Suzaku (and XMM) Observation of the extended TeV gamma-ray source VER J2019+368(3)

September 23, 2016@JPS meeting, Miyazaki
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(based on Mizuno+, submitted)
Past Obs. by Milagro & VERITAS

- Milagro reported an extended TeV $\gamma$-ray source MGRO J2019+37 in Cygnus-X direction ($\sigma=0.7$deg)
- It was resolved into multiple sources by VERITAS. The most luminous one, VER J2019+368, has the following properties:
  - $\sigma_{\text{major}}=0.34$deg, positional coincidence with MGRO J2019+37, consistent spectrum in high energy => main contributor
- Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1
Past Obs. in X-Rays

- Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1
  - PSR J2021+3651: young and energetic pulsar ($\tau=17.2$ kyr, $dE_{\text{rot}}/dt=3.4\times10^{36}$ erg/s)
  - Chandra revealed a $\sim20''\times10''$ pulsar wind nebula (PWN G75.2+0.1)
  - XMM reported faint emission of 5'-10' length in east and west

Zabalza+10, J. of Mod. Phys. D. 19, 811
Issues of the PSR/PWN Scenario

• Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1
  – PSR J2021+3651: $\tau=17.2$ kyr, $dE_{\text{rot}}/dt=3.4\times10^{36}$ erg/s
  – PWN G75.2+0.1: revealed by Chandra and found to extend out 5’-10’ in length in east and west by XMM

• Several issues of the PSR/PWN scenario have been pointed out (e.g., Abdo+09, ApJ 799, 1059; Parades+09, A&A507, 241)
  – Large dispersion measure (370 pc/cm$^3$) and rotation measure (524 rad/m$^2$) indicate large distance to the source ($d>10$ kpc).
    • $\gamma$-ray luminosity of PSR too high compared to $dE_{\text{rot}}/dt$
    • Source size (~90 pc for 0.5 deg at 10 kpc) too large for high-energy electrons to propagate before cooling
  – X-rays from only small portion of TeV emission

• Detailed study of the PWN properties (spectrum, morphology) and search for unknown extended emission by Suzaku-XIS
X-ray Obs. of VER J2019+368

- Two Suzaku observations conducted in 2014 November
  - S1 covers region of the PSR/PWN and TeV centroid
  - S2 covers the west part of VER J2019+368, in which no strong X-ray sources has been reported
- Also analyzed archival XMM data to complement Suzaku observations

<table>
<thead>
<tr>
<th>Position</th>
<th>RA (deg)</th>
<th>DEC (deg)</th>
<th>Net exp. (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suzaku, S1</td>
<td>305.06</td>
<td>36.87</td>
<td>35.0</td>
</tr>
<tr>
<td>Suzaku, S2</td>
<td>304.79</td>
<td>36.83</td>
<td>35.7</td>
</tr>
<tr>
<td>XMM, X1</td>
<td>305.27</td>
<td>36.85</td>
<td>127.0</td>
</tr>
</tbody>
</table>
XIS Image (soft band)

- Soft band (0.7-2 keV) intensity map (XIS3, in unit of photos/s/cm²/sr, NXB subtracted)
- PWN clearly detected in S1
- No extended emission detected in S2 (see slide #8)
XIS Image (hard band)

- Hard band (2-10 keV) intensity map (nxb subtracted)
- PWN clearly detected in S1
- No obvious extended emission in S2
- Size of PWN similar to that in soft band

PSR J2021+3651
USNO-B1.0 1268-044892
background AGN?
PWN-West Morphology

- Source regions: 25 rectangles of 1’ x 5’ and 10 rectangles of 1’ x 3’ along the major axis and minor axis, respectively

- PWN-west emission is detected at least 15’ x 10’ for the first time
- No significant emission beyond the TeV emission peak

