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# X-ray observation of HESS J1809-193: indication of an X-ray halo and implication for its gamma-ray origin

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HESS J1809-193 is an extended TeV -ray source, but the exact origin of its -ray emission is still uncertain. One possible candidate for its emission source is the pulsar wind nebula (PWN) of PSR J1809-1917, located within the extended -ray emission region. Driven by the central pulsar, ultrarelativistic electrons within the PWN can give rise to emissions ranging from radio to X-ray through synchrotron processes, and -ray emissions through inverse Compton (IC) scattering.To determine if this PWN might be the counterpart of HESS J1809-193, we examined the Chandra X-ray radial intensity profile and the spectral index profile of this PWN. We also employed a one-zone isotropic diffusion model to fit the keV and the TeV data. Our analysis reveals a diffuse nonthermal X-ray emission that extends beyond the PWN. This is likely an X-ray halo generated by electron/positron pairs escaping from the PWN. Interestingly, a substantial magnetic field of 20 G is needed to account for the spatial evolution of the X-ray spectrum, notably the marked softening of the spectrum as we move further from the pulsar. However, such a strong magnetic field would likely dampen the IC radiation of the pairs. This suggests that a hadronic component might be necessary to fully explain the nature of HESS J1809-193..

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## 1. Introduction

Pulsar wind nebula (PWN) is believed to formed by the interaction between pulsar wind and the surrounding interstellar medium(ISM). Pulsar wind consists of ultrarelativistic charged particles (usually electrons and positrons) and can produce termination shock where the particles can be further accelarated. The particles can produce radio to X-ray emission by synchrontron in the magnetic field. They can also scatter background photons to produce $\gamma$-ray emission by inverse Compton scattering mechanism. In 2018, HESS collaboration announced 78 new very high energy(VHE) $\gamma$-ray sources, 12 of them are associated with PWN, which takes the most proportion among the identified sources[1]. Therefore PWNe are very significant in the study of origin of VHE $\gamma$-ray emissions as well as the accelaration and transportation of cosmic-rays.

Evolution of PWN can be divided to threee stages[2]. In stage 1, the pulsar resides inside the supernove remnant(SNR) and the reverse shock has not met PWN. The PWN is a symmetric sphere. In stage 2, the reverse shock has broken the PWN into pieces and made it irregular in morphology. Some particles can escape from the PWN into SNR and even into the ISM. In stage 3, the pulsar has left the SNR and moved into ISM due to proper motion. The PWN is a bow-shock shape due to supersonic velocity. In this stage, a lot of particles can escape from the PWN into surrounding ISM and form a diffuse halo, where they can scatter the background photons (for example, CMB) to produce $\gamma$-ray emission. The diffuse $\gamma$-ray halo has been observed by HAWC around Geminga and monogem pulsars[3]. Concerning the $\gamma$-ray halo, one can expect the escaped particles can produce synchrontron emission in the magnetic field of ISM to create a corresponding X-ray halo. There were some work looking for the diffuse emission around Geminga but no evidence has been found[4]. Perhaps Geminga is too old and the magnetic field around is too weak to produce enough X-ray emission to observe. We selected a middle-aged pulsar, PSR J1809-1917 to look for the X-ray halo.

PSR J1809-1917 has a spin-down age of 51.3 kyr and a distance of 3.5 kpc. Its spin-down luminosity is $1.8 \times 10^{36}$ erg s$^{-1}$. This pulsar is associated with HESS J1809-193 and there are a lot of investigations to its $\gamma$-ray origin. Di Mauro et al fit the TeV surface brightness profile(SBP) of with a simple one-zone model and supported the leptonic scenario that diffuse $\gamma$-ray originates from electrons escaped from PWN[5]. However, radio observation by JVLA found no radio counterpart to PWN[6]. Instead, radio image shows some SNR and molecular clouds(MC). The authors argued a hadronic scenario that the diffuse $\gamma$-ray originates from protons from the SNR and the MC by pion-decay. On the other hand, Klingler conducted Chandra X-ray observation to this region and found very bright X-ray PWN. So they qualitatively supported the leptonic scenario [7][8]. The dispute between leptonic scenario and hadronic scenario also motivated us to revisit Chandra observation to the PWN and quantatively determine whether the electrons escaped from PWN can produce enough $\gamma$-ray observed by HESS.

