Modeling of Broadband Spectra and Radial Profiles of Emission of Pulsar Wind Nebulae

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Introduction – Pulsar Wind Nebulae –

- Pulsar Wind Nebulae (PWNe)
  - Extended source around a rotation powered pulsar
  - Broadband non-thermal spectrum from radio to TeV-γ
- Non-thermal emission
  - Radio – X : Synchrotron
  - γ-rays : Inverse Compton (external or SSC)
  - X-ray photons are emitted by e± with highest energy

Crab Nebula

~4 pc

G21.5-0.9

~2 pc

(Buhler & Blandford, 2014)
Observed Quantities

- eg. G21.5-0.9
  - Spectrum integrated over the whole nebula

X-ray Surface Brightness

Most simplified spatial model → 1D model!
“Standard model” of PWNe

- 1D-steady model; Rees & Gunn (1974), Kennel & Coroniti (1984)
  - Assuming a radial flow and a trojidal field.
  - Non-thermal e\(\pm\) produced at termination shock \(r_s\)
  - Propagating in PWN with radiative cooling
  - Non-thermal e\(\pm\) only advect with flow

Well explains observed property of the Crab Nebula
What KC model explains

- SED (Spectrum of the whole nebula)

KC model can explain these properties
→ KC model was accepted as a standard model

- Energy dependent morphology

Q. How decelerates?
A. Low sigma flow

However, such a test has performed for the Crab Nebula ONLY.
3C 58, G21.5-0.9

PWNe which show **large extent of X-ray emission** (unlike the Crab Nebula).

**Q**: Can these observation explain by KC model?

**A**: Lack of information.

It is necessary to calculate the SED and constraint the parameters.

Can KC model reproduce SED & X-ray profile **simultaneously**?
Test of KC model

- SED
- X-ray surface brightness
- X-ray photon index

Test of KC model

- **SED**: almost reproduced w/ KC model
  - Obtained the parameters almost uniquely
- X-ray surface brightness
- X-ray photon index

Test of KC model

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- X-ray surface brightness: NOT reach the edge
  - High energy $e^\pm$ exhaust their energy by emission.
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KC model CANNOT reproduce SED and X-ray profile simultaneously!

Why cannot?

"Magnetic Field to reproduce the SED" > "Magnetic field to reproduce the X-ray extent"

How do we do?

B-field to reproduce SED: determined from the flux ratio of synchrotron and ICS.
Why cannot?

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How do we do?

B-field to reproduce SED: determined from the flux ratio of synchrotron and ICS.

Determined by the balance of cooling and advection time.
Why cannot?

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How do we do?

B-field to reproduce SED: determined from the flux ratio of synchrotron and ICS.

⇒ It is necessary to propagate outward more efficiently. (rather than to suppress cooling)
Efficient transport?

- To solve the problem of X-ray extent...
  A) Suppress the radiative cooling
  B) Transport efficiently
  ⇒ Spatial diffusion by interacting with disturbed B-field

(Tang & Chevalier 2012, Porth+ 2016)
Efficient transport?

- To solve the problem of X-ray extent...
  - A) Suppress the radiative cooling
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⇒ Spatial diffusion by interacting with disturbed B-field

(Tang & Chevalier 2012, Porth+ 2016)

Let us consider the situation

“While advecting with the fluid, deviating from the fluid by diffusion little by little.”

Diffusion by the turbulent B-field

Spin-down: $L_{sd}$

$\gamma$
Result -G21.5-0.9-

- Result for G21.5-0.9 (Omitted 3C 58)
  diffusion coefficient of X-ray emitting particles: $\kappa \sim 10^{27} \text{ cm}^2 \text{ s}^{-1}$

SED: The hard spectrum of X-rays is reproduced better (than KC).

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  diffusion coefficient of X-ray emitting particles: $\kappa \sim 10^{27}$ cm$^2$ s$^{-1}$
  
  SED: The hard spectrum of X-rays is reproduced better (than KC).

Consistent with previous models

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  diffusion coefficient of X-ray emitting particles: $\kappa \sim 10^{27}$ cm$^2$ s$^{-1}$

  SED: The hard spectrum of X-rays is reproduced better (than KC).

  X-ray surface brightness: Extends to the edge!


\[
\tilde{k} = k_0 \left( \frac{E}{E_b} \right)^{1/3}
\]
Result -G21.5-0.9-

- Result for G21.5-0.9 (continues)

Photon index: The problematic softening is solved. The radial dependence is in good agreement. However it is shifted by the constant systematically.

SED: flux around 1 TeV is about 2 times \(10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) insufficient as observed value.
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SED: flux around 1 TeV is about 2 times (10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}) insufficient as observed value.
Escaped particles...?

- The γ-ray emission from the particles which escaped out of the nebula.
  → predict a “**young TeV-halo**” which extends larger than the radio or X-ray nebula.

Contribution from the escaped particles: \[ \sim 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \] → CAN cover the shortfall.

Assuming that the diffusion coefficient outside the nebula is same as inside one, the extent of the γ-ray halo is \( \sim 2 \text{ pc} \) (corresponding to 90′′)

Spin-down: \( L_{\text{sd}} \)

Diffusion by the turbulent B-field

Disturbed Field

IC emission from escaped particles!
Conclusion

• Summary :
  
  ❌ The standard 1D steady model (KC model) CANNOT explain observation facts of PWNe where X-rays extends to the same as radio nebula.
  
  🌺 We have shown that the SED and the extent of X-ray can be reproduces simultaneously by the 1-D steady diffusion model.
  
  • Assuming that the diffusion coefficient outside the nebula is the same as in the nebula, we have suggest that the “young TeV-halo” extends larger than the radio or X-ray nebula.

• Future prospects and issues :
  
  • A physical interpretation of the obtained diffusion coefficient $\kappa(E = 10^{14} \text{ eV}) \sim 10^{27} \text{ cm}^2\text{s}^{-1}$, which is much larger than the predicted value by the standard cosmic-ray diffusion model.
  
  • More quantitative modeling of the process of particle escaping from PWNe.
  
  • More objects.