A Leptonic Interpretation of the UHE Gamma-ray Emission from V4641 Sgr

Su-Yu Wan, Jie-Shuang Wang and Ruo-Yu Liu

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Speaker: Su-Yu Wan (万苏豫)

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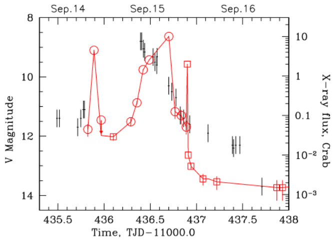
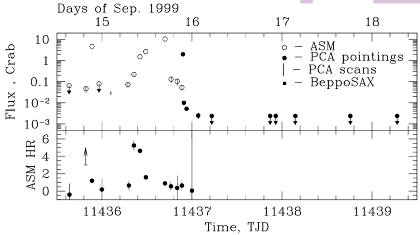
Outline

Microquasar system: V4641 Sgr

- Low-mass binary, a $6.4 \pm 0.6 M_{sun}$ black hole and a $2.9 \pm 0.4 M_{sun}$ companion star.
- d = 6.2 kpc, l = 6.77, b = - 4.79.
- Show frequent bursts ($\sim$ 1 - 2 years)
- Experienced a supper-Eddington outburst with X-ray intensities reaching 12.2 Crab.



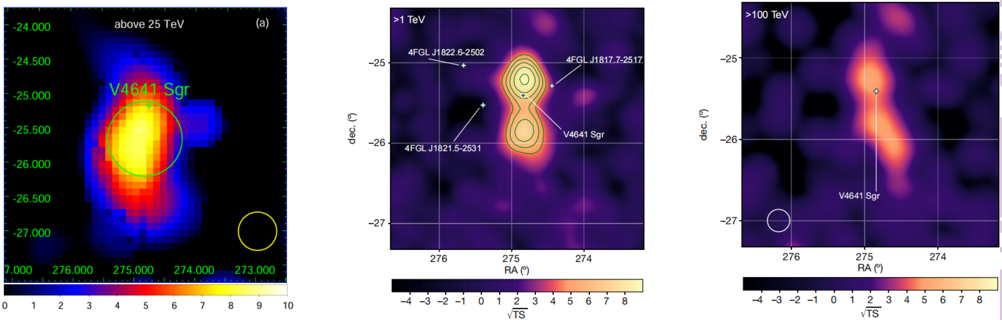
(a) The light curves of V4641 Sgr in the optical V-band and in the X-ray band, from Revnivtsev et al. [2002a]



(b) The light curve of V4641 Sgr in 1999 according to observations of RXTE and BeppoSAX satellites., from Revnivtsev et al. [2002b]

Picture in TeV - PeV band

- Evidence for UHE γ-ray emission from the source (H.E.S.S. + LHAASO + HAWC).



(a) LHAASO (> 25 TeV), from Collaboration et al. [2024]

(b) HAWC (> 1 TeV), from Alfaro et al. [2024]

(c) HAWC (> 100 TeV), from Alfaro et al. [2024]

- Elongated morphology ($\sim$ 100 pc) + Ultrahigh energy photons ($\sim$ 0.8 PeV) .
- Two point sources or an extended source ?

Possible explanations

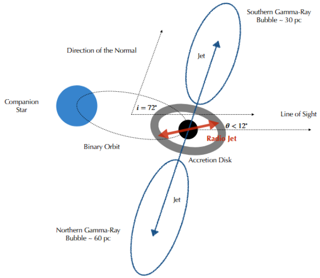


Figure: Two - lobe scenario. [Alfaro et al., 2024]

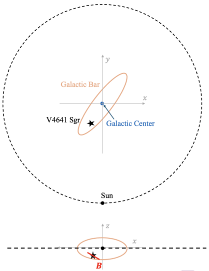


Figure: Escaping cosmic ray particles. [Neronov et al., 2025]

- No sufficient medium.
- Acceleration may not be efficient enough.

- Total proton energy $\sim 10^{50}$ erg
- Long-term injection of protons is required.

Leptonic modelling

Klein-Nishina effect would steepen the spectrum + More efficient cooling

- A hard spectrum is needed.
- A 'distributed' acceleration mechanism is required (in jet/outflow).

