ± 0.57 |
| Bright portion (PN)       | 2.10             | 2445 ± 49| 1791 ± 42| 654 ± 70  | 9.2   | 6.70 ± 0.72 |

**Notes.**—Total ($N_{tot}$), background ($N_{bg}$), and source ($N_{src}$) counts are in the 0.5–8 keV band for the Chandra data, and the 0.4–10 keV band for the XMM-Newton combined data, extracted from the regions of area $A$ shown in Figs. 1 and 3 for J1509 and J1740, respectively. The mean surface brightness, $S$, is in units of counts ks$^{-1}$ arcmin$^{-2}$ in the 0.5–8 keV and 0.4–10 keV bands for J1509 and J1740, respectively.
The very long tails of the J1509 and J1740 pulsars are extreme examples of ram pressure–confined outflows from supersonically moving pulsars. To date, about 13 extended X-ray sources likely associated with fast-moving pulsars have been found, although in some cases the interpretation of the observed elongated structures as tails is tentative (see KP08 for a review). The sample of well-established X-ray PWNe with long ram pressure–confined tails is still very limited (see § 3.3 and Table 5). We expanded the sample by adding the two pulsars, J1740 and J1509, with remarkably long, prominent X-ray tails.

Despite the similarities in their appearance, pulsar tails show significant differences in their X-ray spectra, luminosities, apparent lengths, surface brightness distributions, and multiwavelength properties. Below we derive physical properties of the J1509 and J1740 tails, compare them with model predictions, and discuss the physical processes that determine the tails’ appearance and spectra. We also provide a comparison with other pulsar tails, stressing the differences and discussing their possible origin.

### 3.1. Morphology of the Tails and Pulsar Speeds

The appearance of the X-ray PWNe around J1509 and J1740 clearly shows that the pulsars move with supersonic speeds. If the pulsar speed is supersonic, the shocked pulsar wind (PW) ahead of the pulsar is confined between the termination shock (TS) and the contact discontinuity (CD) surface, while the shocked ambient matter is confined between the CD surface and the forward shock (FS). The PW behind the pulsar acquires an elongated shape stretched in the direction opposite the direction of the pulsar’s motion. Numerical simulations (e.g., Gaensler et al. 2004; B05) show that for the idealized case of an isotropic...
PW\(^7\) the TS acquires a bullet-like shape, with the TS apex (bullet head) at the distance

\[ R_h \approx \left( \frac{\dot{E}}{4\pi C (p_{amb} + p_{ram})} \right)^{1/2} \]

from the pulsar, where the PW pressure, \( p_w \approx \dot{E}(4\pi C r^{-3})^{-1} \), is balanced by the sum of the ambient pressure, \( p_{amb} \), and the ram pressure, \( p_{ram} = \rho v^2 = 1.67 \times 10^{-10} n v^2 \) dyn cm\(^{-2}\) (here \( v_7 = v/10^7 \) cm s\(^{-1}\) is the pulsar speed, and \( n = \rho/m_H \) is in units of cm\(^{-3}\)). Assuming \( p_{ram} \gg p_{amb} \) [equivalent to \( M \gg 1 \), where \( M = v/c_s = (3p_{ram}/2p_{amb})^{1/2} \) is the Mach number], we obtain

\[ R_h \approx 4.0 \times 10^{16} \dot{E}_{35}^{1/2} n^{-1/2} v_7^{-1} \text{ cm}, \]

or, equivalently, \( p_{ram} \approx 2.65 \times 10^{-9} \dot{E}_{35} R_{h,16}^{-2} \) dyn cm\(^{-2}\), where \( \dot{E}_{35} = \dot{E}/(10^{35} \text{ ergs s}^{-1}) \) and \( R_{h,16} = R_h/10^{16} \) cm.

For large Mach numbers and small values of the magnetization parameter \( \sigma \) of the preshock pulsar wind, the TS bullet’s cylindrical radius is \( r_{TS} \sim R_h \), and the distance of its back surface from the pulsar is \( R_b \sim 6R_h \) (Gaensler et al. 2004; B05). The numerical simulations (B05) and analytical models (Romanova et al. 2005) also show that an extended tail forms behind the back surface of the bullet.\(^8\) According to B05, the flow speed within this tail ranges from 0.8–0.9c in its sheath to 0.1–0.3c in the narrow inner channel of the tail.

For J1509, the 300 long region of enhanced surface brightness immediately behind the pulsar (see Fig. 4, top) can be interpreted as emission from the TS bullet, implying the distance \( R_{h,16} (d_4/\sin i) \) cm to the (unresolved) TS apex (\( i \) is the angle between the pulsar velocity and the line of sight).

