Suzaku searches for WD pulsars with a spectral model of post-shock regions

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WDS Pulsars

“Is WD origin of cosmic-rays?”

- Electrostatic potential
  \[ V \sim vBR \sim 10^{13} \text{ V} \]
  with typical values of magnetic WD
  \[
  \begin{align*}
  B &\sim 10^6 \text{ G} \\
  R &\sim 10^9 \text{ cm} \\
  P &\sim 5 \times 10^3 \text{ s} \\
  v & = 2\pi R / T
  \end{align*}
  \]

- Signal from the cosmic-rays (Terada et al. 2008)
  Non-thermal hard X-ray (up to 30 keV)
  was detected from a WD binary, AE Aquarii
  \rightarrow “WD pulsars”

“WD is one of origin of cosmic-rays”

Next question: “How much of cosmic-rays does WD accelerate?”

In a number of WDs, the accelerating amount should be measured
Concentrate on binaries i.e. magnetic CV

WD pulsar

Credit: NASA, Casey Reed
Obstacles to WD Pulsars Search

1. Signal from high-energy particles is weak
2. Thermal radiation is hard (photon-index ~ 1.1) and brighter
3. Compton reflection from WD surface makes spectral hump ~10-30 keV

To detect the non-thermal signal hidden in the thermal and reflection
→ we need
- wide energy band and good statistic spectrum
- high accuracy thermal model
- consideration of Compton reflection
Suzaku Satellite

Wide energy band and good statistic

- X-ray telescope + X-ray CCD

Comparison of effective area with others
(Serlemitsos et al. 2007)

- Hard X-ray Detector

Comparison of sensitivity with others
(Mitsuda et al. 2007)
Thermal & Reflect Models

- Accurate thermal model → *Post-shock plasma model* (Cropper et al. 1999)
  
  Temperature and density distributions in the plasma flow
  (Calculated by hydrodynamics)

- Compton reflection → *Reflect model* (Magdziarz & Zdziarski 1995)
  
  ※Multi temperature and reflection have not been involved for past WD pulsar searches
Samples

The two hardest CVs: **IGR J00234+6141** and **V2487 Ophiuchus** in Swift CV catalog + INTEGRAL CV catalog (39 CVs)
IGR J00234+6141

Suzaku observation: June 2010
X-ray CCD: 82 ks, Hard X-ray detector: 65 ks

Past results
- Photon index ~ 1.1
- $P_{\text{spin}} = 561.6$ sec
- Temperature
  - Swift: 23 keV
  - XMM-Newton: 28 keV
Fitting (1) of IGR J00234+6141

(partial absorb)×("post-shock plasma model"+ Gaussian)

- Thermal
- Gaussian for FeKα

$M_{\text{WD}}: \sim 1.4 \, M_\odot$
too close to $1.44 \, M_\odot$
→ inconceivable

$\chi^2 = 1.29$
(d.o.f. = 526)
Fitting (2) of IGR J00234+6141

(partial absorb) × (“post-shock plasma model” × reflect + Gaussian)

- - Thermal
- - Gaussian for FeKα
- - Reflection

\[ M_{WD} = 1.03 \pm 0.06 \, M_\odot \]

\[ Z = 0.16_{-0.05}^{+0.07} \, Z_\odot \]

\[ \chi^2 = 1.16 \]

(d.o.f. = 525)

F-test p-value

\[ = 5.1 \times 10^{-14} \]

Reasonable

&

Not need

powerlaw
V2487 Ophiuchus

Suzaku observation: October 2010
X-ray CCD: 56 ks, Hard X-ray detector: 47 ks

Past results
- Classical nova
- Temperature
  - \textit{XMM-Newton}: >48 keV
  - \textit{INTEGRAL}: 55.6 keV
- \( P_{\text{spin}} = 235 \text{ sec} ? \)
Fitting (1) of V2487 Ophiuchus

(ppartial absorb)×("post-shock plasma model"+ Gaussian)

- - Thermal
- - Gaussian for FeKα

\[ M_{WD} = 0.86^{+0.09}_{-0.07} \, M_\odot \]

\[ Z = 0.72^{+0.16}_{-0.13} \, Z_\odot \]

\[ \chi^2 = 1.68 \] (d.o.f. = 282)

Residual above 10 keV
Fitting (2) of V2487 Ophiuchus

$\Delta S \chi^2$ vs. normalized counts s$^{-1}$ keV$^{-1}$

- - Thermal
- - Gaussian for FeIKα
- - Reflection

$M_{WD} = 0.84^{+0.09}_{-0.08} M_{\odot}$

$Z = 0.60^{+0.15}_{-0.13} Z_{\odot}$

$\chi^2 = 1.57$

(d.o.f. = 281)

