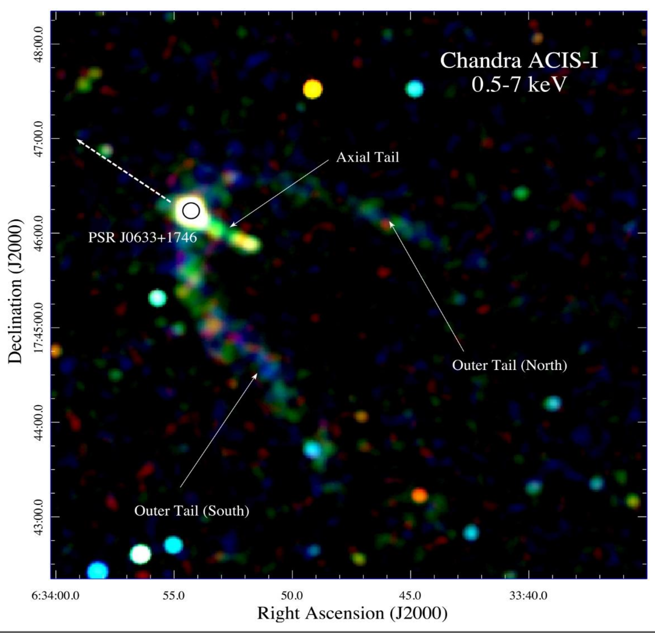
Rapid X-Ray Variations of the Geminga Pulsar Wind Nebula

C. Y. Hui : Department of Astronomy and Space Science, Chungnam National University, Korea
Jongsu Lee : Department of Space Science & Geology , Chungnam National University, Korea
K. H. Kong : Institute of Astronomy and Department of Physics, National Tsing Hua, Taiwan
P. H. T. Tam : School of Physics & Astronomy, Sun Yat-sen University, China
J. Takata : Institute of Particle Physics and Astronomy, Huazhong University od Science and Technology, China
K. S. Cheng : Department of Physics, University of Hong Kong, Hong Kong
Dongsu Ryu : Department of Physics, UNIST, Korea

1. Abstract

We have discovered variabilities on timescales from a few days to a few months from different components of Geminga pulsar wind nebula (PWN). The fastest change occurred in the circumstellar environment at a rate of 80% of the speed of light. One of the most spectacular results is the wiggling of a half light-year long tail as an extension of the jet, which is significantly bent by the ram pressure. The jet wiggling occurred at a rate of about 20% of the speed of light. This twisted structure could possibly be a result of a propagating torsional Alfven wave. We have also found evidence of spectral hardening along this tail for a period of about nine months.

2. Variability Analysis of Various Spatial Components

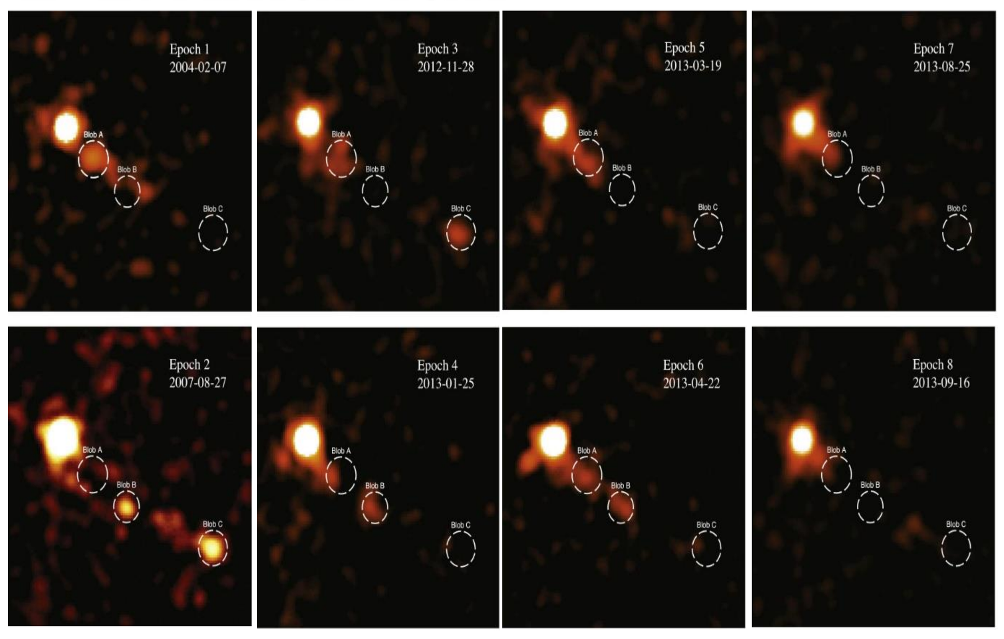


This image is a $6' \times 6'$ deep X-ray color image that combines all *Chandra* data except for those obtained in 2004 (red : 0.5-1 keV; green : 1-2 keV; blue : 2-7 keV). The effective exposure of this image is ~660 ks.

