Onsala Proposal

Tafoya 0115.F-9307

Deciphering Hadronic Signatures: Exploring Molecular Clouds Near a Powerful Cosmic-Ray Accelerator V4641 Sgr (continuation)

Semester: feb2025 **Science Cat.: ISM and star formation**

Abstract

Micro-quasars are powerful cosmic particle accelerators within our Galaxy, known for emitting gamma rays at energies exceeding the multi-teraelectronvolt (TeV) range. Recent observational studies have detected gamma-ray emissions surpassing tens of TeV from several micro-quasars. Notably, the High Altitude Water Cherenkov (HAWC) Observatory has observed gamma rays with a median energy of 25 TeV from the micro-quasar SS 433, demonstrating the capability of gamma-ray binaries to accelerate particles to energies exceeding 100 TeV. Additionally, HAWC has detected gamma-ray emissions above 20 TeV from V4641 Sgr, a low-mass X-ray binary characterized by a radio jet-like structure. Building upon our previously accepted proposal, we have already conducted initial observations of V4641 Sgr, and our proposed follow-up observations with the Atacama Pathfinder Experiment (APEX) telescope, focusing on the 13CO(2-1) emissions, will provide deeper insights into the nature of this source. We aim to investigate whether its gamma-ray emissions have a hadronic origin, thereby advancing our understanding of these extraordinary cosmic phenomena.

Applicants

Name	Affiliation	Email	Country		Potential observer
Dr. Daniel Tafoya	Chalmers University of Technology (Space, Earth and Environment)	daniel.tafoya@chalmers.se	Sweden	Pi	
Dr Xiaojie Wang	Michigan Technological University (Physics)	xwang32@mtu.edu	United States		
Dr. Eduardo de la Fuente Acosta	CUCEI, Universidad de Giadalajara (IAM, Departamento de Fisica)	edfuente@gmail.com	Mexico		

Contact Author

Title	Dr.	***Institute***	Chalmers University of Technology
Name	Daniel Tafoya	***Department***	Space, Earth and Environment
Email	daniel.tafoya@chalmers.se	***Address***	Onsala Space Observatory
Phone(first)	+46 31 772 5502	***Zipcode***	SE-43992
Phone(second)		***City***	Onsala
Fax		***State***	
		Country	Sweden

Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	nFLASH230 (200-270 GHz)	22h (22h)	220.3987	any	16-20	If possible, it would be good to observe the 13CO(2-1) and 12CO(2-1) simultaneously

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
V4641 Sgr	18:19:21.63	-25:24:25.8	J2000	0.0	1300	A	three separate regions

1.Scientific rationale

Microquasars serve as natural laboratories for investigating jets of relativistic particles formed through the accretion of matter onto a spinning black hole. Their relative proximity enables high-resolution imaging of spatial structures across multiple wavelengths. In the case of the broadly studied microquasar SS 433, measurements of its TeV gamma-ray spatial morphology have localized electron acceleration at shocks within the jet, far from the black hole. V4641 Sagittarii (V4641 Sgr) is a comparable binary system, hosting a black hole with a mass of $6.4 \pm 0.6, M_{\odot}$ and a B9III companion star of mass $2.9 \pm 0.4, M_{\odot}$ [1]. This microquasar is distinguished by its super-Eddington accretion, violent X-ray outbursts characterized by rapid onset and exponential decay [2], and one of the fastest superluminal radio jets in the Milky Way [3]. Recently, very-high-energy (VHE) gamma-ray emission exceeding 200 TeV was unexpectedly detected near this microquasar by the High Altitude Water Cherenkov (HAWC) Gamma-ray Observatory [4]. The observed HAWC gamma-ray emission exhibits a bipolar morphology, extending across an angular size of approximately $1°$, significantly surpassing the spatial extent seen in radio wavelengths (see Fig. 1).

