White dwarf pulsar as Possible Cosmic Ray Electron-Positron Factories

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Background: “Electron–Positron Excess”

PAMELA
(capable of identifying CR ray charge)

The positron excess in the energy range $10-100\text{GeV}$
(Adriani, et al 2008)

ATIC/PPT–BETS/H.E.S.S/Fermi

The excess in the $e^-+e^+$ flux up to TeV
(Abdo, et al 2009 etc)
What is the source?

- **Neutron star pulsar?**
  Shen 70; Aharonian+ 95; Atoyan et al. 95; Chi+ 96; Zhang & Cheng 01; Grimani 07; Yuksel+ 08; Buesching+ 08; Hooper+ 08; Profumo 08; Malyshev+09; Grasso+ 09; Kawanaka, Ioka & Nojiri 10

- **Supernova Remnant?**
  Shen & Berkey 68; Pohl & Esposito 98; Kobayashi+ 04; Shaviv+ 09; Hu+ 09; Fujita, Kohri, Yamazaki & Ioka 09; Blasi 09; Blasi & Serpico 09; Mertsch&Sarkar 09; Biermann+ 09; Ahlers, Mertsch & Sarkar 09

- **Microquasar (Galactic BH)?** Heinz & Sunyaev 02

- **Gamma-Ray Burst?** Ioka 10

- **Propagation Effect?** Delahaye+ 08; Cowsik & Burch 09; Stawarz+09; Schlickeiser & Ruppel 09

- **Dark matter decay or annihilation ???** So many references

High accuracy, broadband CR e± observations are coming. ex ) AMS–02, CALET, CTA

Is there any new sources?
Goal

We propose “White Dwarf Pulsars” as a new candidate for TeV $e^\pm$ emitters, and discuss the possibility of the detection by PAMELA/Fermi or the future observations like AMS–02/CALET/CTA.
Candidates of White Dwarf Pulsars

AE Aquarii
- MCVs
- Long term spin down $\sim 6 \times 10^{-14} \text{s s}^{-1}$
  $\rightarrow$ inferred magnetic field $B \sim 5 \times 10^7 \text{ Gauss}$
- Rapid rotation $P \sim 33 \text{ sec}$
- Hard X-ray pulsations

EUVE J0317-855
- single magnetized white dwarf $B \sim 4.5 \times 10^8 \text{ Gauss}$
- rapid rotation $P \sim 725 \text{ sec}$
- large mass $\sim 1.3M_\odot$
- No pulse emission have been reported yet.
White dwarf pulsar model

- formation scenario
  “WD–WD mergers”
  - MCVs may also contribute?
  - Gravitational wave sources for LISA.

- fiducial parameters
  mass: $M > 1.0M_{\odot}$ (typical WD: $0.6M_{\odot}$)
  period: $P \sim 50$ sec (typical: $10^{4-5}$[sec])
  magnetic field: $B \sim 10^{7-9}$ G (typical: less than $10^6$[G])
Energetics

- **Energy of a WD pulsar**
  Intrinsic energy is its rotational energy

\[
\frac{1}{2} I \Omega^2 \approx \frac{1}{2} M_{\text{WD}} V^2 \approx \frac{G M_{\text{WD}}}{R_{\text{WD}}} \approx 10^{50} \text{[erg]}
\]

  - Rotational energy just after merger
  - Rotational energy just before merger
  - Gravitational energy just before merger

  \[\rightarrow\text{comparable to rotational energy of new born NS pulsars}\]

- **Total number of WD pulsars**
  WD–WD merger rate in our galaxy \(\sim 1/100\text{yr}\)

  \[\rightarrow\text{comparable to birth rate of NS pulsars in our galaxy}\]

**Total energy budget is comparable to NS pulsars!**
WD pulsar can produce TeV $e^{\pm}$?

• Check point ①
e$^{\pm}$ pair production can occur?

• Check point ②
WDs can accelerate $e^{\pm}$ up to TeV?

Point: WD pulsars $\equiv$ NS pulsars
e± pair production in pulsar magnetosphere

**Polar cap (PC) model**

- e− acceleration in PC region
- γ–ray production by curvature radiation and Inverse Compton scattering
- γ + B field → e±
- Pair production avalanche!

![Diagram showing e± pair production in pulsar magnetosphere](image-url)
The condition for $e^\pm$ pair creation occurs

“$\gamma$-ray emitted by accelerated particle in the gap is energetic enough to produce $e^\pm$.”

\[ 4 \log B - 7.5 \log P + 9.5 \log R \geq 96.7 \] in units of [Gauss], [sec], [cm]

WD pulsars can satisfy the above condition!
**e± acceleration in the pulsar wind nebula**

**Assumptions**

In the wind region,

- the energy equipartition between B and e±.
- the flux conservation of B and e±.

\[
\frac{e \Delta V_{\text{max}}}{\mathcal{M}} \sim 10 \mathcal{M}^{-1} \left( \frac{B_p}{10^8 \text{G}} \right) \left( \frac{\Omega}{0.1 \text{s}^{-1}} \right)^2 \left( \frac{R}{10^8.7 \text{cm}} \right)^3 \text{ TeV}
\]

\[\mathcal{M} : \text{e± multiplicity}\]

WD pulsars can accelerate e± up to TeV !
e± cooling in the wind nebula

• Adiabatic cooling $\rightarrow$ negligible!
  $\because$ The shocked stops soon since the wind is weak.