Various components of the PWN are illustrated accordingly. The dashed arrow shows the direction of Geminga's proper motion.

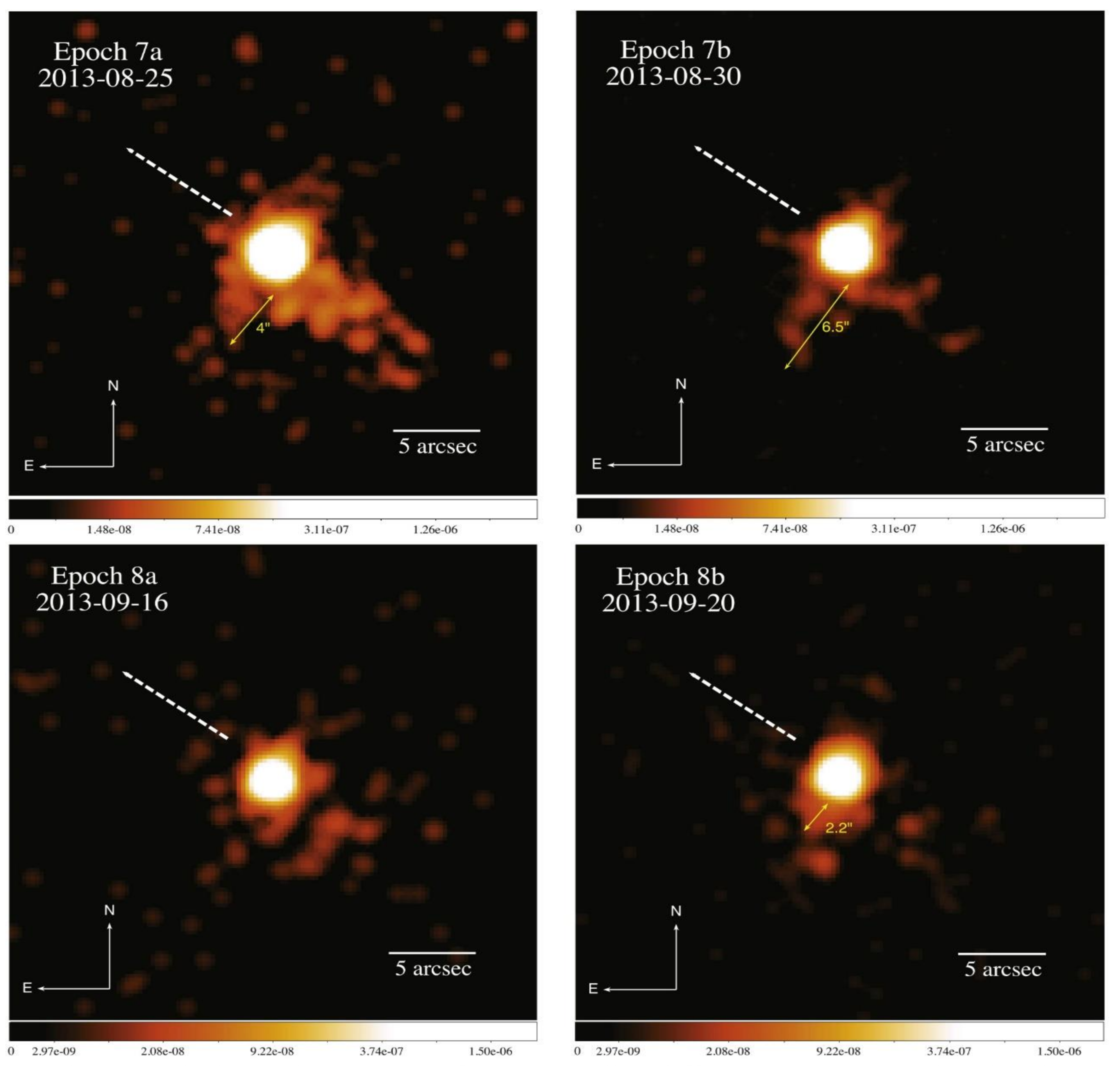
The axial tail is intimately connected to the pulsar and spans an apparent length of ~42" (0.05pc) from the pulsar position to a bright blob at the end of the feature. Besides the axial tail, two outer tails extending out to about 2' (0.15pc) can be clearly seen.