This assumption and equation (2) give \( p_{ram} \approx 1.5 \times 10^{-9} (d_4/\sin i)^{-2} \) dyn cm\(^{-2}\) and an estimate for the pulsar speed as a function of ambient number density,

\[ v \approx 400 \dot{E}_{35}^{1/2} n^{-1/2} R_{h,16}^{-1} \text{ km s}^{-1} \]

\[ \sim 300 n^{-1/2} (d_4/\sin i)^{-1} \text{ km s}^{-1}. \]

Alternatively, we can estimate the Mach number as a function of ambient pressure,

\[ M \approx (3\dot{E}/2\pi R_h^2 C p_{amb})^{1/2} \sim 30 (d_4/\sin i)^{-1} p_{amb}^{-1/2}, \]

\(^8\) Note that the numerical solutions by B05 do not extend beyond \( \sim 10R_h \) from the pulsar.

\(^{7}\) If the PW is mostly confined in the equatorial plane (i.e., in the plane perpendicular to the pulsar’s spin axis), as we see in young pulsars, then the TS shape may strongly depend on the angle between the pulsar’s velocity and the spin axis (see Vigeland et al. 2007).

\(^{8}\) If the PW acquires a bullet-like shape, with the TS apex (bullet head) at the distance

\[ R_h \approx \left( \frac{\dot{E}}{4\pi C (p_{amb} + p_{ram})} \right)^{1/2} \]

from the pulsar, where the PW pressure, \( p_w \), is balanced by the sum of the ambient pressure, \( p_{amb} \), and the ram pressure, \( p_{ram} = \rho v^2 \) dyn cm\(^{-2}\) (here \( v_7 \) is the pulsar speed, and \( n = \rho/m_H \) is in units of cm\(^{-3}\)). Assuming \( p_{ram} \gg p_{amb} \) [equivalent to \( M \gg 1 \)], where \( M = v/c_s = (3p_{ram}/2p_{amb})^{1/2} \) is the Mach number, we obtain

\[ R_h \approx 4.0 \times 10^{16} \dot{E}_{35}^{1/2} n^{-1/2} v_7^{-1} \text{ cm}, \]

or, equivalently, \( p_{ram} \approx 2.65 \times 10^{-9} \dot{E}_{35} R_{h,16}^{-2} \) dyn cm\(^{-2}\), where \( \dot{E}_{35} = \dot{E}/(10^{35} \text{ ergs s}^{-1}) \) and \( R_{h,16} = R_h/10^{16} \) cm.

For large Mach numbers and small values of the magnetization parameter \( \sigma \) of the preshock pulsar wind, the TS bullet’s cylindrical radius is \( r_{TS} \sim R_h \), and the distance of its back surface from the pulsar is \( R_b \sim 6R_h \) (Gaensler et al. 2004; B05). The numerical simulations (B05) and analytical models (Romanova et al. 2005) also show that an extended tail forms behind the back surface of the bullet.\(^8\) According to B05, the flow speed within this tail ranges from 0.8–0.9c in its sheath to 0.1–0.3c in the narrow inner channel of the tail.

For J1509, the 300 long region of enhanced surface brightness immediately behind the pulsar (see Fig. 4, top) can be interpreted as emission from the TS bullet, implying the distance \( R_{h,16} (d_4/\sin i) \) cm to the (unresolved) TS apex (\( i \) is the angle between the pulsar velocity and the line of sight).

This assumption and equation (2) give \( p_{ram} \approx 1.5 \times 10^{-9} (d_4/\sin i)^{-2} \) dyn cm\(^{-2}\) and an estimate for the pulsar speed as a function of ambient number density,

\[ v \approx 400 \dot{E}_{35}^{1/2} n^{-1/2} R_{h,16}^{-1} \text{ km s}^{-1} \]

\[ \sim 300 n^{-1/2} (d_4/\sin i)^{-1} \text{ km s}^{-1}. \]

Alternatively, we can estimate the Mach number as a function of ambient pressure,

\[ M \approx (3\dot{E}/2\pi R_h^2 C p_{amb})^{1/2} \sim 30 (d_4/\sin i)^{-1} p_{amb}^{-1/2}. \]

\(^{8}\) Note that the numerical solutions by B05 do not extend beyond \( \sim 10R_h \) from the pulsar.
where \( p_{\text{amb},-12} = p_{\text{amb}} / 10^{-12} \) dyn cm\(^{-2}\) (\( p_{\text{amb},-12} \sim 1 \) is a typical ISM pressure in the Galactic plane; e.g., Ferrière 2001).

Unfortunately, the poor angular resolution of XMM-Newton and the shortness of the Chandra exposure do not allow us to constrain the size of the TS bullet around J1740. However, the Chandra image of the vicinity of J1740 (see Fig. 8, inset) shows a brightening \( \sim 0.7'' \) ahead of the moving pulsar. One can speculate that the brightening corresponds to the TS apex, which gives \( R_b \sim 1.5 \times 10^{16} d_{1.4}^2 \sin i \) cm. This corresponds to the pulsar speed

\[
v \sim 400 n^{-1/2} d_{1.4}^2 \sin i^{-1} \text{ km s}^{-1}
\]

and the Mach number

\[
M \sim 130 d_{1.4}^2 \sin i^{-1/2} p_{\text{amb},-12}^{-1/3}.
\]