Persistent gamma-ray emission is anticipated from the extended synchrotron lobes and jets of microquasars. Previous observations by HAWC have established the presence of gamma-ray emission from SS 433, with a median energy of 25 TeV, as well as from LS 5039, where emissions exceeding tens of TeV have been detected [5]. These findings indicate that microquasars can accelerate particles to energies exceeding 100 TeV within their jets [6; 7]. Prior to the recent HAWC detection, V4641 Sgr was classified as a non-detection in gamma-ray observations, with an upper limit of < 237 gigaelectronvolts (GeV) reported by H.E.S.S. and RXTE in 2018 [8]. The newly observed gamma-ray emission from V4641 Sgr suggests that its jet-accelerated particles may reach energies approaching the petaelectronvolt (PeV) scale. This detection not only expands the known population of gamma-ray-emitting microquasars but also highlights their role as potential sources of the highest-energy cosmic rays in our Galaxy.

High-energy gamma rays in microquasar systems can be produced through two primary mechanisms: leptonic and hadronic. In the leptonic scenario, relativistic electrons upscatter low-energy photons—originating from the cosmic microwave background (CMB), the accretion disk, or the companion star—via Inverse Compton Scattering (ICS), thereby boosting them to gamma-ray energies. **Alternatively, in the hadronic scenario, accelerated protons interact with dense molecular clouds, leading to the production of pions that subsequently decay into gamma rays.** The relative contribution of these mechanisms to the observed emission remains uncertain. In microquasars, both electrons and protons can be efficiently accelerated by relativistic jets or by shocks formed as these jets interact with the supersonic stellar winds of the companion star. As a result, gamma-ray emission may originate from compact regions near the black hole as well as from extended synchrotron lobes at parsec-scale distances [9]. Identifying the dominant mechanism responsible for the observed gamma-ray emission in microquasars, and determining whether it is linked to localized jet interactions or large-scale outflows, remains an open question of significant astrophysical interest.

A crucial aspect of pinpointing the source of gamma-ray emissions from V4641 Sgr involves constraining the maximum energy and overall energy budget of the parent particles. **Accurately determining the location of V4641 Sgr, obtaining a well-constrained spectral energy distribution across various wavelengths, and characterizing the surrounding molecular environment are essential for understanding the nature of its emissions.** As part of a previously approved proposal, we have already carried out initial APEX observations to map the $^{13}CO(2-1)$ emission toward V4641 Sgr. These observations have provided valuable insights into the association of the molecular gas to this source, its spatial distribution, and the column density (see right side of Fig. 1). However, these maps provide a limited view of the molecular clouds in the direction of V4641 Sgr. To extend the mapping region and better define the extent of the molecular clouds, we propose additional observations. These follow-up observations will allow us to more precisely characterize the molecular hydrogen density (H_2) over a larger area. Such maps will provide stronger constraints on the underlying mechanism of the observed high-energy gamma-ray emission and further illuminate the interaction between the jet and the surrounding environment.

2. Proposed observations and methodology

In order to understand the mechanism behind gamma-ray emission in a region of the galaxy, an accurate measurement of the nucleon density, $n(\mathrm{H}) = 2n(\mathrm{H_2}) + n(\mathrm{H\ I})$, is crucial. By characterizing the hydrogen content, both in its atomic and molecular forms, reliable values of the nucleon density can be obtained. While atomic hydrogen can be probed through its 21 cm line emission, molecular hydrogen is primarily traced by the emission of the CO molecule, which is a sensitive tracer of the cold (10–30 K) and dense (10^3–10^4 cm^{-3}) molecular gas phase of the ISM in the Galaxy (e.g., [10; 11]). Thus, a detailed survey and study of CO emission from molecular clouds and material in the vicinity of gamma-ray sources allow us to better constrain the nature and origin of the high-energy cosmic rays (CR). In particular, conducting a detailed study of the molecular gas near microquasars like V4641 Sgr is essential for exploring the hadronic component of the gamma-ray emission.

