Year 2022-2023
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Very high energy gamma-ray emission from M87 and its environs with HESS and CTA

Astrophysical context, the AGN central engine and variability:

Active galactic nuclei (AGN) are a class of galaxies in which bright, broad-band, non-thermal radiation is detected from the central region of the galaxy. Amongst the most extreme objects in the Universe, the centres of these objects are thought to house a supermassive black holes (up to 10 billion solar masses) onto which material from the galaxy is captured, releasing gravitational potential energy as it spirals towards the black hole in a disk-like structure, and launching jets of relativistic plasma perpendicular to the galactic plane which extend up to millions of light-years into the environment around the galaxy. Shocks formed in these jets accelerate charged particles up to highest energies seen in Nature (possibly as high as a EeV), which produce gamma rays that can be detected on the Earth, even from sources at cosmological distances. However many questions remain : how does the in-falling material launch and collimate the jets, what is the composition of the jets, what is the role of protons and electrons in producing high-energy gamma rays, do the jets give rise to the flux of charged particles (cosmic rays) we detect on the Earth ?

Figure 1: X-ray (Chandra) and radio (VLA) composite image, hot matter (blue in X-ray) from the Virgo cluster falls toward the core of M87 and cools, where it is met by the relativistic jet (orange in radio), producing shock waves in the galaxy's interstellar medium.

ICM-AGN interaction and feedback

AGN are also recognized as critical objects in the formation and evolution of galaxies in the Universe. They are believed to significantly contribute to shaping the large scale structures of the cosmic web via feedback mechanisms. The most powerful AGN are located at the center of galaxy clusters, i.e., the largest gravitationally bound structures in the Universe. The gravitational collapse of the surrounding gas onto the central engine triggers spectacular outbursts that inject huge amounts of energy into the neighbouring environment. Their imprint on the intra-cluster medium is seen clearly in X-rays, which have revealed giant cavities filled with radio jets that are pushing the thermal gas, visible around many cluster central AGN. Today, we have solid evidence that AGN feedback can prevent catastrophic in-fall of gas, but the details of energy release are yet unknown. Nevertheless, it is clear that cosmic rays should play an important role and induce diffuse gamma ray emission via hadronic interactions within the thermal gas. The detection and characterization of such a signal would be invaluable to understand AGN feedback and large scale structure formation.

M87 as the perfect target:

The radio galaxy M87 is a perfect “AGN laboratory” for addressing these fundamental questions. Often referred to as a misaligned blazar, it offers a unique opportunity to study how and where particle acceleration happens in the jets and with which variability time-scale, with the help of multiwavelength observing campaigns. M87 is also the central galaxy of the Virgo galaxy cluster. Its interaction with its surrounding intra-cluster gas has been revealed in radio and X-ray data. Given its distance, sky location, and the available multi-wavelength data, the diffuse gamma-ray emission is expected to be resolved and M87 is one of the best sources to study this physics. Moreover, M87 is observable under good conditions from all ground based very high energy gamma ray facilities currently operating (HESS, CTA, MAGIC, VERITAS ; see also the next paragraph). For all these reasons, M87 has been studied for more than two decades in the high energy gamma-rays.

Instrumental context

HESS observations and analysis

The H.E.S.S. array of 5 telescopes is currently operating at energies above about 100 GeV, and has the best sensitivity of any telescope system at these energies. H.E.S.S. has detected gamma rays from M87 but to date it has not allowed the site of the acceleration to be unambiguously resolved. However the LLR group has been instrumental in developing an enhanced analysis methodology, in which detailed simulations of every observation are made in order to reduce systematic errors and increase the instrument’s power to resolve structure in astrophysical objects. This analysis method has allowed structure to be detected in a different AGN, Centaurus A. This methodology, applied to M87 data, could reveal the extended emission and probe, for the first time, the role of cosmic rays in AGN outbursts feedback on the surrounding intra-cluster thermal gas.

Observations prospects with CTA

In parallel, the Cherenkov Telescope Array (CTA) is a ground-based gamma-ray observatory under construction on two sites: one on the La Palma Canary island (CTA-

North) and the other one in the Atacama desert in Chile (CTA- South). CTA will probe the very high energy gamma-ray emission in the range between about 50 GeV to 100 TeV with unprecedented sensitivity, and can thus be used to study AGN such as M87, and possibly its interaction with the intra-cluster medium in the Virgo cluster. Such studies would very well complement one of the ten key science projects of CTA which aims at detecting the diffuse gamma-ray emission from galaxy clusters and understanding the underlying cosmic-ray physics. The beginning of observatory observations is expected in 2023.

PhD student envisioned contribution

We propose a PhD thesis on the data analysis and modelling of M87 and its environment using H.E.S.S. and CTA. The underlying goal will be to unambiguously detect, for the first time, the gamma-ray emission arising from AGN - cluster interactions and to characterise the feedback from AGN in the non-thermal pressure support in clusters. The study will also aim at characterising the emission region associated with the AGN itself in order to constrain the particle acceleration physics in the jets.

H.E.S.S data analysis

The PhD student will have the opportunity to carry out analysis of existing data obtained with the H.E.S.S. telescope array. He/she will benefit from an important existing archive, but new data are also expected. This work will focus on applying new run-wise simulation based analysis techniques to obtain preliminary constraints on the feedback processes acting on the intra-cluster medium in the Virgo cluster via spatial extension constraints of the M87 galaxy. The PhD student will also participate in on-site observing campaigns in Namibia.