(Note that we changed the scaling here to account for the lower pressure at large distances from the Galactic plane.) The estimated pulsar speed is consistent with \( v \sim 200 \) km s\(^{-1}\), inferred from the interstellar scintillation measurements by McLaughlin et al. (2002), if \( n \sim 4 d_{1.4}^2 \sin i \) cm\(^{-3}\). It can be reconciled with the space-averaged density \( n \sim 0.04\)–0.05 cm\(^{-3}\), expected at \( z \sim 400\)–500 pc (Ferrière 2001, Fig. 2), if \( \sin i \sim 0.3 d_{1.4}^{1/2} \), which would correspond to \( v \sim 600 d_{1.4}^{-1/2} \) km s\(^{-1}\), \( M \sim 40 p_{\text{amb},-12}^{-1/2} d_{1.4}^{-1/2} \), and the tail’s length \( l \sim 6 d_{1.4}^{-1/2} \) pc.

As the ISM pressure is much more uniform than the density, the Mach number values (eqs. [4] and [6]) are more certain than the speed values in equations (3) and (5). On the other hand, the ambient pressure in the pulsar vicinity may be higher than the typical ISM pressure because the pulsar’s UV emission heats and ionizes the surrounding medium (e.g., Bucciantini & Bandiera 2001). Therefore, the Mach numbers can be somewhat lower than the numerical values in equations (4) and (6). In addition, we should not forget that our estimates are based on the assumption of isotropic distribution of the unshocked pulsar wind. The estimates may change considerably if the wind is essentially anisotropic, but no relativistic MHD models have been published for this case so far.

FIG. 10.—Confidence contours (68% and 90%) in the \( n_{\text{H}}-T \) plane for the PL fit to the J1509 head (blue contours), R1 (green contours), and the entire tail (black contours) spectra. The contours are obtained with the PL normalization fit at each point of the grid. The \( \chi^2 \)-values obtained from the fits with fixed \( n_{\text{H},22} = 0.42 \) (inferred from the DM value assuming 10% ISM ionization) are shown by the error bars.

FIG. 11.—Confidence contours (68% and 90%) for the PL fits to the J1509 PWN regions (labeled in the plot) for the fixed \( n_{\text{H},22} = 2.1 \). The PL normalization is in units of \( 10^{-18} \) photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at 1 keV. The dashed curves are the loci of constant unabsorbed flux in the 0.5–8 keV band; the flux values near the curves are in units of \( 10^{39} \) ergs cm\(^{-2}\) s\(^{-1}\).
TABLE 3
PL FITS TO THE J1509 AND J1740 PWN SPECTRA

| Model          | $m_{1,22}$ | $N_\gamma$ | $\Gamma$ | $\chi^2$/dof | $L_{X,22}$ | $L_{17}$ | $B_\gamma$ |
|----------------|-----------|------------|----------|--------------|------------|----------|------------|
| J1509          |           |            |          |              |            |          |            |
| Head           | [1.3]     | 0.7 ± 0.2  | 1.27 ± 0.25 | 7.56/9       | 1.15 ± 0.32 | 23       | 2.7        |
|               | [2.1]     | 1.4 ± 0.15 | 1.83 ± 0.30 | 8.37/9       | 1.33 ± 0.41 | 27       | 5.3        |
| R1            | [2.1]     | 5.7 ± 1.9  | 2.12 ± 0.22 | 3.60/8       | 4.4 ± 0.4  | 5.5       | 1.4        |
| R2            | [2.1]     | 4.3 ± 1.2  | 2.36 ± 0.40 | 1.68/4       | 2.9 ± 0.6  | 3.7       | 0.95       |
| R3            | [2.1]     | 4.7 ± 1.6  | 2.37 ± 0.35 | 2.16/4       | 3.2 ± 0.7  | 2.0       | 0.58       |
| Entire tail    | [2.1]     | 16.5 ± 2.4 | 2.36 ± 0.15 | 9.1/14       | 11.2 ± 1.0 | 3.5       | 1.0        |
| J1740          |           |            |          |              |            |          |            |
| Bright tail    | 0.05±0.11 | 0.73±0.20  | 1.37±0.25 | 50.9/38      | 0.16±0.04  | 0.91      | 0.1        |
|                | [0.1]     | 0.80±0.11  | 1.48±0.19 | 51.539       | 0.15±0.04  | 0.88      | 0.1        |

Note.—The uncertainties are given at the 68% confidence level for one interesting parameter.

a The fits for J1509 are for fixed $m_{1,22} = m_1/10^{22}$ cm$^{-2}$. For J1740, the fits are for both free and fixed $m_{1,22}$ (fixed values are in brackets).
b Spectral flux in units of $10^{-1}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV.
c Isotropic luminosity in units of $10^{32}$ ergs s$^{-1}$.
d Mean unabsorbed intensity in units of $10^{-1}$ photons cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ in the 0.5–8 keV band for J1509 and the 0.4–10 keV band for J1740.