2-1. Axial Tail



Time sequence of Chandra $1' \times 1'$ exposure-corrected images (0.5-7 keV) of the filed around Geminga's axial tail ($0.5'' \times 0.5''$ for 1 pixel). The start date of the corresponding epoch is given in each image. All images are smoothed with a Gaussian kernel of σ=2.5". The dashed circles illustrate the locations of Blobs A, B, and C, detected previously (Pavlov et al. 2010).

2-2. Circumstellar Environment



- The morphological variation of circumstellar diffuse emission can be clearly seen in Epoch 7 and 8.

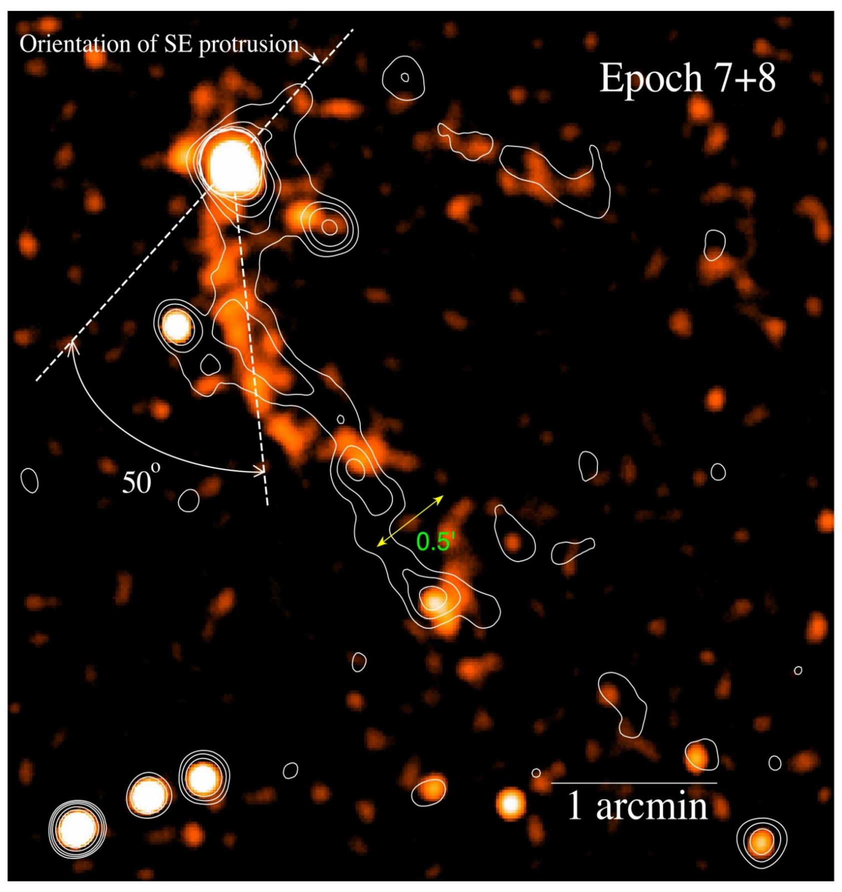
We have performed a high-resolution morphological study of the circumstellar environment to search for the possible diffuse X-ray feature around Pulsar in Epochs 4, 6, 7, and 8.

