CHANDRA VIEW OF PULSAR WIND NEBULA TORI

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ABSTRACT

The results from a systematic study of 11 pulsar wind nebulae with a torus structure observed with the Chandra X-ray Observatory are presented. A significant observational correlation is found between the radius of the tori, \( r \), and the spin-down luminosity of the pulsars, \( \dot{E} \). A logarithmic linear fit between the two parameters yields \( \log r = (0.57 \pm 0.22) \log \dot{E} - 22.3 \pm 8.0 \) with a correlation coefficient of 0.82, where the units of \( r \) and \( \dot{E} \) are pc and ergs s\(^{-1}\), respectively. The value obtained for the \( \dot{E} \) dependency of \( r \) is consistent with a square-root law, which is theoretically expected. This is the first observational evidence of this dependency, and provides a useful tool to estimate the spin-down energies of pulsars without direct detections of pulsation. Applications of this dependency to some other samples are also shown.

Key words: pulsars: general – shock waves – stars: neutron – X-rays: stars

1. INTRODUCTION

Active pulsars eject relativistic pulsar winds comprised of relativistic particles and magnetic field. Such winds are terminated by a strong shock where pressure balance is attained with the ambient medium. High-energy particles diffusing out in the downstream of the shock emit radio to very high-energy gamma rays via synchrotron or inverse Compton processes, which are observed as pulsar wind nebulae (PWNe). The distance from the pulsar to the termination shock, \( r_s \), is expected to be

\[
r_s = \left( \frac{\dot{E}}{4\pi c^3 \eta P_{\text{ext}}} \right)^{1/2},
\]

where \( \dot{E} \), \( c \), \( \eta \), and \( P_{\text{ext}} \) are the spin-down luminosity of the pulsar, the light speed, the filling factor, and the external pressure (Rees & Gunn 1974). The size of shocks should be roughly 0.01–0.1 pc with typical parameters of PWNe (Kennel & Coroniti 1984). In the case of a weakly-magnetized pulsar wind, which is believed to apply to most of these systems, particle energy density dominates that of magnetic field energy at the shock in which the emissivity of synchrotron radiation is relatively low. Then, the shock is generally invisible with the current instruments except for the brightest example, the Crab Nebula (Weisskopf et al. 2000). The equipartition between particle and magnetic field energy, at which the synchrotron emissivity is the highest, is reached at a distance of a few times of \( r_s \), as the post-shock flow decelerates (Kenneal & Coroniti 1984). Considering that most of the pulsar wind energy is blown near the equatorial plane and that synchrotron cooling becomes efficient at the outer region, a torus-like structure is expected in this system whose radius is a few times of \( r_s \).

The Chandra X-ray Observatory has actually revealed the torus (and jet-like) structures from several PWNe, thanks to the excellent spatial resolution of 0.5 arcsec (compare Kargaltsev & Pavlov 2008). Ng & Romani (2004) developed a sophisticated method to fit three-dimensional model to the tori, which they applied to the Chandra data of several PWNe (Ng & Romani 2008), providing the most reliable values of the torus radius. Since the termination shock radius is expected to be proportional to the square root of the spin-down luminosity, the torus radii may scale in the same way as the shock radii, if so, one would expect a correlation between the torus radii and the spin-down luminosities following the square-root law. In this paper, we confirm this relationship for the first time, and show its astrophysical use for some PWNe.

2. SAMPLES

In this paper, we used 11 samples for our study with the following criteria. Chandra observed several tens of PWNe (Kargaltsev & Pavlov 2008). Thanks to the excellent spatial resolution of the X-ray telescope, equatorial tori and polar jet structures are discovered in more than 10 PWN systems. Ng & Romani (2004, 2008) measured the torus radius of 10 PWNe with the developed method by Ng & Romani (2004). Romani et al. (2005) used the same method to B1706–44, and we added this PWN to our sample.

Table 1 shows details of our samples. Our samples are so young that the pulsar wind is still strong and morphological distortion due to pulsar motion is still relatively small; old systems sometimes show cometary structure controlled by this effect. Actually, they are categorized under “PWNe with toroidal components” in Kargaltsev & Pavlov (2008) except for J0537–6910, which has a cometary nebula (Chen et al. 2006). Ng & Romani (2008) derived the size of its torus (\( r_{\text{arcsec}} \)) after subtracting the diffuse nebula, and we use the parameters by Ng & Romani (2008). The latest distance estimates are used to calculate the physical radius of the tori (\( r \) in Table 1) with references in Table 1.