3.2. Magnetic Field and Flow Speed

Assuming some value for the ratio $k_m = w_{mag}/w_{rel}$ of the magnetic energy density, $w_{mag} = B^2/(8\pi)$, to the energy density of relativistic particles, $w_{rel}$, the magnetic field in the tails can be estimated from the measured synchrotron surface brightness (Pavlov et al. 2003):

$$B = 7.2 \left( \frac{k_m}{a_p(3 - 2\Gamma)} \right) \left[ E_{mp}^{(3-2\Gamma)/2} - E_{mp}^{(3-2\Gamma)/2} \right]^{2/7} \mu G.$$  (7)

Here $B = N/A = 10^{-8} B_\gamma$ photons (s$^{-1}$ keV arcsec$^{-2}$)$^{-1}$ is the average spectral surface brightness at $E = 1$ keV (see Table 3), $N$ is the normalization of photon spectral flux measured in area $A$, $A = 10^{17} s_{17}$ cm$^2$ is the average length of the radiating region along the line of sight, $E_{mp} = E_{mp}^y y_{mp}, E_{mp} = E_{mp}^y y_{mp}, E_{mp}$ and $E_{mp}^{y_{mp}}$ are the lower and upper energies of the photon power-law spectrum (in keV), and $y_{mp}, y_{mp}$, and $a_p$ are the numerical coefficients whose values depend on the slope $p = 2\Gamma - 1$ of the electron power-law spectrum.
power-law spectral energy distribution (see Table 4 and Ginzburg & Syrovatskii 1965).

The quantities $B$ and $\Gamma$ have been directly measured (Table 3), and $\delta$ can be estimated assuming that it is close to the observed tail’s width. In addition to these parameters, the strength of the magnetic field depends on the boundary energies of the photon power-law spectrum, which are rather uncertain because of the lack of sensitive high-resolution observations outside the X-ray range. However, the observed softening of the J1509 tail spectrum is smaller than the lower energy of the ACIS band, $(2 \pm 3) \times 10^8$ (i.e., the maximum electron energy $E_{\text{e,M}} \simeq 150$ TeV), for the J1509 tail.9 The Larmor radius for such electrons is $r_{\text{L}} \sim 10^{-4} - 10^{-2}$ km (depending on the $\Gamma$-value; see § 3.3 and Fig. 14), which would correspond to a factor of 1.5–6 higher magnetic fields. On the other hand, the magnetic field strength may be lower than $B_{\text{eq}}$ if $k_m < 1$ (e.g., by a factor of 1.9 if $k_m = 0.1$.) Overall, it seems reasonable to conclude that the magnetic fields in the J1509 tail are in the range $\sim 10^{-10} - 100$ G (probably closer to the upper end of this range), while the magnetic field in the J1740 tail is a factor of a few lower. To obtain more certain estimates, deeper ACIS observations and observations outside the X-ray range would be most important.

Using the magnetic field estimates, we can constrain the maximum electron Lorentz factor required for producing the observed X-ray power-law spectrum: $\gamma_M \approx 7.6 \times 10^7 (E_{\text{e,M}}/\mu G)^{1/2} (B/10 \mu G)^{-1/2} \gtrsim 3 \times 10^9$ (i.e., the maximum electron energy $E_{\text{e,M}} \simeq 150$ TeV), for the J1509 tail.9

9 We should note that HB07 assumed $\gamma = 10^6$ and derived the magnetic field $B \sim 5 - 7$ $\mu G$ in the shocked region. Such parameters are inconsistent with the X-ray data because they correspond to the characteristic energy of synchrotron radiation, $E \sim 0.03$ eV, in the infrared range ($\lambda \sim 30 \mu m$), 9 orders of magnitude below the observed X-ray energies.
The magnetic fields derived above and the measured projected tail length allow one to constrain the average projected flow speed in the tail:

\[ v_{\text{flow,}} \sim \frac{I_{\perp}}{\tau_{\text{syn}}} \]

\[ \sim 860 \left( \frac{I_{\perp}}{1 \, \text{pc}} \right) \left( \frac{B}{10 \, \mu\text{G}} \right)^{3/2} \left( \frac{E}{1 \, \text{keV}} \right)^{1/2} \text{ km s}^{-1}, \quad (8) \]

\[ \tau_{\text{syn}} = 5.1 \times 10^{8} \gamma^{-1} B^{-2} \text{ s} \]

\[ \sim 1100 \left( \frac{B}{10 \, \mu\text{G}} \right)^{-3/2} \left( \frac{E}{1 \, \text{keV}} \right)^{-1/2} \text{ yr} \quad (9) \]