Count rate profiles (2-10 keV), vignetting corrected

T. Mizuno et al.
• Procedure of the spectral analysis (15’ x 5’)
  – 1) subtract the NXB
  – 2) apply vignetting correction in subtracting the BG (GRXE and CXB)
  – 3) calculate the response (arf) assuming linear decrease of the intensity in 0-15’

\[ \chi^2/d.o.f. = 211/188 \]
\[ N(H) = 0.83(+/-0.12) \times 10^{22}, \Gamma = 2.05(+/-0.12) \]
\[ f(0.5-2 \text{ keV}) = 6.04 \times 10^{-13} \text{ erg/s/cm}^2 \]
\[ f(2-10 \text{ keV}) = 20.1 \times 10^{-13} \text{ erg/s/cm}^2 \]

Significantly softer spectrum than that of TeV \( \gamma \) rays (\( \Gamma_{\gamma} \sim 1.75 \))

[XMM data indicates PWN-east and west have similar spectra (flux, \( \Gamma \))]

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<table>
<thead>
<tr>
<th>Reg.</th>
<th>N(H)</th>
<th>$\Gamma$</th>
<th>$f$(0.5-2keV) (10$^{-13}$ erg/s/cm$^2$)</th>
<th>$f$(2-10keV) (10$^{-13}$ erg/s/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.82 (+/-0.21)</td>
<td>2.07 (+/-0.21)</td>
<td>1.96</td>
<td>8.27</td>
</tr>
<tr>
<td>B</td>
<td>0.63 (+/-0.16)</td>
<td>1.96 (+/-0.18)</td>
<td>1.68</td>
<td>6.52</td>
</tr>
<tr>
<td>C</td>
<td>0.72 (+/-0.17)</td>
<td>2.06 (+/-0.18)</td>
<td>1.22</td>
<td>4.71</td>
</tr>
<tr>
<td>D</td>
<td>1.28 (+/-0.36)</td>
<td>2.30 (+/-0.32)</td>
<td>0.57</td>
<td>2.77</td>
</tr>
<tr>
<td>E</td>
<td>1.44 (+/-0.51)</td>
<td>2.29 (+/-0.42)</td>
<td>0.30</td>
<td>1.69</td>
</tr>
</tbody>
</table>

• No significant spectral change observed
• Absorption of ~0.8x10$^{22}$ cm$^{-2}$ indicates d<<10 kpc. We adopted d=1.8 kpc estimated by Kirichenko+15
Multiwavelength Spectrum

- $\Gamma_x \sim 2.05$ and $\Gamma_\gamma \sim 1.75$ require a break of electron spectrum at $\sim 100$ TeV
- If we assume constant injection of electrons into uniform $B$ over the lifetime of pulsar for simplicity, synchrotron break at $\sim 80$ TeV is expected, consistent with $\Gamma_x$ and $\Gamma_\gamma$ observed

$$E_{bk} \approx 80 \text{ TeV} \left( \frac{t_0}{17.2 \text{ kyr}} \right)^{-1} \left( \frac{B}{3 \mu\text{G}} \right)^{-2}$$

- A model assuming $B=3$ $\mu$G and a break at 80 TeV from $\Gamma=2.1$ to 3.1 explains $\sim 70\%$ of TeV emission $\Rightarrow$ X-ray PWN is a main contributor of VER J2019+368
- (The model does not fully account for morphologies in X-ray and $\gamma$ ray. Future observations by CTA is anticipated to reveal the TeV $\gamma$-ray properties in more detail)
Particle Transport

- Absence of spectral softening requires that highest energy electrons (producing 10 keV X-rays) should propagate a distance $\geq 15'$. If advection is the dominant process, this requires

$$\beta_{\text{adv}} \geq 7.9 \times 10^{-3} \left( \frac{B}{3 \mu \text{G}} \right)^{1.5} \left( \frac{d}{1.8 \text{ kpc}} \right).$$

- Alternatively, in the case of energy-independent diffusion (e.g., Porth+15), diffusion coefficient should satisfy

$$D \geq 2.9 \times 10^{27} \text{ cm}^2 \text{ s}^{-1} \left( \frac{B}{3 \mu \text{G}} \right)^{1.5} \left( \frac{d}{1.8 \text{ kpc}} \right)^2.$$

- [In those scenario (under the assumption of uniform B) the absence of X-ray emission beyond the TeV peak position is due to the lower surface brightness of synchrotron X-rays]
Summary