Stochastic acceleration (STA) + Shear acceleration (SHA), described by Fokker - Planck equation:

$$\frac{\partial n(\gamma,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial\gamma}[\langle\frac{\Delta\gamma^2}{\Delta t}\rangle\frac{\partial n(\gamma,t)}{\partial\gamma}] - \frac{\partial}{\partial\gamma}[(\langle\frac{\Delta\gamma}{\Delta t}\rangle - \frac{1}{2}\frac{\partial}{\partial\gamma}\langle\frac{\Delta\gamma^2}{\Delta t}\rangle + \langle\dot{\gamma}_c\rangle)n(\gamma,t)] - \frac{n(\gamma,t)}{t_{\rm esc}} + Q(\gamma,t).$$

- Steady-state solution ($\partial n/\partial t = 0$):

$$N(\gamma) = \begin{cases} K_0\gamma^{1-q} & \gamma < \gamma_{\rm eq}\,, \\ K_2\gamma^{s_-}\,{}_1F_1\left(a_-, b_-; z(\gamma)\right) & \gamma_{\rm eq} \le \gamma < \gamma_{\rm rsn}\,, \\ D_2\gamma^{p_-} & \gamma_{\rm rsn} \le \gamma\,. \end{cases}$$

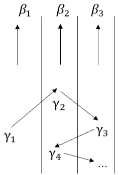


Figure: Sketch of shear acceleration.

Parameter constraints

1. The maximum luminosity:
   $L_{\mathrm{kin}} \leq L_{\mathrm{Edd}}$
2. Hillas criterion ($r_{\mathrm{L}} < R_{\mathrm{jet}}$):
   The maximum energy is defined by
   $\gamma_{\mathrm{Hillas}} = \frac{eB_0 R_{\mathrm{jet}}}{m_e c^2}$.
3. Electrons' mean free path (MFP) ($\lambda < R_{\mathrm{jet}}$):
   The maximum energy is defined by
   $\gamma_{\mathrm{MFP}} = \frac{eB_0}{m_e c^2} \left(\xi \Lambda_{\max}^{1-q} R_{\mathrm{jet}}\right)^{\frac{1}{2-q}}$.
4. Cooling rates should not be too high:
   $t_{\mathrm{acc,SHA}} \leq t_{\mathrm{cool}}$.

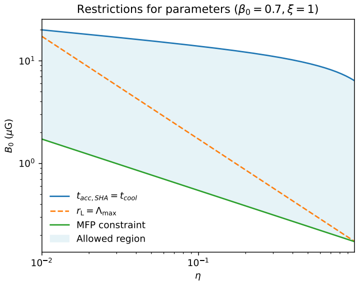


Figure: $\eta - B_0$ planes which show the potential parameter sets under two confinements: $c\tau_{\mathrm{sc}} \leq R_{\mathrm{jet}}$ and $t_{\mathrm{acc,SHA}} \leq t_{\mathrm{cool}}$, with $\beta_0 = 0.7$, q=5/3, $R_{\mathrm{jet}} = 5$ pc and $\gamma = 0.8\ \mathrm{PeV}/\left(m_e c^2\right)$. The orange dashed line indicates the limit for the 1st-order resonance and the shaded area represents the allowed parameter regions when $\xi = 1$.

Results: Data fitting

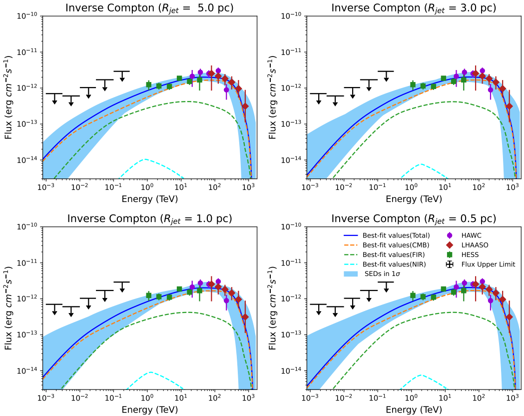


Figure: The fitting results for the UHE spectrum of V4641 Sgr (derived from MCMC).

- Three photon fields, considering the optical depth $\tau_{\gamma\gamma}$.
- MCMC is used to fit the data with various $R_{\rm jet}$ values.