is the synchrotron cooling time [here we used the characteristic Lorentz factor, \( \gamma \sim 1.4 \times 10^{4} (B/10 \, \mu\text{G})^{-1/2} (E/1 \, \text{keV})^{1/2} \) for the electrons that give the main contribution to the synchrotron radiation at energy \( E \)]. Using equation (8), the magnetic fields in Table 4, and the highest energies at which the different regions of the J1509 tail are seen, we obtain \( v_{\text{flow,}} \gtrsim 7500 \text{ km s}^{-1} \) for R1, and \( v_{\text{flow,}} \sim 13,000 \) and \( 12,000 \, \text{km s}^{-1} \) for R1 + R2 and R1 + R2 + R3, respectively, for \( d = 4 \, \text{kpc} \). Given the uncertainty of the magnetic field estimates, the actual average flow speeds can be in the range \( v_{\text{flow,}} \sim 5000–100,000 \, \text{km s}^{-1} \), with higher values more plausible than lower ones. A similar consideration for the J1740 tail yields \( v_{\text{flow,}} \gtrsim 1000 \, \text{km s}^{-1} \), but we should note that this is only a conservative lower limit (because the actual projected tail length is likely larger than observed), and \( v_{\text{flow}} = v_{\text{flow,}} / \sin i \) can substantially exceed the projected velocity for small \( \sin i \). More certain estimates for \( v_{\text{flow}} \) could be obtained by direct measurements of the proper motion of the emission “clumps” (local brightenings) in the J1509 tail (see Fig. 5, bottom left), similar to the proper-motion measurements of moving “blobs” in the Vela pulsar jet (Pavlov et al. 2003), which would require a series of deep ACIS observations.

Even with account for the large uncertainty, we can conclude that, at least for the J1509 tail, the flow speed is much larger than any reasonable pulsar speed. This means that the equation \( \tau_{\text{syn}} = l / v_{\text{syn}} \), used in many papers on bow shock–tail PWNs (e.g., HB07), is inapplicable.\(^{10}\) (The latter equation implies that the downstream flow instantly acquires the velocity of the ambient medium [i.e., \( v_{\text{flow}} = v_{\text{syn}} \) in the pulsar reference frame], leaving a synchrotron-emitting “trail” behind the moving pulsar.) On the other hand, the inferred flow speed is smaller than \( v_{\text{flow}} \sim 0.8c \sim 0.9c \) obtained in numerical simulations by B05 for the bulk of the tail volume behind the TS bullet. However, those simulations were done only for the beginning of the tail (e.g., for distances \( \leq 10R_{\text{d}} \) from the pulsar in B05), whereas we analyze a much larger extent of the tail (up to \( l_{\perp} \sim 600R_{\text{d}} \)). It seems plausible that the flow is mildly relativistic in the immediate vicinity behind the TS bullet, and it decelerates at larger distances because of the expansion of the overpressurized flow, entrainment of the ISM material (e.g., caused by the shear instability at the CD surface separating the fast-moving shocked PW from the shocked ambient ISM), or internal shocks in the tail.

The broadening of the J1509 X-ray tail with increasing distance \( z \) from the pulsar (Fig. 6) suggests that the cross-sectional area of the tail increases up to \( z \approx 1.5l_{\perp} \), as \( S(z) \propto z^{\kappa} \), with \( \kappa \approx 0.7–1.5 \). At larger distances, \( 2l_{\perp} \approx z \approx 5l_{\perp} \), the tail seems to have more or less constant width, although this requires confirmation with deeper observations. The observed radial expansion of the tail at large \( z \) significantly exceeds the predictions by Romanova et al. (2005, eqs. [32]–[34]), for plausible values of \( v_{\text{flow}} \) and \( v_{\text{pol}} \) (see Fig. 7). Including the interaction between the shocked pulsar wind and shocked ambient gas at the CD surface might help to bring the model predictions in agreement with the observations. Polarimetric observations in the radio would allow one to measure the direction of the magnetic field in the tail and test whether it is consistent with the toroidal field assumption adopted in the current models.\(^{11}\) We should note that the relationship between \( B, S, \) and \( v_{\text{flow}} \) at given \( z \) depends on the magnetic field topology. For instance, in ideal MHD models, \( B \propto v_{\text{flow}}^{1} S^{-1/2} \) for purely toroidal magnetic field (B05), while \( B \propto S^{1} \) if the magnetic field is parallel to the tail direction. Deep X-ray observations would allow one to measure both \( S(z) \) and \( B(z) \) and test the validity of the ideal MHD approximation and the impact of the ambient matter entrainment.

### 3.3. Multiwavelength Aspects

The good alignment between the X-ray tail of J1509 and the elongated radio feature seen in the SUMSS image (Fig. 13) suggests their physical association (HB07). As it was noted by HB07, the larger length of the J1509 radio tail could be explained by slower synchrotron cooling of the radio-emitting electrons. However, the elongated radio feature has highly nonuniform surface brightness, with two maxima. The maximum located at \( \approx 8l_{\perp} \) from the pulsar is clearly associated with an unrelated point source, possibly an active galactic nucleus. (The source is also seen in X-rays; it is marked “R” in Fig. 1.) The origin of the other maximum (located about \( 5l_{\perp} \) from the pulsar) is unclear. It appears to be extended and could be a remote supernova remnant (SNR, as suggested by Whiteoak & Green 1996), a radio galaxy, or an inhomogeneity in the pulsar wind flow (e.g., due to an internal shock or instability). To discriminate between these possibilities, deeper radio and X-ray observations are needed.