## 2. Data analysis

We chose 14 *Chandra* Advanced CCD Imaging Spectrometer (ACIS)-I observations (405.1 ks exposure time in total) of PSR J1809-1917 in 2018. These data were dealt with *Chandra* Interactive Analysis of Observations software package (CIAO) version 4.14 as well as Calibration Database

(CALDB) version 4.9.8[1]. After reprocessing the original datasets, we merged the 0.5 – 7 keV images with MERGE_OBS by setting the parameter 'bands = broad'. Then we used WAVDETECT for the merged event to detect the X-ray point sources ($> 5\sigma$) which would be masked in later analysis. We also manually chose 11 other bright regions as point sources to be masked. There are 319 point sources masked in total. We removed flaring detector background ($> 3\sigma$) by analyzing the lightcurve of 2.3 – 7.3 keV band and derived the clean events. Then we merged the clean events, removed the point sources, filled the holes, and subtracted the blank-sky files to get a clean image. This image was further divided by the exposure map to get the real diffuse emission of PWN[2].

To measure the intensity profile and the spectral profile of the X-ray PWN and the possibly existed X-ray halo, we divide the region into several sectors based on the distance to the pulsar and extract spectra of each individual region, as shown in Fig. 1. Klingler [8] suggested that a kinetic jet appears in the southeast part of the PWN. We therefore divide the J1809 field into region *a* (green) and region *b* (white) to separate this possible structure from the rest part of the extended emission. Then we extract the X-ray properties of these regions with the clean events and the corresponding blank-sky files for each observation. We use clean events as source spectra while blank-sky files as background spectra.

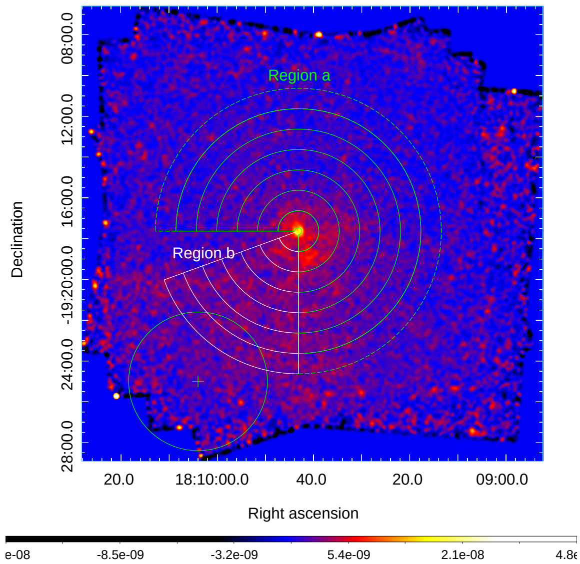


**Figure 1:** Exposure-corrected image of diffuse emission of the PWN on the merged ACIS-I events with quiescent particle background subtracted, binned by a factor of 2 and smoothed with a 10-pixel (r=10″) Gaussian kernel[11]. Point sources are removed. PSR J1809-1917 lies in the center of the annuli. Green (namely region *a*) and white (namely region *b*) annular sectors are selected to extract spectra separately. Dashed green annular sector was chosen as local background region. The green circle marks the shell of SNR G11.0-0.0 in the radio band and the green cross is the center of this SNR.

We manually rescale the background spectrum with the count rate of 9.5 – 12 keV photons to subtract background spectrum correctly. Finally, we jointly fit the spectra and calculate flux in XSPEC. To begin with, we abruptly chose the outermost annulus of region *a* as local cosmic X-ray

[1] https://cxc.harvard.edu/ciao/index.html
[2] https://cxc.harvard.edu/ciao/threads/diffuse_emission/

background. It may cause some bias because if there are diffuse X-ray emission corresponding to TeV halo, it will cover the whole Chandra field of view(FOV). The local background will overestimate the cosmic X-ray background. To find a clean cosmic X-ray background free from any contamination of $\gamma$-ray sources, we searched for nearby *Chandra* observations and chosen observation to M17SW and W31 North as nearby background (Fig. 2).