3. RESULTS

In this section, we search for a correlation between the torus radius \( r \) and spin-down luminosity \( \dot{E} \). Figure 1 represents the plot of \( r \) as a function of \( \dot{E} \). Uncertainties of \( r \) in the figure are obtained simply by multiplication of the nebula distances and the statistical uncertainties in apparent torus radii determined by Ng & Romani (2004, 2008) and Romani et al. (2005). It is apparent that there is a strong positive correlation between log \( \dot{E} \) and log \( r \), yielding a correlation coefficient of 0.82. This power-
law-like correlation is as expected as we review in Section 1. On the other hand, it is also obvious that there is a non-negligible fluctuation beyond a simple power-law function owing to the statistical uncertainties. These facts suggest that $r$ is certainly a function of $E$ but that there are other hidden parameters which give a larger fluctuation to this relation than the given statistical uncertainties. We will discuss the possible origin of the parameters later. We thus fit the data weighting them equally with a power-law function,

$$\log r = \alpha \log E + \beta,$$

where $\alpha$ and $\beta$ are constant values. We obtained

$$\alpha = 0.57 \pm 0.22,$$

$$\beta = -22.3 \pm 8.0,$$

respectively. The best-fit model is shown in Figure 1 with a thick solid line.

In order to check our result from a different point of view, we calculated the correlation coefficient between $\log E$ and $r/E^\alpha$, which should be 0 with the best-fit $\alpha$. Figure 2 shows the relation between $\alpha$ and the correlation coefficient. We can see that the correlation coefficient becomes close to 0 when $\alpha$ is between 0.5 and 0.6. This result indicates again that $\alpha$ is around 0.5–0.6.

The value of $\alpha$ agrees well with the expected 0.5 (Equation (1)). It also implies that the torus radius scales in the same manner as the radius of the termination shock. If we fix $\alpha$ to be 0.5, the equation becomes

$$\log r = 0.5 \log E - 19.6 \pm 0.2.$$  \hspace{1cm} (4)

This result is also shown in Figure 1 with a thick dashed line.

There are three samples that are well below the best-fit lines: Vela, PSR J2229+6114, and PSR J1124–5916. The former two are known to show clear evidences of interaction with ejecta or the interstellar medium (LaMassa et al. 2008; Kothes et al. 2001). In such a case, as is indicated by Equation (1), the torus radii could be smaller confined by higher external pressure compared to those without interaction with the surrounding medium. As for the last one, Park et al. (2004) showed that the reverse shock has not yet begun to interact with it. However, the latest 510 ks Chandra observation revealed the almost 3 times larger torus compared with that seen in the previous 50 ks Chandra observation which Ng & Romani (2008) analyzed (Park et al. 2007).

Taking these facts into account, we made another fit where Vela and PSR J2229+6114 are excluded and the original value...
of PSR J1124−5916 is multiplied by a factor of 3. In this fit, we found the better correlation factor of 0.93 and obtained the best-fit model of

$$\log r = (0.49 \pm 0.12) \log \dot{E} - 19.2 \pm 4.7$$

(5)
as shown with a thin solid line in Figure 1.

We also searched for correlation between the torus radius and other physical parameters, such as age of PWNe, magnetic field, and so on, but could not find any significant correlation.

4. DISCUSSION

4.1. Termination Shocks and Tori

Equation (3) shows that the tori radii ($r$) show a square-root dependence on $\dot{E}$ like the termination shock radii ($r_\text{t}$). This is the first clue of the termination shocks in PWNe.

Here, we introduce $z \equiv r/r_\text{t}$, the ratio between the radii of observed torus and the shock. The value of $z$ can be common among pulsars in spite of different pulsar parameters and environment. Assuming Equation (4),

$$z = r/r_\text{t}
= \frac{10^9 (4\pi c^2 \eta P_\text{ext})^{1/2}}{1.6 \times 10^{-9} \text{[g cm}^{-2} \text{s}^{-1}]^{1/2}
= 1.9^{+1.1}_{-0.7} \left(\frac{\eta}{1}\right)^{1/2} \left(\frac{P_\text{ext}}{1.6 \times 10^{-9} \text{[g cm}^{-2} \text{s}^{-1}]}ight)^{1/2}

(6)

When the temperature, number density, and filling factor of external environment of the termination shock is 1 keV, 1 cm$^{-3}$, and 1, ($P_\text{ext} = 1.6 \times 10^{-9}$ g cm$^{-2}$ s$^{-2}$), the ratio of radii of X-ray torus and termination shock is almost unity. The X-ray emission should come from the outside region of the termination shock according to Kennel & Coroniti (1984), which supports our result.

The best-fit $\alpha$, 0.57, is slightly larger than the theoretical value in Equation (1). The data scatter seems to be larger at lower values for spin-down energy. It could be due to an age effect. The fitting without Vela and J2229+6114, which interact with values for spin-down energy. It could be due to an age effect.