Table: Best-fit parameters from χ^2 tests

	Jet radius $R_{\rm jet}$			
Parameters	5 pc	3 pc	1 pc	0.5 pc
$\log B_0$ (μG)	$-0.32^{+0.20}_{-0.35}$	$-0.02^{+0.13}_{-0.40}$	$0.49^{+0.07}_{-0.45}$	$0.73^{+0.10}_{-0.40}$
η ($R_{\rm shear}/R_{\rm jet}$)	$0.38^{+0.39}_{-0.13}$	$0.29^{+0.43}_{-0.07}$	$0.28^{+0.46}_{-0.05}$	$0.30^{+0.44}_{-0.06}$
β_0 (Spine velocity)	$0.70^{+0.21}_{-0.08}$	$0.64^{+0.25}_{-0.05}$	$0.62^{+0.28}_{-0.02}$	$0.65^{+0.25}_{-0.03}$
$\log N_{\rm tot}$ (Norm.)	$46.90^{+0.72}_{-1.02}$	$46.42^{+1.47}_{-0.43}$	$46.59^{+1.95}_{-0.49}$	$46.42^{+2.17}_{-0.25}$
χ^2/d.o.f.	13.5/12	13.5/12	13.4/12	13.5/12

- B_0 depends on the radius of the jet.

Results: X-ray emission

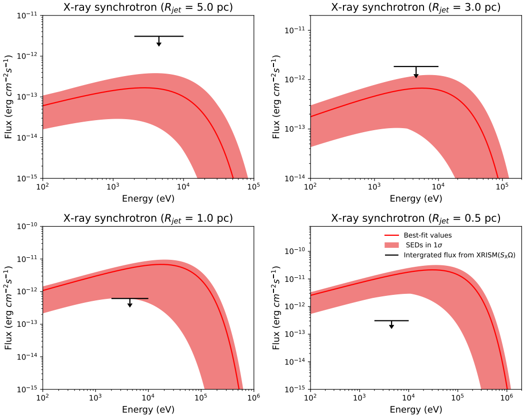


Figure: The synchrotron emission produced by the same electron population responsible for the UHE gamma-ray emission.

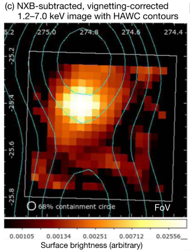


Figure: Recent observation of XRISM has revealed an extended X-ray source around V4641 Sgr ([Suzuki et al., 2025]

- $R_{\rm jet} > 1\,$pc is favored for this model, and the constraint may be relaxed if future observations detect X-ray emission from the region outside its field of view.

Discussions - Dependence on the turbulence spectrum

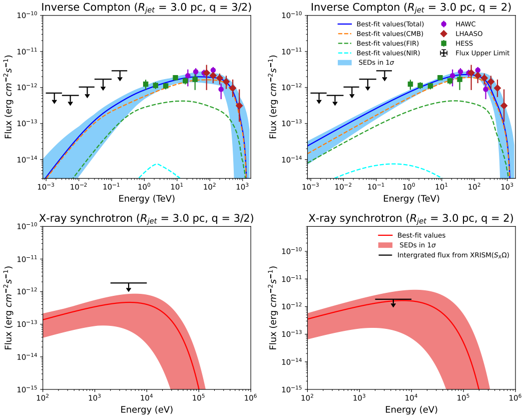


Figure: The fitting results for the UHE spectrum and predicted X-ray synchrotron flux, with different types of turbulence.

- The main parameters do not vary much from those with $q = 5/3$, except for $N_{\rm tot}$ when $q = 2$.
- The electron kinetic luminosity of the jet ($\epsilon_{\rm e}$) keeps $\sim 10^{35-36}\,{\rm erg\,s^{-1}}$

Table: Best-fit parameters from χ^2 tests

Parameters	Type of turbulence	
	$q = 3/2$	$q = 2$
$\log B_0$ (μG)	$-0.09^{+0.10}_{-0.36}$	$0.16^{+0.14}_{-0.49}$
η ($R_{\rm shear}/R_{\rm jet}$)	$0.42^{+0.31}_{-0.20}$	$0.11^{+0.21}_{-0.01}$
β_0 (Spine velocity)	$0.78^{+0.15}_{-0.10}$	$0.38^{+0.25}_{-0.01}$
$\log N_{\rm tot}$ (Norm.)	$46.51^{+0.84}_{-0.76}$	$51.67^{+0.50}_{-1.41}$
χ^2/d.o.f.	13.6/12	13.4/12

- A highly relativistic jet is required if q $\rightarrow$ 1.