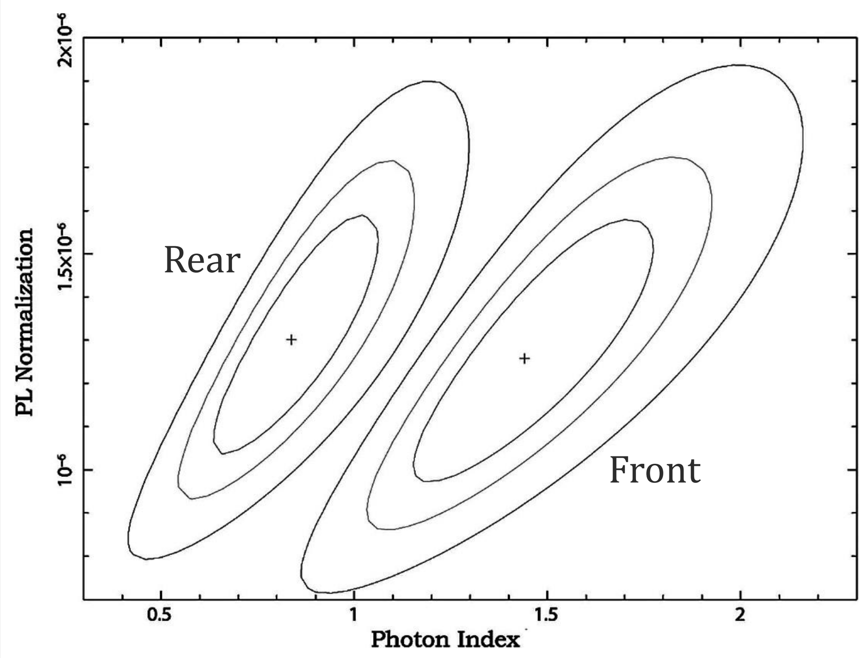
We can see the compact extended feature at perpendicular proper motion of Geminga, which is detected at an S/N of 5.1 σ. Comparing the frame of Epochs 7 and 8, this feature is found to be lengthened by ~2.5" within ~5 days. At a distance of 250 pc, the change in the its physical length is ~9.4×10^{15} *cm*. This implies that the variability of this feature occurred at a speed of ~0.8c.

Its spectrum can be described by a power-law model with a photon index of $\Gamma = 1.16 \pm 0.48$.

While the protrusion is undetected in Epoch 8a, it is found at a significance of 5.3 σ in Epoch 8b. The protrusion was extended by ~2". These show the rapid variability of this feature at a timescale of a few days. Its spectrum can be described by a power-law model with a photon index of $\Gamma = 2.19^{+0.47}_{-0.43}$.

2-3. Outer Tails





In Epochs 7 and 8, the southern tail is found to be significantly twisted with respect to the contours, which was computed from the Epoch 3 with a high S/N (~9,4σ) and no intervention of any CCD gap.

An S-shaped structure can be clearly seen in these images. We combined the exposure corrected images of Epoch 7 and 8 so as to enhance its significance.

Comparing the images in Epoch 3 and 7 (separated by ~9 months), the maximum deviation of the southern tail is ~0.5'. At a distance of 250 pc, the physical length is ~10^{17}cm. These imply that the twisting of the southern tail occurred at a speed of ~0.2c.

In Epoch 7, the spectrum became the hardest among all epochs when the tail was significantly twisted.

As X-ray emission is harder in the far away region ("Rear") than the close region ("Front"), we further investigate the spectral hardening.

There is an indication of spectral softening along the southern tail found in Epochs 2 and3. On the contrary, spectral hardening toward the end of the feature has been observed from Epochs 4 to 8.

By simultaneously fitting their front spectra in theses five epochs, the confidence contours are shown in left-down Figure, which clearly shows the significant spectral variation along the southern outer tail.

3. Summary and Discussion

All these results can be interpreted in the context of general model of PWN structure that consists of a torus around pulsar, jets along the spin axis, and a synchrotron nebula resulting from the post-shock (cf. Gaensler & Slane 2006).

Both outer tails can be interpreted as bipolar outflows from the pulsar that are bent by the ISM ram pressure. Such significant jet bending has not been seen in other PWNe. Our interpretation is supported by the discovery of the collimated southern protrusion that is connected to the southern outer tail.

In this scenario, the significant bending of the jets indicates that the ram pressure of the ISM is comparable with that of the jet. The ram pressure of the jet, P_j and ISM, P_a can be expressed as:

$$P_j \sim \frac{\dot{E}}{\pi \theta_j^2 r_j^2 c} \quad \text{and} \quad P_a \sim \rho_{ISM} \upsilon_{psr}^2,$$

θ_j and r_j are the open angle and the length of the jet. ρ_{ISM} and υ_{psr} are the ISM density and the pulsar's velocity.

For $P_j \sim P_a$, the curvature radius, $P_c \sim \frac{P_J}{P_a} h$ of the bent jet can be h, that implies a bending angle of ~60°.