We estimate how large fluctuation of $r$ is required to reproduce the correlation coefficient of 0.82 by a simple simulation. A single trial of the simulation generates 11 samples from a parent population with fluctuated environment, which is simulated by log-normal variation in the product $\eta P_\text{ext}$ with a given standard deviation of $\sigma_0$. We made 1000 trials with a given $\sigma_0$ to calculate an expected correlation coefficient ($A$) and the probability for $A$ to be larger than 0.82. Table 2 lists the expected correlation coefficient and the probability with different $\sigma_0$'s. The simulation suggests that the observed scatter is explained if $\sigma_0 \sim 0.6$, i.e., if fluctuation in $\eta P_\text{ext}$ is a factor of $\sim 4$.

One may think that the distance uncertainty may be a primary source of this fluctuation. If it is the case, we need a factor of 2 fluctuation of distance since the fluctuation of the torus radii is linearly connected to the distance uncertainty, which is the square root of $\eta P_\text{ext}$ fluctuation. Although distance to astronomical bodies is not always constrained very well, the factor of 2 appears to be too large to be attributed to the distance uncertainty alone, especially for such famous and well-studied samples. One of the most famous and general measurement method of distance to supernova remnants (SNRs) is to use the $\Sigma$-$D$ relation (e.g., Case & Bhattacharya 1998); the distances to more than $200 \text{SNRs}$ are estimated using the surface brightness at 1 GHz and diameter relation, although there is $\sim 40\%$ dispersion between distance from their method and those from other methods. This is because $\Sigma$-$D$ relations can be used to estimate properties of ensembles of SNRs, not for individual one, as Case & Bhattacharya (1998) mentioned. Our relation on the PWN tori can be used in similar way to $\Sigma$-$D$ relation to estimate their distance.

The fluctuations of $\eta$ and $P_\text{ext}$ result in that of $r_\text{t}$, and thus that of $r$ as well. A fluctuation of $r$ by a factor of 2 roughly corresponds to that of $\eta P_\text{ext}$ by a factor of 4. This level of fluctuation could easily occur about $P_\text{ext}$. The density of external gas, which is inside SNR shells, differ by about three orders of magnitude from SNR to SNR, from $\sim 0.1 \text{SN 1006; Yamaguchi et al. 2008}$ up to $\sim 200 \text{SN 1006; Lazendic et al. 2006}$. Thus, we believe that the variation of $P_\text{ext}$ is the primary cause of the scatter. Actually, the torus of Vela X, which evidently interacts with ejecta, has a smaller radius relative to the best-fit function, which may be due to the larger $P_\text{ext}$ effect among our samples. Samples without these PWNe show clearly tighter correlation. The fluctuation of $\eta P_\text{ext}$ is also estimated with Equation (5) to be 2.5, as shown in Table 3, which is much smaller than those with all samples.

The interesting thing is that all of the samples with small tori are categorized into combined type SNRs, which have radio shells and PWNe. It could be due to that SNRs with bright shells have higher densities inside the remnants. The detailed systematic and observational study of $P_\text{ext}$ for individual objects might give a better explanation of this fluctuation, although it is beyond the scope of this paper.

All we mentioned above are the “negative” factors which tend to wash out the correlation between $\dot{E}$ and $r$. Nonetheless, we found it with relatively high significance, which in turn suggests the robustness of this correlation.

### Table 2

| $\sigma_0$ | $\sigma_0/2$ | ($\alpha$) | $P(A > 0.82)$ |
|-----------|-------------|-----------|--------------|
| 0.4...    | 0.2         | 0.90      | 0.93         |
| 0.56...   | 0.28        | 0.82      | 0.56         |
| 0.6...    | 0.3         | 0.80      | 0.49         |
| 0.8...    | 0.4         | 0.71      | 0.23         |
| 1.0...    | 0.5         | 0.62      | 0.12         |

### Table 3

| $\sigma_0$ | $\sigma_0/2$ | ($\alpha$) | $P(A > 0.93)$ |
|-----------|-------------|-----------|--------------|
| 0.2...    | 0.1         | 0.98      | 1.00         |
| 0.3...    | 0.15        | 0.95      | 0.79         |
| 0.36...   | 0.18        | 0.93      | 0.56         |
| 0.4...    | 0.2         | 0.91      | 0.42         |
| 0.6...    | 0.3         | 0.83      | 0.11         |
| 0.8...    | 0.4         | 0.74      | 0.04         |
5. APPLICATION

Once the correlation between $\dot{E}$ and $r$ is established, it will provide a useful tool to estimate the spin-down energy of pulsars without direct detections of pulsation, although the large error range prevents us from precise parameters determinations. We show some examples of the application. In this section, we cite Equation (3), although using Equation (5) does not alter the results here so much.