Modelling and constraints

The second part of the thesis will consist in the modelling of the very high energy gamma-ray of the M87 galaxy, including the central AGN engine and its environment. The PhD student will contribute to the development of mode ling software, simulations and analysis to be applied to H.E.S.S. data to extract physical constraints. The same tools will also be applied to CTA in order to estimate the expected signal and predict the scientific outcomes of the observations. This work will make use of extensive datasets at different wavelengths, available in the literature.

Outcomes

The PhD student will be expected to participate and lead publications within the involved collaborations, and will have the opportunity to present results or ongoing work at conferences and workshops, as well as contribute to collaboration meetings.

Environment

The PhD student will join the gamma-ray astronomy team at LLR. The team is made of experts of ground-based and space-based gamma-ray observations. Current activities include the scientific exploitation of the H.E.S.S. telescope array in Namibia, that of the Fermi-LAT satellite, and the construction and scientific preparation of the CTA ground-based observatory.

The gamma-ray astronomy LLR team gathers experts in the analysis of astrophysical objects such as active galactic nuclei, galaxy clusters and pulsars. In particular, the LLR has major implications in the H.E.S.S. international collaboration. The team is co-leading the CTA working group dedicated to the preparation of the galaxy clusters Key Science Project. The LLR team is also strongly involved in instrumental and raw data analysis and is currently participating in the construction of the NectarCAM camera to be installed on CTA. The LLR gamma-ray astronomy team is involved in several international collaborations related to the H.E.S.S., CTA and Fermi instruments, which will benefit the PhD thesis.

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Thesis Adivsor

- Mathieu de Naurois: direction, H.E.S.S. data analyis
- Stephen Fegan: co-direction, CTA prospective
- Rémi Adam: co-direction, Modelling (AGN-cluster interaction)

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Summary

Active galactic nuclei (AGN) are a class of galaxies in which bright, broad-band, non-thermal radiation is detected from the central region of the galaxy. Amongst the most extreme objects in the Universe, the centres of these objects are thought to house a supermassive black holes (up to 10 billion solar masses) onto which material from the galaxy is captured, releasing gravitational potential energy as it spirals towards the black hole in a disk-like structure, and launching jets of relativistic plasma perpendicular to the galactic plane which extend up to millions of light-years into the environment around the galaxy. Shocks formed in these jets accelerate charged particles up to highest energies seen in Nature (possibly as high as a EeV), which produce gamma rays that can be detected on the Earth.

AGN are also recognized as critical objects in the formation and evolution of galaxies in the Universe. They are believed to significantly contribute to shaping the large scale structures of the cosmic web through the injection of huge amounts of energy into the neighbouring environment.

The radio galaxy M87 is the central galaxy of the nearby Virgo galaxy cluster. Often referred to as a misaligned blazar, it offers a unique opportunity to study how and where particle acceleration happens in the jets and with which variability time-scale, with the help of multiwavelength observing campaigns.

We propose a PhD thesis on the data analysis and modelling of M87 and its environment using the H.E.S.S. array of Atmospheric Cherenkov Telescope located in Namibia and its successor, the Cherenkov Telescope Array (CTA) currently under construction. The underlying goal will be to unambiguously detect, for the first time, the gamma-ray emission arising from AGN - cluster interactions and to characterise the feedback from AGN in the non-thermal pressure support in clusters. The study will also aim at characterising the emission region associated with the AGN itself in order to constrain the particle acceleration physics in the jets.

Résumé

Les noyaux actifs de galaxie (AGN) sont une classe de galaxies dans lesquelles un rayonnement lumineux à large bande et d'origine non thermique est détecté en provenance de la région centrale de la galaxie. Parmi les objets les plus extrêmes de l'Univers, ces objets abritent en leur centre un trou noir supermassif (jusqu'à 10 milliards de masses solaires) sur lequel le matériau de la galaxie est capturé, libérant de l'énergie gravitationnelle lorsqu'il tombe en spiralant vers le trou noir, en formant dans une structure en forme de disque, appelée « disque d'accrétion ». Dans ce processus, deux jets de plasma relativiste sont émis perpendiculairement au plan galactique, qui s'étendent jusqu'à des millions d'années-lumière dans l'environnement autour de la galaxie. Les chocs formés dans ces jets accélèrent les particules chargées jusqu'aux énergies les plus élevées observées dans la nature (éventuellement aussi élevées qu'un EeV), en produisant des rayons gamma qui peuvent être détectés sur la Terre.

Les AGN sont également reconnus comme des objets importants dans la formation et l'évolution des galaxies dans l'Univers. On pense qu'ils contribuent de manière significative à façonner les structures à grande échelle de la toile cosmique en injectant d'énormes quantités d'énergie dans l'environnement voisin et en redistribuant ainsi de la matière.

La radiogalaxie M87 est la galaxie centrale du proche amas de galaxies dit de la Vierge. Souvent qualifié de blazar désaligné, il offre une opportunité unique d'étudier comment et où l'accélération des particules se produit dans les jets et avec quelle échelle de temps de variabilité, à l'aide de campagnes d'observation multi-longueurs d'onde.

Nous proposons une thèse de doctorat sur l'analyse des données et la modélisation de M87 et de son environnement à l'aide du réseau de télescopes à effet Cherenkov atmosphérique H.E.S.S. situé en Namibie et de son successeur, le réseau de télescopes Cherenkov (CTA) actuellement en construction. L'objectif sous-jacent sera de détecter sans ambiguïté, pour la première fois, l'émission de rayons gamma résultant des interactions AGN - amas et de caractériser la rétroaction de l'AGN sur la pression non thermique dans les amas. L'étude visera également à caractériser la région d'émission associée à l'AGN lui-même afin de contraindre la physique de l'accélération des particules dans les jets.