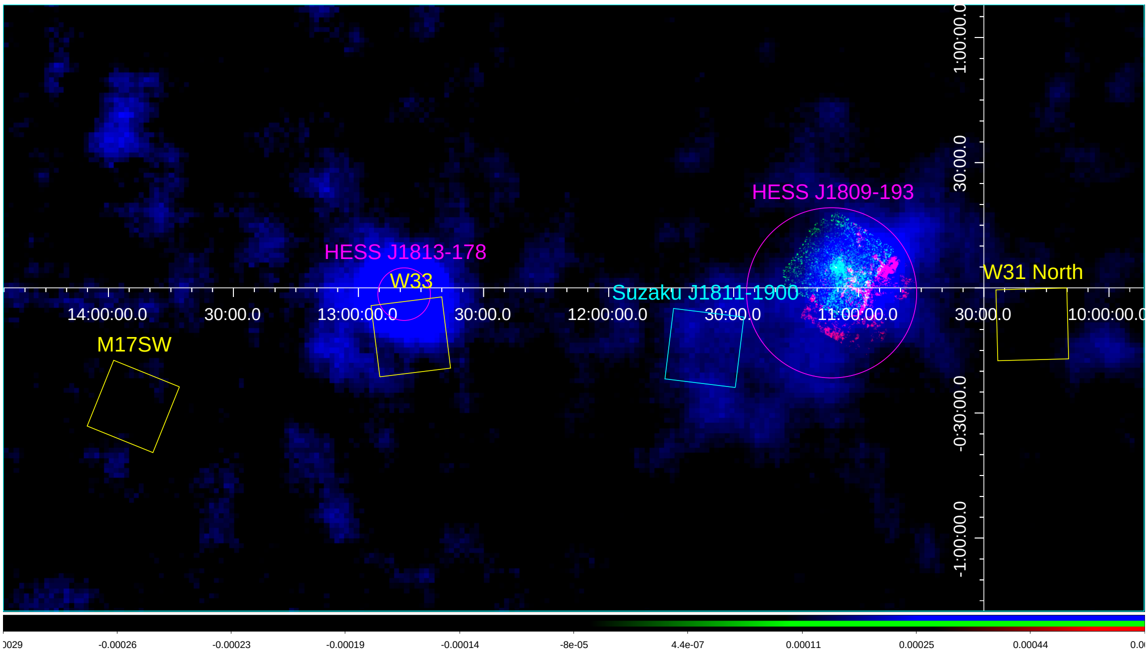


**Figure 2:** Multiwavlength image of HESS J1809-193 and its nearby region[11]. Red: radio (JVLA, 1.4 GHZ, from [6]); Green: X-ray (*Chandra* 0.5-7 keV, binned by a factor of 2 and smoothed with a 10" Gaussian kernel); Blue: TeV (HESS Galactic Survey [H. E. S. S. Collaboration et al. 1]).The squares show four nearby *Chandra* observations and corresponding target name we chose to be background candidates. Note that we excluded the observation to Suzaku J1811-1900 (cyan box) and combined the spectra of the other three observations (yellow boxes) to calculate the average background spectra. Magenta circles show 70% containment radius of HESS sources.

## 3. Results

Fig. 3 shows the radial profile of intensity and photon index. The Intensity continues to decend beyond PWN ($\sim 2'$) to $6'$, indicating the existence of X-ray halo. Photon index profile with local background subtracted is weird while with nearby background subtracted is consistent with our expectation that particles are escaping from PWN. It further supports the existence of X-ray halo. But the best-fit parameters of TeV data can not reproduce X-ray profile. On the one hand, the measured photon index of the data softens much faster than the model prediction. On the other hand, the measured intensity is systematically lower than the model prediction. We fit the radial profile of intensity and photon index simutaneously with a simple one-zone isotropic diffusion model and the best-fit requires a strong magnetic field($\sim 20\,\mu$G). Such strong magnetic field will cool the electrons very quickly and suppress inverse Compton scattering. Therefore electrons escaping from the PWN

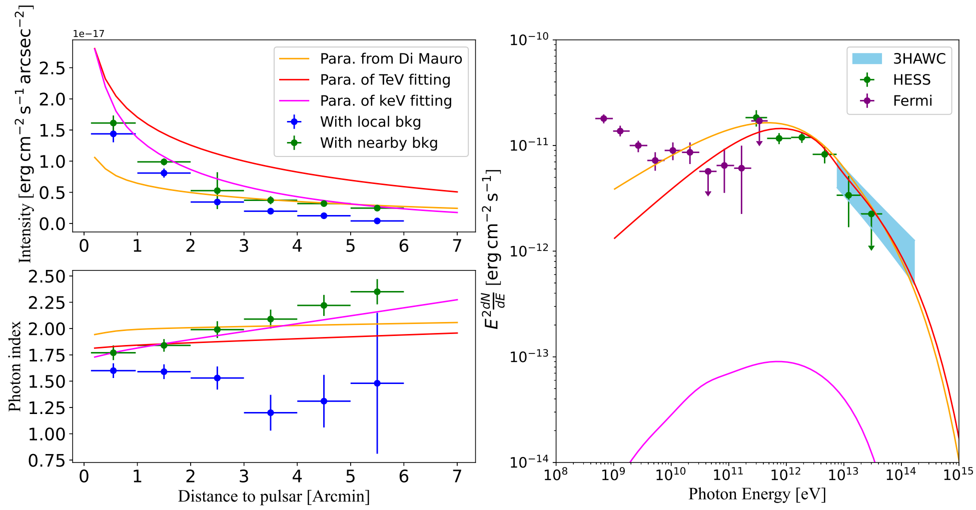


**Figure 3:** Left: keV radial profile of intensity and spectral index from *Chandra* data[11]. Orange and red lines are one-zone model prediction with the parameters from Di Mauro[5] and best-fit of Fermi, HESS and HAWC data. Magenta lines are the best-fit to keV data with our one-zone model. Blue and green points are from region *a* (Fig. 1) with local & nearby blank-sky background subtracted separately. Right: Spectral energy distribution from Fermi[9], HESS[1] and HAWC[10]

cannot produce enough $\gamma$-ray emission observed by Fermi, HESS and HAWC. Integrating over a circular region around the pulsar with a 1° radius, we find the predicted IC flux is lower than the measured one by more than 1 order of magnitude. Thus our result does not support the one-zone model leptonic scenario.