• VER J2019+368 is an extended ($\sigma_{major}=0.34$deg) and hard ($\Gamma=1.75$) TeV $\gamma$-ray source in Cyg-X direction
• PSR J2021+3651/PWN G75.2+0.1 is a possible counterpart, but several issues are pointed out (distance, morphology)
• We analyzed X-ray data (Suzaku and XMM)
  – PWN-west detected in 15’x10’ with $N(H)=8.2\times10^{21}$ cm$^{-2}$, $\Gamma=2.05$ (Suzaku)
  – No significant spectral change found (Suzaku)
  – PWN-east shows similar properties (XMM)
• Properties of the system
  – $B\sim3$ $\mu$G is required ($\Gamma_x$ and $\Gamma_\gamma$)
  – X-ray PWN is a major contributor of VER J2019+368 (MW spectrum)
  – $\beta_{adv}$ and D are constrained from X-ray data

Thank you for your Attention
References

- Aharonian+06, A&A 460, 365
- Parades+09, A&A 507, 241
- Porter+08, ApJ 682, 400
- Porth+16, MNRAS 460, 4135
- Uchiyama+08, PASJ 60, S35
- Zabalza+10, J. of Mod. Phys. D. 19, 811
Appendix
Past Obs. by Milagro & VERITAS

- Milagro reported an extended TeV $\gamma$-ray source MGRO J2019+37 in Cygnus-X direction ($\sigma=0.7\text{deg}$)
- It was resolved into multiple sources by VERITAS. The most luminous one, VER J2019+368, has the following properties
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Abdo+12, ApJ 753, 159

XMM View of the VER J2019+368 Region

- Advantages of XMM for the study of VER J2019+368
  - Good spatial resolution => reduction/estimation of the point-source contaminations
  - Large FOV => overall property of the PWN

<table>
<thead>
<tr>
<th>Region</th>
<th>$N(H) \times 10^{22}$ cm$^{-2}$</th>
<th>$\Gamma$</th>
<th>$f(0.5-2$ keV) (erg/s/cm$^2$),</th>
<th>$f(2-10$ keV) (erg/s/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>$0.68+/-0.12$</td>
<td>$2.11+/-0.18$</td>
<td>$\sim 4.1$</td>
<td>$\sim 14.1$</td>
</tr>
<tr>
<td>East</td>
<td>$0.47+/-0.07$</td>
<td>$1.85+/-0.13$</td>
<td>$\sim 4.6$</td>
<td>$\sim 16.8$</td>
</tr>
</tbody>
</table>
Comparison with Other PWNe (1)

- X-ray PWN and VER J2019+368 show similar properties with those of other PWNe associated with TeV $\gamma$ rays ($F_\gamma/F_X$ could be smaller; see next)

**Mattana+09**

**Bamba+10**
Comparison with Other PWNe (2)

- Comparison with the archetype evolved PWN HESS J1825-137 and its extended PWN (Aharonian+06, Uchiyama+09)

<table>
<thead>
<tr>
<th>Object</th>
<th>$P_f$, d$P_f$/dt, $B_s$ (G)</th>
<th>characteristic age, d$E_{rot}$/dt</th>
<th>F(2-10 keV) (unabsorbed; erg/s/cm$^2$), $\Gamma_x$</th>
<th>F(1-10 TeV) (erg/s/cm$^2$), $\Gamma_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VER J2019+368</td>
<td>104 ms, 9.6e-14, 3.2e12</td>
<td>17.2 kyr, 3.4e36 erg/s</td>
<td>~6e-12, ~2.05 (no significant softening)</td>
<td>12e-12, ~1.75</td>
</tr>
<tr>
<td>HESS J1825+137</td>
<td>101 ms, 7.5e-14, 2.8e12</td>
<td>21.4 kyr, 2.8e36 erg/s</td>
<td>~4.5e-12, ~2 (no significant softening)</td>
<td>~50e-12, ~2.4</td>
</tr>
</tbody>
</table>

VER J2019+368 shows harder spectral index in TeV and smaller $F_\gamma/F_x$ ratio, indicating weaker magnetic field or younger age.