Another puzzling aspect is the gradual decrease in the radio surface brightness of the tail toward the pulsar (the brightness drops by at least a factor of 5 from its maximum value at \( \approx 5l_{\perp} \) from the pulsar), in contrast with the X-ray surface brightness that increases toward the pulsar (see Fig. 13). Unfortunately, the SUMSS image is not deep enough to show whether or not the putative radio tail actually connects to the pulsar. If the radio emission is indeed associated with the J1509 tail, the decrease in the radio surface brightness toward the pulsar cannot be explained by the synchrotron cooling because the corresponding cooling time, \( \tau_{\text{syn}} = 1.7 \times 10^{7} (B/10 \, \mu\text{G})^{-3/2} (\nu/1 \, \text{GHz})^{-1/2} \, \text{yr} \), greatly exceeds the pulsar’s age. To explain the lack of radio emission closer to the pulsar, one has to assume that the number density of particles, \( n(z) \), increases with the distance from the pulsar [e.g., \( n(z) \propto 1/v_{\text{flow}}(z) \) for a constant cross-sectional area of the tail]. This increase would not result in higher X-ray surface brightness if the most energetic electrons, responsible for the X-ray emission, undergo strong synchrotron cooling, such that their emission moves out of the X-ray band by the time when the flow reaches the distance where \( n(z) \) increases substantially. Similar spatial radio–X-ray anticorrelation has been reported for the

\(^{10}\) It was also pointed out by Kaspi et al. (2001) for the tail of PSR B1757–24.

\(^{11}\) So far, only the Mouse PWN tail has been thoroughly studied in the radio, and the direction of the detected polarization suggests that the magnetic field is predominantly aligned with tail direction (Yusef-Zadeh & Gaensler 2005), contrary to the current models.
PWNe around the Vela pulsar (Dodson et al. 2003; Kargaltsev & Pavlov 2004) and PSR B1706−44 (Romani et al. 2005), which are moving with \( M \leq 1 \). On the other hand, in the Mouse PWN both the radio and X-ray emission are brightest near the pulsar and gradually fade with increasing \( z \). Note that the Mouse X-ray tail appears to be shorter (\( l_1 \sim 1 \) pc), or at least its X-ray surface brightness drops faster with the distance from the pulsar than in the J1509 and J1740 tails, which could result from faster cooling or lower flow speed. We also note that the remarkable 12-fold \( l_1 \) of the J1740 tail is substantially harder than those of the J1509 and Mouse tails, suggesting a less efficient cooling or a different injection spectrum. In addition, one should keep in mind that, most likely, we have detected only the \( \sim 2 \) pc brighter part of the J1740 tail, where the cooling makes no significant effect, while the entire tail can be substantially longer. A deep Chandra ACIS observation is necessary to reveal the true extent of the J1740 tail and search for spectral changes associated with the cooling.

So far, no TeV emission has been found in the vicinity of bow shock−tail X-ray PWNe, with the possible exception of the nebula associated with PSR B1509−58 (Aharonian et al. 2005), where the origin of the bright feature southeast of the pulsar (Gaensler et al. 2002) is not completely understood (it could be a jet, a tail, or, more likely, a combination of those, i.e., a jet behind the pulsar moving at \( M \sim 1 \)). However, the X-ray images of J1509 and J1740 reveal the presence of relativistic electrons with \( \gamma \sim 10^4 \), which, for a plausible magnetic field \( B \sim 10 \mu G \), can produce TeV emission via the inverse Compton scattering of the background IR and cosmic microwave background photons. Furthermore, given the large angular extent of these tails, their TeV emission can be resolved with the current TeV observatories such as H.E.S.S., MAGIC, and VERITAS. The high-energy GeV emission may also be detectable with GLAST (Gamma-Ray Large Area Space Telescope) if there is a substantial density of synchrotron radio photons that will be upscattered into the GeV range.

### 3.4. Comparison with Other Pulsar Tails

Table 5 summarizes the X-ray properties of eight PWNe with firmly established long X-ray tails. The two most luminous tails belong to the very young, energetic PSR J0537−6910\(^2\) (located in the LMC SNR N157B), whose 26 yr old PSR J1747−5928 (the Mouse PWN), whose X-ray efficiencies, \( \epsilon_{\text{pwn}} \equiv L_{\text{pwn}}/E \), are \( 2.2 \times 10^{-2} \) and \( 1.6 \times 10^{-2} \), respectively. The J1509 tail ranks among the most luminous X-ray tails in the Galaxy.