For the hadronic mechanism, with a cosmic ray (CR, protons) count, $N_p(\mathrm{CR})$, and a total ambient volumetric hydrogen gas density, $n(\mathrm{H})$, it is possible to relate these properties to the very high-energy (VHE) gamma-ray emission observed by HAWC (N_γ^{obs}), the leptonic component, $N_g(\mathrm{leptonic})$, and the hadronic component, $N_\gamma(\mathrm{hadronic})$, according to the relation: $N_\gamma^{obs} - N_g(\mathrm{leptonic}) = N_\gamma(\mathrm{hadronic}) \propto n(\mathrm{H}) \times N_p(\mathrm{CR})$, as discussed in [10; 12]. The nucleon column density, $n(\mathrm{H})$, appears in this equation because molecular and atomic hydrogen clouds serve as targets for CR protons. The value of $n(\mathrm{H}) = n(\mathrm{H_2} + \mathrm{HI})$ can be determined from the column densities of atomic and molecular hydrogen, with the relation $N(\mathrm{H_2} + \mathrm{HI}) = [2 \times N(\mathrm{H_2})] + N(\mathrm{HI})$, taking into account the geometry of the emitting region. The column density of atomic hydrogen, $N(\mathrm{HI})$, will be derived from observations of the Dominion Radio Astrophysical Observatory (DRAO) Synthesis Telescope [13], following the methodology outlined in [14]. We have already conducted initial APEX observations to estimate the column density of molecular hydrogen, $N(\mathrm{H_2})$, in the vicinity of V4641 Sgr using optically thin ^{13}CO emission, following standard calculations (e.g., [15–17]). However, to extend the mapping region and improve the overall analysis, we propose additional APEX observations. These will allow us to refine the column density estimates and enhance our understanding of the gamma-ray emission.

While the region from which the gamma-ray emission originates is extensive, approximately $1^\circ \times 1^\circ$ (see Fig. 1), our previous mapping efforts focused on three smaller, more manageable regions, as indicated by the boxes on the right side of Fig. 1. For this follow-up work, we aim to map the same area, with a similar signal-to-noise ratio, but shift our focus to a slightly different direction along the bipolar outflow of V4641 Sgr. Therefore, we have again chosen to concentrate on three regions, each measuring 345 arcsec $\times$ 345 arcsec. For technical reasons related to the observations, each region will be subdivided into nine sub-regions of 115 arcsec $\times$ 115 arcsec, resulting in a total of 27 sub-regions. Similar to our previous observations, we aim to achieve a noise level of 50 mK with a spectral resolution of 1 km s^{-1}. Using the APEX Observing Time Calculator, we have determined that the total required integration time for each 115 arcsec $\times$ 115 arcsec sub-region would be 0.8 hours. Consequently, the total observing time requested for this study amounts to 27×0.8 hours $= 21.6$ hours.