But our results does not necessarily exclude the leptonic scenario because considering a more complex model such as the joint play of advection and diffusion, or inhomogeneous magnetic field and diffusion coefficient, the leptonic scenario may still be a possible solution. On the other hand, we investigated the hadronic scenario by fitting the $\gamma$-ray SED (Fig. 4). We assumed a broken power-law proton spectrum:

$$f(E) = \begin{cases} A(E/E_b)^{-\alpha_1}, & E < E_b \\ A(E/E_b)^{-\alpha_2}, & E > E_b \end{cases} \tag{1}$$

and the best-fit parameters show that $\alpha_1 = 1.5$ and $\alpha_2 = 2.9$ with $E_b = 20$ TeV. The total energy of protons is $2.6 \times 10^{50}(n/1cm^{-3})$ erg where $n$ is the number density of target protons. Castelletti [6] proposed three molecular clouds near SNR G11.0-0.0 with an average proton density of $\sim 2.5 \times 10^3$ cm$^{-3}$ can be the target for the hadronic interaction. Based on this, we obtain that the total energy of injected protons above 1 GeV is $1.1 \times 10^{47}$ erg, which is a tiny fraction of the expected CR energy budget of an SNR. Alternatively, ISM could also serve as the target for hadronic interactions if injected CRs are confined around the source (probably via the streaming instability). Indeed, for a typical hydrogen density in ISM, i.e., $n = 1$ cm$^{-3}$, the required proton energy $W_\mathrm{p} = 2.6 \times 10^{50}$ erg is not extreme for an SNR. As shown in Fig. 4, the broken power-law proton spectrum can give a satisfactory fitting to the gamma-ray data above 0.1 TeV. The break could be caused by the energy-dependent escape of CRs from SNRs so that a large fraction of low-energy CRs has not reached the molecular clouds.

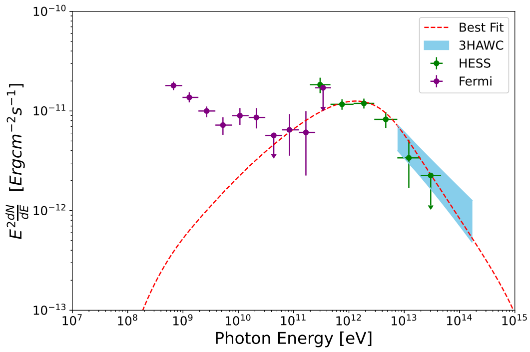


**Figure 4:** Hadronic model for HESS J1809-193[11]. The data are the same as the right panel of Fig. 3. The particle distribution is broken power-law (index 1.5 before break and 2.9 after break with break energy being 20 TeV).

## 4. Summary

In our study, we conducted an in-depth analysis of the Chandra ACIS-I observations focused on the PSR J1809-1917 field. Our goal was to identify diffuse X-ray emissions and establish the connection between its PWN and the extended -ray source HESS J1809-193. The PWN displayed a luminous core encircled by a compact nebula approximately 2 arcmin in size. Our observations revealed faint diffuse X-ray emission beyond this compact nebula. The emission's intensity decreased as the distance from the pulsar increased, hinting at the presence of an X-ray halo formed by electrons escaping the PWN. Moreover, we noticed a steady softening of the spectrum correlating with the increasing distance from the pulsar, aligning with our hypothesis of an expansive X-ray halo enveloping the compact PWN.

Then we utilized the one-zone model, fitting both the intensity and photon index profiles of the X-ray emission. The resulting best-fit parameters, however, didn't align with the HESS profile measurements above 1 TeV. This misalignment can be attributed to a comparatively strong magnetic field, approximately 20 G, essential to account for the observed quick softening in the X-ray photon index profile. Such a robust magnetic field would dramatically diminish the IC radiation from the electrons, making it inadequate to match the recorded TeV flux of HESS J1809-193. Besides, we considered a hadronic origin for the $\gamma$-ray emission in the vicinity. Our findings suggest its plausibility under certain reasonable parameters.

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