#### Table 5: Properties of Long Pulsar Tails

| PSR          | SNR       | \( d \) (kpc) | \( v_z \) (km s\(^{-1}\)) | \( \log \tau \) (yr) | \( \log E \) (erg s\(^{-1}\)) | \( l_1 \) (pc) | \( \log L_{\text{pwn}} \) (erg s\(^{-1}\)) | \log \( t_{\text{pwn}} \) | Rad.\(^a\) | Ref.\(^f\) |
|--------------|-----------|---------------|---------------------------|-------------------|-------------------------|-------------|-----------------------------|-----------------|---------|---------|
| J0537−6910... | N157B     | 50            | 600                       | 3.70              | 38.68                   | 3.7         | 36.43 ± 0.02                | −2.24           | Y       | 1, 2    |
| B1757−24....  | ...       | 5             | 130                       | 4.19              | 36.41                   | 0.5         | 33.20 ± 0.14                | −3.21           | Y       | 3       |
| J1747−2958... | ...       | 5             | 300                       | 4.41              | 36.40                   | 1.1         | 34.75 ± 0.15                | −1.65           | Y       | 4       |
| J1509−5850... | ...       | 4             | 400                       | 5.19              | 35.71                   | 6.5         | 33.04 ± 0.05                | −2.67           | P       | 5       |
| B1853+01..... | W44       | 3             | 100                       | 4.31              | 35.63                   | 1.3         | 32.39 ± 0.10                | −3.24           | Y       | 6       |
| J1740+1000... | ...       | 1.4           | 400                       | 5.06              | 35.36                   | 2           | 31.54 ± 0.20                | −3.82           | N       | 5       |
| B0355+54..... | ...       | 1.04\(^b\)    | 61\(^c\)                  | 5.75              | 34.66                   | 1.5         | 31.49 ± 0.10                | −3.16           | N       | 7       |
| B1929+10..... | ...       | 0.36\(^b\)     | 177\(^c\)                 | 6.49              | 33.59                   | 1.5         | 29.87 ± 0.25                | −3.72           | P, 8    | 9       |

**Note:**—The table includes pulsars with established parsec-scale X-ray tails. 

\(^a\) Adopted distance to the pulsar. 

\(^b\) Pulsar’s transverse velocity, either obtained from proper-motion and parallax measurements (for B0355+54 and B1929+10; Chatterjee et al. 2004) or estimated from eq. (3), with \( n = 1 \) cm\(^{-3}\) and \( R_5 \) measured from the X-ray data. The exception is J0537−6910, for which we quote the velocity estimated by Wang et al. (2001) from the pulsar travel time (this pulsar may be moving subsonically because of the high sound speed in the young host SNR). Also note that since PSR B1853+01 is embedded in a plasma that shows strong thermal X-ray emission, the assumption \( n = 1 \) cm\(^{-3}\) likely overestimates \( v_z \) in this case. On the contrary, since PSR J1740+1000 is likely moving in a rarefied medium above the Galactic plane, its speed is probably underestimated (see text for discussion). 

\(^c\) Projected length of the tail. 

\(^d\) X-ray luminosity of the tail (including the brighter compact component in the pulsar vicinity) in the 0.5–8 keV band as we measured it from Chandra and XMM-Newton data. The values may differ from those published in the original works (see the references in the last column). 

\(^e\) \( \log L_{\text{pwn}} \) of the allowed range \( 10^{12} \) and \( 10^{16} \) Hz, for the allowed range of the X-ray spectral slopes (an example of such a break is shown in Fig. 14 for \( \Gamma_X = 2.16 \)). Low-frequency breaks (in the 10–100 GHz range) have been previously reported in a number of PWNe, such as G11.2−0.3, G16.7+0.1, and G29.7−0.3 (Bock & Gaensler 2005). The spectrum of the Mouse also shows similar behavior, indicating a break around \( 10^{16} \) Hz (Fig. 14).

\(^f\) Distances obtained from parallax measurements. 

**References:**—(1) Wang et al. 2001; (2) Chen et al. 2006; (3) Kaspi et al. 2001; (4) Gaensler et al. 2004; (5) this work; (6) Petre et al. 2002; (7) McGowan et al. 2006; (8) Becker et al. 2006; (9) Misanson et al. 2007.

\( \text{rad} \) is a factor of \( \sim 20 \) longer than its X-ray tail, yet \( \log \tau \) of the X-ray surface brightness (an example of such a break is shown in Fig. 14 for \( \Gamma_X = 2.16 \)). Low-frequency breaks (in the 10–100 GHz range) have been previously reported in a number of PWNe, such as G11.2−0.3, G16.7+0.1, and G29.7−0.3 (Bock & Gaensler 2005). The spectrum of the Mouse also shows similar behavior, indicating a break around \( 10^{16} \) Hz (Fig. 14).
third in terms of its efficiency, $\eta_{\text{PWN}} \approx 2.6 \times 10^{-3}$, which exceeds the efficiency of, e.g., the Duck PWN ($\eta_{\text{PWN}} = 3.2 \times 10^{-4}$), created by the younger and more powerful PSR B1757−24, whose spin-down properties are very similar to those of PSR J1747−5928. This once again suggests that, although there is a positive correlation of $L_{\text{PWN}}$ with $E$ (see Fig. 15), the X-ray PWN luminosity also depends on other parameters (see KP08). The remaining four pulsars (B1853+01, J1740+1000, B0355+54, and B1929+10) show similar PWN efficiencies, $\eta_{\text{PWN}} = (2−7) \times 10^{-4}$, despite the fact that their spin-down ages and powers differ by more than 2 orders of magnitude. Although some of this scatter could be attributed to the poorly known distances and different sensitivities of the individual X-ray observations, it is likely that, in addition to the spin-down parameters, there are other parameters governing the radiative efficiency of the winds in extended pulsar tails, such as the pulsar speed, the ambient pressure, and the angles between the NS magnetic and spin axes and the velocity vector.