Discussions - Possibilities for STA to work solely

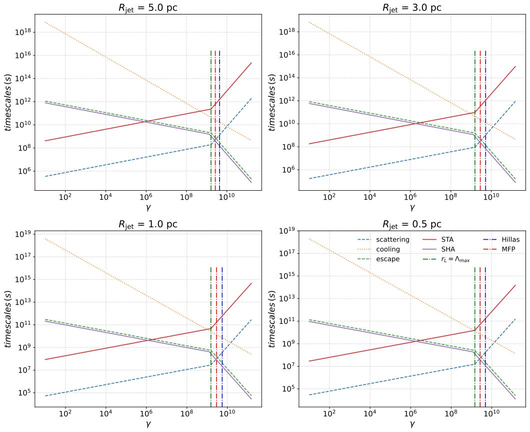


Figure: Timescales for different processes with the best-fit parameters from MCMC fittings.

- From MCMC results (q $= 5/3$), the escape of accelerated electrons is efficient.
- Generally, the accelerated particle spectrum of STA is too hard to explain the measured spectrum of V4641 Sgr.
- However, the spectrum can be softened when q $= 2$ (Both $t_{\rm acc,STA}$ and $t_{\rm esc}$ become energy-indepedent).
- To accelerate the electrons to ~ 0.8 PeV, a very low baryon density of the jet is needed to overcome cooling:

$$\xi = 1,\ B_0 = 2\,\mu\text{G}, \Lambda_{\rm max} = 0.8\,\text{PeV}/\left(eB_0\right)$$

$$\downarrow$$

$$\beta_{\rm A} > 0.09\,, n_{\rm p} < 2.4\times 10^{-8}\,\text{cm}^{-3}$$

Conclusions

- A jet with velocity-shear flows have the potential to accelerate electrons to $\sim$ PeV level via shear acceleration mechanism, given favorable parameters.
- The magnetic field inside the jet under four chosen values of $R_{\rm jet}$ are constrained at μG level and the bulk jet speed is around $0.6c - 0.7c$.
- The X-ray synchrotron emission from the same electron population, whose total flux in $2-10\,$keV could range from 10^{-13} to $10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$. Recent observations of XRISM on V4641 Sgr may favor $R_{\rm jet} > 1\,$pc.
- The model would predict a truly elongated morphology of the UHE gamma-ray source, and future X-ray observations of full coverage of the UHE source may give a stronger constraint on the model.

Regards

Thanks for listening !

Please feel free to contact me: sywan2002@smail.nju.edu.cn

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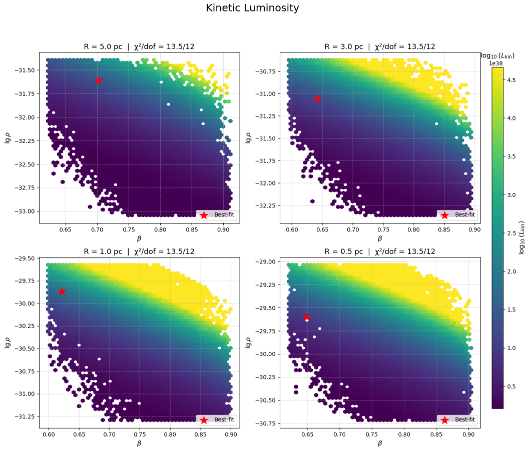

Figure: Protons' kinetic luminosity for all samples within 1-σ statistical uncertainties.

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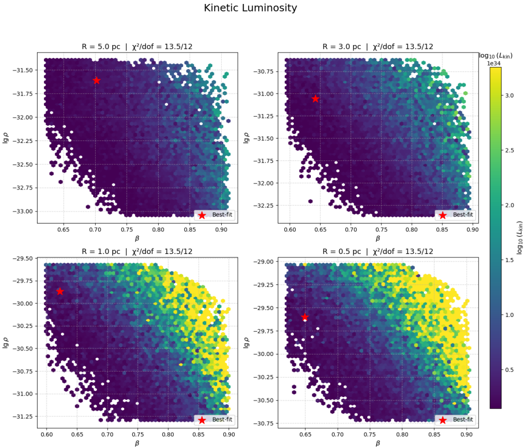

Figure: Electrons' kinetic luminosity for all samples within 1-σ statistical uncertainties.