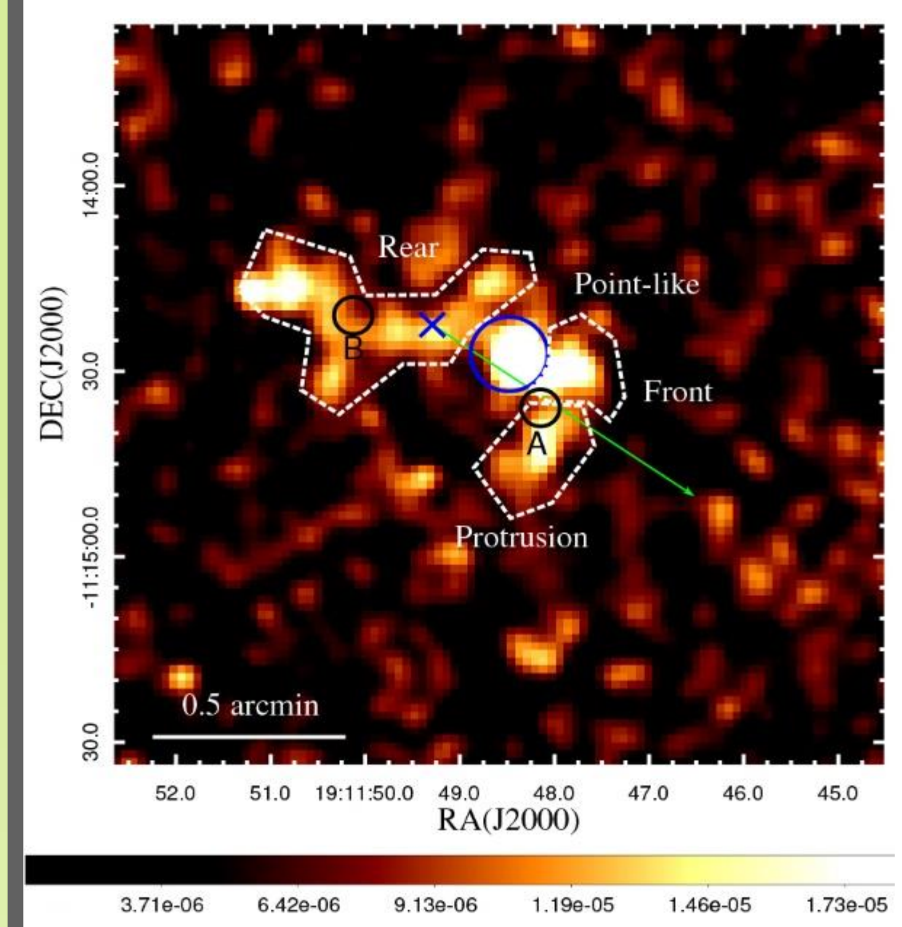
The twisted structure does not have any propagation. The absence of propagation in the case of the southern outer tail suggests that it can possibly be a helical structure resulting from torsional Alfven waves. Similar phenomena have been seen in the solar coronal jets (Srivastava et al. 2017; Szente et al. 2017).

A similar wiggling motion has also been observed in the jets of Vela and Crab (Pavlov et al. 2003); Mori et al. 2004). These variations are found on the order of a few tens of percent of the speed of light.

Reference.

Cheng , K. S., Taam, R. E., & Wang, W. 2006, ApJ, 641, 427
Gaensler, B. M., &Slane, P. O. 2006, ARA&A, 44, 17
Li, T. –P., & Ma, Y. –Q. 1983, ApJ, 273, 317
Srivastava, A. K., Shetye, J., Murawski, K., et al. 2017, NatSR, 7, 43147
Szente, J., Toth, G., Manchester, W. B., IV, et al. 2017, ApJ, 834, 123
Pavlov, G. G., Bhattacharyya, S., & Zavlin, V. E. 2010, ApJ, 715, 66
Posselt, B., Pavlov, G. G., Slane, P. O., et al. 2017, ApJ, 835, 66
Pavlov, G. G., Teter, M. A., Kargaltsev, O., & Sanwal, D. 2003, ApJ, 591, 1157

Extra - Discovery of an X-ray nebula in the field of MSP PSR J1911-1114



We have discovered an extended X-ray feature, apparently associated with millisecond pulsar (MSP) PSR J1911-1114. The feature, which extends for ~1', was discovered from an *XMM-Newton* observation; the radio timing position of J1911-1114 is in the midpoint of the feature (blue cross). Its X-ray spectrum can be well-modeled by an absorbed power-law with a photon index of $\Gamma = 1.8^{+0.3}_{-0.2}$. We speculated that the feature may be the result of bipolar outflow along the spin axis of the pulsar. If this feature is confirmed to be a PWN, this will be the third case where an X-ray PWN has been found to be powered by a MSP.

All figure and table from Hui et al. 2017, ApJ, 846, 116
+ Lee et al. 2018, A&A, 620, L14

David C.Y. Hui[1] - huichungyue@gmail.com
Jongsu Lee[2] - skyljs1234@gmail.com