In addition, for the collimated tails with nearly relativistic flow speeds near the pulsar, the orientation with respect to the observer can be important because the tail brightness is proportional to $(1 + \beta \cos i)^{1/2}$, where $\beta = v_{\text{flow}}/c$ and $i$ is the angle between the velocity vector and the direction to the observer. For instance, the ratio of the brightnesses at $i = 30^\circ$ (approaching flow) and $i = 120^\circ$ (receding flow) can be as large as $\approx 10$ for $\beta = 0.3$ and $\Gamma = 2.3$. In addition to the brightness changes, the outflow components approaching and receding at small angles will appear shorter simply as a result of projection. This might explain why the luminous X-ray tail of the more energetic Mouse PWN is so much shorter than that of the less energetic J1740, or why the X-ray tail of the Duck PWN is not only short but also very dim compared to the X-ray tail of the Mouse.

In comparing the X-ray luminosities of pulsar tails with those of PWNe around slowly moving pulsars, we see that, on average, the tails show higher X-ray efficiencies (see Fig. 15). This is natural because in the ram pressure–confined PWNe the energy of the wind flow is channeled into a narrow cylindrical structure (the tail). This results in a higher column density of emitting electrons, hence a higher surface brightness, which allows one to detect the wind emission at larger distances from the pulsar compared to PWNe around slowly moving pulsars where the wind flow is more isotropic.

If the starting flow speed just downstream of the TS back surface is more or less the same (mildly relativistic) for different pulsars, then the observed tail lengths are determined by the magnetic field strengths in the tails (because the synchrotron cooling limits the length) and by the rates at which the tail widths increase with increasing distance $z$ from the pulsar (because the tail broadening reduces its surface brightness). The magnetic field in the tail should be proportional to $(\sigma E)^{1/2}$ (where $\sigma$ is magnetization parameter in the preshock wind). The lack of correlation with $E$ in the current, very limited sample (Table 5) might be attributed to different wind magnetization in different pulsars and/or a large spread of the unknown inclination angles of the tails. The tail width is expected to show a negative correlation with the ambient pressure (e.g., $R_{\text{tail}} \propto \left( E / (t_{\text{flow}} P_{\text{amb}}) \right)^{1/2}$ in the Romanova et al. 2005 model); however, the dependence is too weak to be tested with the existing data.

4. SUMMARY

We have presented a detailed analysis of the properties of two PWNe associated with the supersonically moving pulsars J1509−5850 and J1740+1000. In both cases, the X-ray images reveal parsec-scale tails connected to the pulsars. The observed extraordinary lengths of the tails suggest that the tail flow starts as mildly relativistic, and its speed remains much higher than the pulsar speed up to a distance of a few parsecs. The large extent of the J1509 tail suggests an average flow speed in excess of $\sim 5000 \, \text{km} \, \text{s}^{-1}$ (a conservative lower limit). We estimate the average equipartition field in the J1509 tail to be a few $\times 10^{-5}$ G, with a hint of weakening with the distance from the pulsar. The equipartition field in the J1740 tail is likely to be a factor of a few lower. A noticeable difference between the two tails is that the spectrum of the J1740 tail is substantially harder, implying that either the cooling is not as efficient in the J1740 tail (consistent with the inferred lower magnetic field) or the electron injection spectrum of J1740 is intrinsically harder compared to that of J1509. The projected orientation of the J1740 tail on the sky suggests that the pulsar is moving toward the Galactic plane. This means that the pulsar was born well above the Galactic disk rather than ejected from the disk with a high speed.

The existing shallow radio survey data suggest a possible radio counterpart to the J1509 tail; however, a confusion with the background sources remains a possibility until better quality radio data are obtained. If the radio feature is indeed associated with the J1509 tail, then the tail spectrum should exhibit a break between $10^{12}$ and $10^{16}$ Hz.

The comparison between the J1509 and J1740 tails and the X-ray tails from other fast-moving pulsars shows that the X-ray luminosity does not correlate well with the pulsar spin-down luminosity and age; other physical parameters such as the pulsar velocity, the ambient pressure and sound speed, and the angle between the pulsar’s spin and magnetic axis may be equally important. In general, we find that the X-ray efficiencies of the ram pressure–confined PWNe are systematically higher than those of PWNe around slowly moving pulsars with similar spin-down parameters.

We thank Vladi Kondratiev for the help with the archival radio data, and Niccolò Bucciantini and Richard Lovelace for the useful discussions of theoretical models. We are grateful to Bryan Gaensler for careful reading of the paper and useful suggestions. This work was partly supported by NASA grant NNX06AH67G and Chandra award SV4-74018.
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