F-test p-value $= 9.4 \times 10^{-6}$

however, Residual above 10 keV

\[(\text{partial absorb}) \times ("\text{post-shock plasma model}" \times \text{reflect} + \text{Gaussian})\]
Fitting (3) of V2487 Ophiuchus

\[(\text{partial absorb}) \times (\text{"post-shock plasma model" \times reflect + Gaussian + powerlaw})\]

- - Thermal
- - Gaussian for FeKα
- - Reflection
- - Powerlaw

\[M_{WD} = 0.59^{+0.10}_{-0.09} \, M_{\odot}\]

\[Z = 0.46^{+0.15}_{-0.09} \, Z_{\odot}\]

Photon-index\[\gamma = 0.0^{+0.3}_{-0.5}\]

\[\chi^2 = 1.41\]

(d.o.f. = 279)

Residual disappears

F-test p-value \[= 5.1 \times 10^{-8}\]
Conclusion

• IGR J00234+6141
  • Taking into account the multi-temperature plasma and reflection gives reasonable results:
    \[ \chi^2 = 1.16 \text{ (d.o.f. } = 525) \]
    \[ M_{WD} = 1.03 \pm 0.06 \, M_\odot \]
    \[ Z = 0.16_{-0.05}^{+0.07} \, Z_\odot \]
  • A powerlaw component is not needed.
    Hard X-ray spectrum of IGR J00234+6141 is attributed to the reflection and relatively massive WD \(\sim 1 \, M_\odot\).

• V2487 Ophiuchus
  • Even involving reflection, a significant residual leaves in hard X-ray band above 10 keV.
  • Adding a powerlaw removes the residual and improves the fitting (p-value = 5.1 \times 10^{-8})
  • The powerlaw is very hard; photon-index = 0.0_{-0.5}^{+0.3} unlike Ns pulsars.
    V2487 Ophiuchus certainly demands a powerlaw, which is probably non-thermal radiation because of its hardness.
Fitting steps

• Step 1
  pcfabs×("post-shock plasma model" + Gaussian)
  pcfabs → Partial covering absorption: $C_{PC} \exp(-\sigma N_H) + (1-C_{PC})$
  "post-shock plasma model" → multi-temperature optically thin plasma emission in post-shock region (Cropper et al. 1999)
  variables → $M_{WD}$, $Z$, norm
  Gaussian → fluorescence FeKα line
  variable → equivalent width
  (central energy and width fixed at 6.4 keV and 0 eV, respectively)

• Step 2
  pcfabs×("post-shock plasma model"×reflect + Gaussian)
  i.e. involving reflection component in addition to step 1
  reflect → the Compton reflection on WD surface
  variable → $i$; reflection angle
  (solid angle of WD surface viewing from plasma fixed at $2\pi$)

• Step 3
  pcfabs×("post-shock plasma model"×reflect + Gaussian + powerlaw)
  i.e. involving a powerlaw component in addition to step 2
  powerlaw → non-thermal emission
  parameters → photon-index, norm
Strong Shock $\rightarrow \sim 10^8$ K

Cooling

Plasma flow

Accretion

(2) Thermal

(3) Reflection
WD Pulsars

Are WDs origin of cosmic-rays?

- Electrostatic potential
  \[ V \sim \nu BR \sim 10^{13} \text{ V} \]
  with typical values of magnetic WD
  \[
  \begin{align*}
  B &\sim 10^6 \text{ G} \\
  R &\sim 10^9 \text{ cm} \\
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  \end{align*}
  \]

\[ \nu = \frac{2\pi R}{T} \]

→ WD can accelerate high energy particles → “WD pulsar”

WDs are origin of the cosmic-rays

Next question:
How much of cosmic-ray do WDs accelerate?

→ In a number of WDs,
  the accelerating amount should be measured

Concentrating on binaries i.e. magnetic CV
**Suzaku Satellite**

Good photon statistic in Suzaku satellite

- X-ray telescope + X-ray CCD
  Comparison of effective area with others (Serlemitsos et al. 2007)

- Hard X-ray Detector
  Comparison of sensitivity with others (Mitsuda et al. 2007)

**Important band**
Thermal & Reflect Models

- Accurate thermal model → *Post-shock plasma model* (Cropper et al. 1999)

**Temperature and density distributions in the plasma flow**

(Calculated by hydrodynamics)

\[
\frac{T}{T_{\text{max}}} \quad \frac{\rho}{\rho_{\text{min}}}
\]

Parameters:
- WD mass \( M_{\text{WD}} \)
- Abundance \( Z \)

\( (z-R_{\text{WD}})/R_{\text{WD}} \)

- Compton reflection → *Reflect model* (Magdziarz & Zdziarski 1995)

Shock height is assumed to be negligible against WD radius
→ solid angle of WD surface viewing from plasma is \( 2\pi \)

※The two effects have not been ever involved for WD searches