• Radiative cooling $\rightarrow$ at least $\sim 10\%$

\[
\begin{align*}
&\text{Bohm limit} \\
&\text{Synchrotron cooling}
\end{align*}
\]
\[
\frac{\Delta \epsilon}{\epsilon} \sim 0.1 \left( \frac{B_{in}}{3 \times 10^{-6} \text{G}} \right)^3
\]

$B_{in}$: $B$ @ inner edge of the shocked region

TeV $e^\pm$ can escape the wind nebula without serious cooling!
Difference between WD pulsars and NS pulsars

• What is the difference?

  “Spin down luminosity”

  \[ L \approx \frac{B^2 \Omega^4 R^6}{c^3} \approx \begin{cases} 
  10^{38} \text{ [erg]} \text{ for NS pulsar} \\
  10^{34} \text{ [erg]} \text{ for WD pulsar} 
\end{cases} \]

  “life time” = \( \frac{\text{Total energy}}{\text{spin down luminosity}} \)

  \[ \tau_{life} \approx \begin{cases} 
  10^4 \text{ [yr]} \text{ for NS pulsar} \\
  10^8 \text{ [yr]} \text{ for WD pulsar} 
\end{cases} \]

NS is \( 10^4 \) times powerful!

WD is \( 10^4 \) times longer life!

WD pulsars are weak, but active for a long time!!
**WDs is better than NSs as TeV e± source?**

**Point**

TeV e± can propagate only ~1kpc in our galaxy.

\[
\text{source number} \div (\text{life time}) \div (\text{event rate}) \div (\text{volume of galaxy})
\]

\[
\begin{align*}
\text{for NS} & : 10^{-1}[1/\text{kpc}^3] \\
\text{for WD} & : 10^3[1/\text{kpc}^3]
\end{align*}
\]

NS is uncertain. WD is a lot!

WD pulsars may be numerous!
Calculation of $e^\pm$ flux

Solve diffusion eq. including the KN effect for each WD pulsar.

$$
\frac{\partial f}{\partial t} = \frac{D}{r} \frac{\partial}{\partial r} r^2 \frac{\partial f}{\partial r} - \frac{\partial}{\partial \epsilon} (P f) + Q.
$$

Cooling Func : 

$$
P(\epsilon) = -\frac{d\epsilon}{dt} = \frac{4}{3} \sigma_T c \left( \frac{\epsilon}{m_e c^2} \right)^2 \left[ \frac{B_{ISM}^2}{8\pi} + \int d\epsilon_{ph} u_{tot}(\epsilon_{ph}) f_{KN} \left( \frac{4\epsilon_{ph}}{m_e^2 c^4} \right) \right].
$$

Diffusion Co : 

$$
D(\epsilon) = D_0 \left( 1 + \frac{\epsilon}{3 \text{GeV}} \right)^\delta.
$$

Source Func : 

$$
Q(\epsilon, t_0, \hat{t}) = Q_0 \epsilon^{-\nu} \exp \left( -\frac{\epsilon}{\epsilon_{\text{cut}}} \right) \left( 1 + \frac{t_0 - \hat{t}}{\tau} \right)^{-2}.
$$

Sum up the multiple contribution.

$$
F(\epsilon) = \int_{-\tau_{WD}}^{0} d\hat{t} \int_{0}^{r_{\text{dif}}(\epsilon, \epsilon_{\hat{t}})} 2\pi r dr \cdot \alpha \cdot \eta_{\text{WD}} f(\epsilon, r, \hat{t}).
$$

$\alpha \cdot \eta \sim \text{"WD pulsar birth rate in our galaxy" [1/yr/kpc}^2\text{]"}$
Result 1: WD pulsar dominated model

e\pm total flux

WD: cut off energy \sim 1 \text{ TeV}
total energy $10^{49}\text{erg}$ for each

WD pulsars can explain the excess around TeV!
Result 2 : WD + NS pulsar mixed model

**e± total flux**

WD : cut off energy \( \sim 10 \) TeV
  total energy \( 5 \times 10^{48} \) erg for each

NS : cut off energy \( \sim 1 \) TeV
  total energy \( 10^{49} \) erg for each

“Bumps” are formed @ TeV and 10 TeV \( \rightarrow \) detectable by AMS-02, CALET, CTA!?
Summary

- Recently, excess in observed $e^\pm$ flux up to TeV have been presented, and the origin is still under debate.
- There are several observational projects for cosmic ray $e^\pm$ above TeV (AMS-02, CALET, CTA).
- Here, we investigate the possibility of WD pulsars to be TeV $e^\pm$ sources.
- We show that white dwarf pulsars can produce and accelerate $e^\pm$ up to TeV.
- WD pulsars can explain the excess in observed $e^\pm$ flux.
- There may be formed the “bumps” in the $e^\pm$ spectrum around TeV and 10 TeV, which can be detectable by the future observation.