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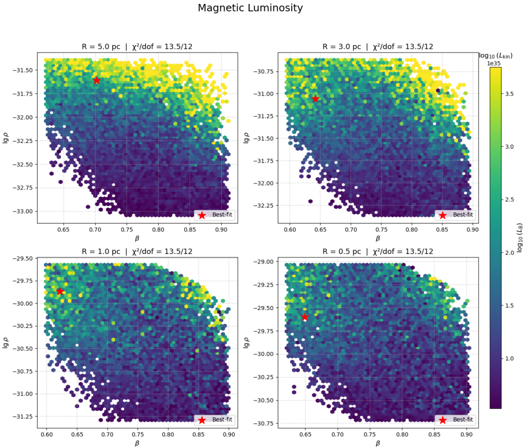

Figure: Magnetic luminosity for all samples within 1-σ statistical uncertainties.

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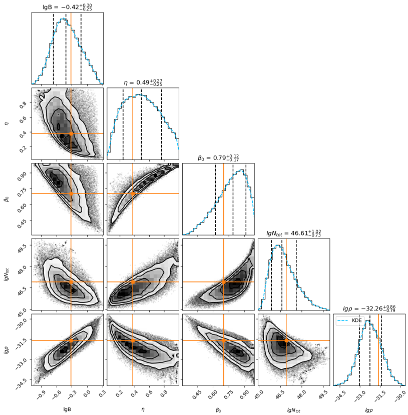
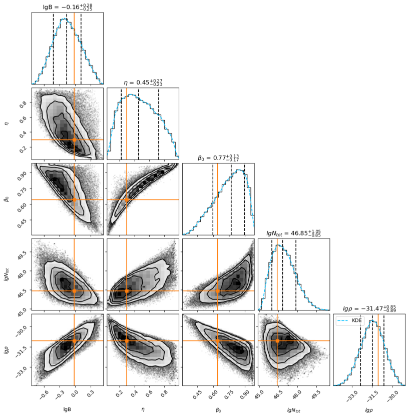


(a) Corner plots for $R_{\rm jet} = 5$ pc.



(b) Corner plots for $R_{\rm jet} = 3$ pc.

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Details for the equation

- SHA term: $\langle\overline{\frac{\Delta\gamma^2}{\Delta t}}\rangle_{\rm SHA} = \frac{\int_0^{R_{\rm jet}} 2\pi r \langle\frac{\Delta\gamma^2}{\Delta t}\rangle_{\rm SHA}\, dr}{\pi R_{\rm jet}^2} = \frac{2}{15}\overline{\Gamma_{\rm j}^4}\left(\frac{\beta_0}{\eta R_{\rm jet}}\right)^2 c^2\tau_{\rm sc}\gamma^2.$

  $\langle\overline{\frac{\Delta\gamma}{\Delta t}}\rangle_{\rm SHA} = \frac{\int_0^{R_{\rm jet}} 2\pi r \langle\frac{\Delta\gamma}{\Delta t}\rangle_{\rm SHA}\, dr}{\pi R_{\rm jet}^2}, \quad \langle\frac{\Delta\gamma}{\Delta t}\rangle = \frac{1}{2\gamma^2}\frac{\partial}{\partial\gamma}\left[\gamma^2\langle\frac{\Delta\gamma^2}{\Delta t}\rangle\right].$
- Radiative cooling: $\langle\dot{\gamma_c}\rangle = -\frac{\sigma_{\rm T} B_0^2\gamma^2}{6\pi m_e c}(1+{\rm X})$, ${\rm X}=\frac{u_{\rm rad}}{u_{\rm B}}$.
- Diffusive escape: $t_{\rm esc} = \frac{R_{\rm jet}^2}{2\kappa}$, $\kappa = \frac{c\lambda}{3}$.
- STA term: $\langle\frac{\Delta\gamma^2}{\Delta t}\rangle_{\rm STA} = \frac{\Gamma_{\rm A}^4\beta_{\rm A}^2\gamma^2}{\tau_{\rm sc}}$.
- The injection energy ($\gamma_{\rm eq}$) is defined as where $\langle\frac{\Delta\gamma}{\Delta t}\rangle_{\rm STA} = \langle\frac{\Delta\gamma}{\Delta t}\rangle_{\rm SHA}$:
  If $\gamma<\gamma_{\rm eq}$: STA dominates, while SHA electrons take over;
  $\gamma_{\rm rsn}$ is defined as where $r_{\rm L} = \Lambda_{\rm max}$:
  If $\gamma>\gamma_{\rm rsn}$, λ would increase sharply due to the loss of low-order wave-particle resonance.
- See Wan et al., 2025 for the complete derivation.