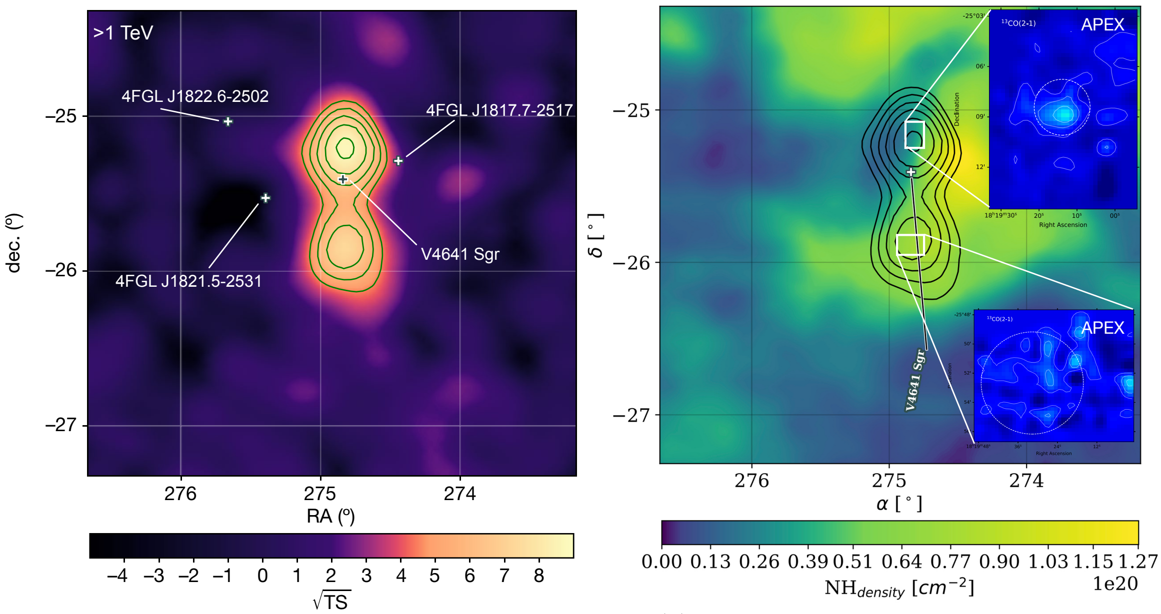

Figure 1: Left: Significance map of the V4641 Sgr region. (a) The map displays events with measured energies exceeding 1 TeV. The test statistic (TS), defined by the likelihood ratio test in equation (1), quantifies the significance of the detection. Green contours correspond to TS values ranging from 4.5 to 8.5, increasing inwards in increments of one from the outermost to the innermost contour. Cross markers indicate the best-fit positions obtained from the two-point-source model. **Right:** Gas distribution in the vicinity of V4641 Sgr. The black contours illustrate the very-high-energy (VHE) gamma-ray excess detected by HAWC. The atomic hydrogen column density (N_H) at the location of V4641 Sgr is derived by integrating the gas survey cubes over the velocity range of 70–120 km s^{-1} and normalizing by the velocity interval. Due to the high noise levels in the molecular hydrogen map, the presence of the target material in molecular form cannot be definitively confirmed or ruled out. The APEX observations of the ^{13}CO(2-1) from our previous proposal are shown in the figure as insets.

OTF time estimator V10.0

Heterodyne receiver:	NFLASH230	
Side Band:	LSB	
Tuning Freq:	220	[GHz]
Line Freq [+2 & -6 GHz from tuning]:	220	[GHz]
Resolution Δv:	1	[km/s]
pwv :	2.0	[mm H_2O]
Source elevation:	45	[deg]
Length axis in scanning direction:	115	[arcsec]
Length in the orthogonal axis:	115	[arcsec]
Dumptime (0.1 <= dt <= 4 [s]):	4	[sec]
rms or sigma requested : (0.05 [K])	50	[mK]

Time per sub map [sec]	48.7
Calibrations per coverage	0
Total map area covered [arcsec^2]	13225
Number of submaps	13
Tau (@ elev 45 deg)	0.124
Transmission (@ elev 45 deg)	0.883
Trec [K]	71.6
Tsys [K] (source elev 45 deg)	140.158
HPBW [arcsec]	28.4
Beam solid angle [arcsec^2]	1011.8
Rows per off position (reference pos.)	1
Scanning speed [arcsec/ s]	2.4
Number of coverages	1
Sigma reached after 1 coverage [mK]	44.2
Sigma reached after 1 coverage(s) [mK]	44.2
On-source time [min,hr]	10.5 I 0.2
Off-source time [min,hr]	5.2 I 0.1
Overhead Sys, Cal, Pointing, Focus [min,hr]	32.2 I 0.5
Telescope time [min,hr]	48 I 0.8

Figure 2: Results from the APEX Time Calculator for the proposed observations. The total required integration time for each sub-region of 115″ × 115″ is 0.8 hours, with a spectral resolution of 1 km s^{-1} and a noise level of 50 mK.

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No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

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No additional remarks

Observing run info :