5.1. $\dot{E}$ Determination for G0.9+0.1

With Equation (3), we can estimate the spin-down luminosity of PWNe from the radius of tori, without information of pulsation.

Let us consider the example of G0.9+0.1. The SNR G0.9+0.1 has a X-ray bright PWN in the Galactic center region. Gaensler et al. (2001) resolved the PWN with Chandra. The size and flux are 5 arcsec × 8 arcsec and $6.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band, respectively. The torus radius should be about half of the longer extension, 4 arcsec, or 0.16 pc with the distance of 8.5 kpc. With this value and Equation (3), we can estimate the log $\dot{E}$ of G0.9+0.1 to be 37.7. There is no difference whether we use Equation (4) or Equation (3).

Possenti et al. (2002) discovered the empirical relation between $\dot{E}$ and the 2–10 keV luminosity $L_X$ (erg s$^{-1}$) of PWNe of

$$\log L_X = 1.34 \log \dot{E} - 15.34,$$

although the dispersion is large (compare Kargaltsev & Pavlov 2008). We can estimate the spin-down luminosity of G0.9+0.1 independently from their relation to be $\log \dot{E} = 37.4$, which shows very good agreement with our estimate.

Very recently, Camilo et al. (2009) discovered coherent pulsation from the central pulsar with the period and the period derivative of 52 ms and 1.5557 $\times 10^{-13}$ s$^{-1}$, respectively. The resultant spin-down energy is $\log \dot{E}$ of 37.6, which also shows good agreement with our result.

5.2. $\dot{E}$ Determination for G328.4+0.2

Gelfand et al. (2007) found an extended structure in the PWN G328.4+0.2 with XMM-Newton with the size of ~1 arcsec, or 0.09 pc at 17 kpc. The coherent pulsation has not been detected yet. We can estimate the spin-down luminosity in the same way as for G0.9+0.1 to be $\log \dot{E} = 37.3$. This is totally consistent with previous estimation using Possenti et al. (2002), $\log \dot{E} = 37.2$ (Gelfand et al. 2007).

5.3. Distance Determination of PSR J1846–0258

PSR J1846–0258 in SNR Kes 75 is one of the mysterious PWNe with soft-Gamma-ray repeater like flares (Gavriil et al. 2008; Kumar & Safi–Harb 2008). The spin-down luminosity is rather large, $\log \dot{E}$ of 36.91. However, the distance of this interesting source is still unclear: Becker & Helfand (1984) estimated that the distance is 19–21 kpc, whereas Leahy & Tian (2008) suggest that this system is much nearer, 5.1–7.5 kpc.

Equation (3) and the spin-down luminosity indicate a torus radius of 0.07 pc, whereas the detected torus by Ng et al. (2008) has the radius of 10 arcsec. It suggests that the expected distance from $\dot{E}$–$r$ relation is about 1.1 kpc. It is too small compared with other distance estimates, or in other words, the torus radius is too large. This would indicate that either an exceptionally low ambient pressure or the pulsar provides additional pressure from the inside. It could be important information to understand the origin of magnetars, which is still hotly debated (e.g., Vink & Kuiper 2006; Ferrario & Wickramasinghe 2006; Duncan & Thompson 1992; Gavriil et al. 2008). Systematic study of PWN tori of magnetars should be done, although we have few samples until now (Rea et al. 2009; Vink & Bamba 2009).

5.4. Torus Search of DEM L241

The SNR DEM L241 in the Large Magellanic Cloud (LMC) has a compact X-ray source in its center detected with XMM-Newton (Bamba et al. 2006). The flux and photon index are 5.0 $\times 10^{-12}$ in the 2.0–10.0 keV band and 1.57, respectively. The spin-down luminosity expected by Possenti et al. (2002) is $\log \dot{E}_{\text{dot}} = 38.4$, which is one of the largest values among known PWNe. We can confirm it when we can detect the torus of the PWN. The size estimated to be 0.39 pc, or 1.6 arcsec using the distance to the LMC of 50 kpc (Feast 1999), which can be detectable with excellent spatial resolution of Chandra, but not with XMM-Newton (Bamba et al. 2006).

6. SUMMARY

We have made a systematic study of PWN spin-down luminosity and tori radii using Chandra data of 11 samples. It is discovered, for the first time, that $\log r$ and $\log \dot{E}$ have very strong positive correlation. The tori could be X-ray emission originating from the outside of the termination shocks as suggested by Kennel & Coroniti (1984). The fluctuation in the correlation is mainly produced by variation of the external pressure and distance uncertainties. With this correlation, we can estimate the spin-down luminosity and distance to the PWN without information of coherent pulsations. This estimation has been applied to G0.9+0.1, G328.4+0.2, PSR 1846–0258, and DEM L241.

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