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ESTHER: a Small Project to Investigate Gamma-Ray Emissions in Thunderstorms on Mt. Etna

Experiment to Study Thunderstorm High-Energy Radiation

A. Ursi[1,2*], D. Reitano[3], M. Marisaldi[4], D. Sarria[4], D. Pennisi[5], R. Campana[6], E. Virgilli[6], and P. Calabretto[6]

1 - INAF-IAPS, National Institute for Astrophysics, Roma, Italy; 2 – Italian Space Agency (ASI), Roma, Italy; 3 - National Institute of Geophysics and Volcanology (INGV), Catania, Italy; 4 – Birkeland Centre for Space Science, University of Bergen, Norway; 5 – Italian Alpine Club of Catania; 6 – INAF-OAS, National Institute for Astrophysics, Bologna, Italy;

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INTRODUCTION

Detecting thunderstorm gamma-ray emissions from the ground is a relatively new frontier in atmospheric science and has opened up new avenues for research. Also, the recent detection of a Terrestrial Gamma-ray Flash (TGF) produced during the massive Hunga Tonga–Hunga Ha'apai eruption [*Briggs et al.*, 2022], pointed out the possibility that even volcanic lightning might produce gamma-ray emissions at MeV energies. In recent years, Italy has played an important role in investigating gamma-ray thunderstorms, especially with the detections from space carried out by the AGILE satellite [*Marisaldi et al.*, 2010a; *Tavani et al.*, 2013; *Ursi et al.*, 2016; *Lindanger et al.*, 2020; *Maiorana et al.*, 2020] and with the observations from ground and aircraft performed in the framework of the Gamma-Flash program [*Ursi et al.*, 2022; *Tiberia et al.*, 2022; *Bulgarelli et al.*, 2023; *Calabretto et al.*, 2024].

THE ESTHER PROJECT

In this context, we present the Experiment to Study Thunderstorm High-Energy Radiation (ESTHER), a small project aimed at monitoring from the ground gamma-ray emissions produced during thunderstorms and, possibly, by volcanic lightning. The ESTHER set-up consists of a portable gamma-ray detection system with a VLF radio receiver, installed on the top of the Mt. Etna volcano (Italy). The selected installation sites are the Citelli Refuge (CAI) located at 1,741 m a.s.l. and the "Pizzi Deneri" Etnean Observatory (INGV) located at 2,818 m altitude, less than 2.7 km from the main volcano craters. The observational campaign started in spring 2024 and it is currently ongoing.

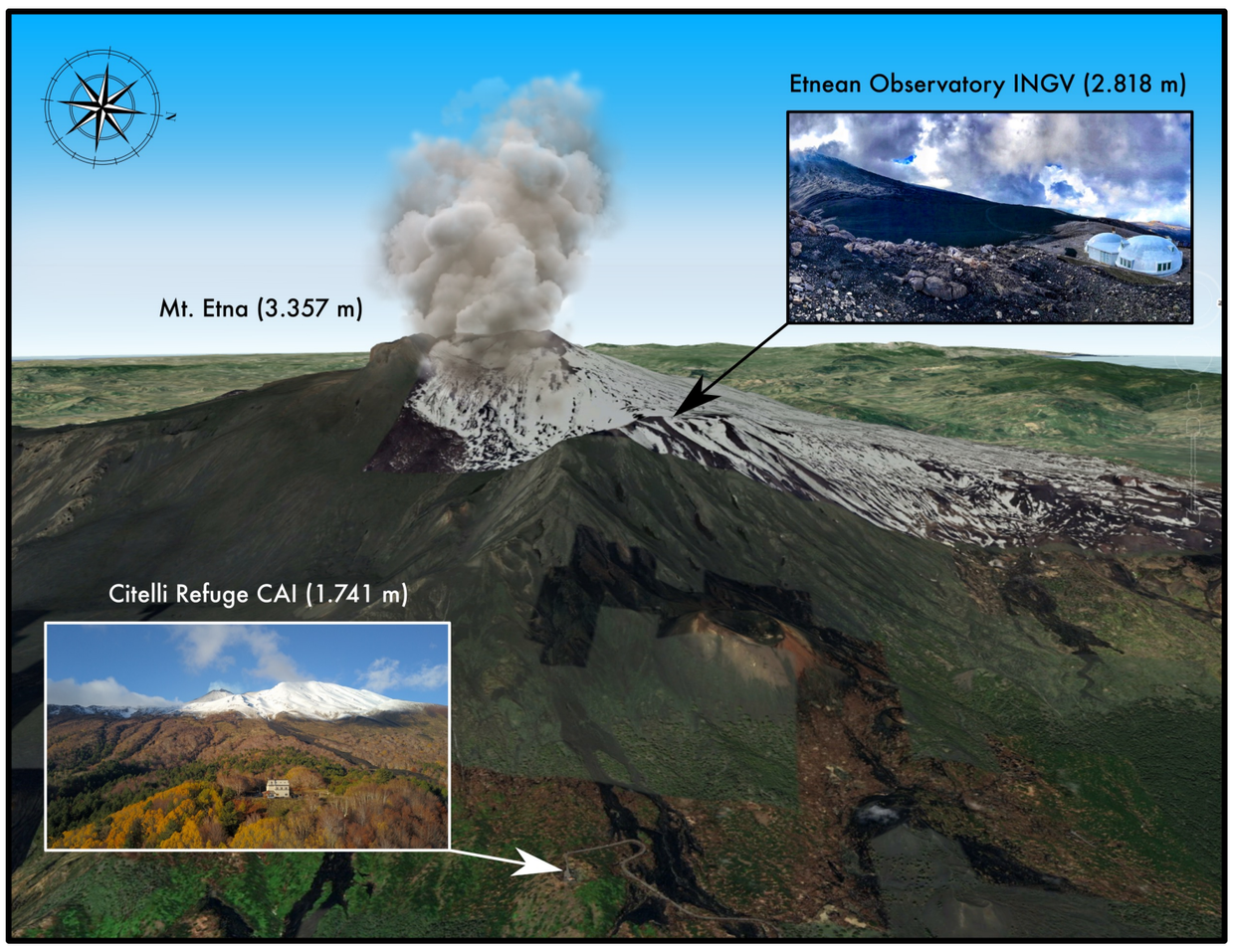

Fig. 1 – The two installation sites of the ESTHER set-up, located on Mt. Etna: the CAI Citelli Refuge and the INGV Etnean Observatory (2,818 m).

The gamma-ray detection system is composed of two NaI(Tl) scintillators (2"ø and 3"ø) coupled to PMTs, overall sensitive in the 200 keV – 12 MeV energy range. Both detectors acquire high-energy photons with a 1-2 μs time resolution. The radio receiver is sensitive in the 20-250 kHz range, with 2 H-field channels (N-S and E-W) and 1 E-field channel (omnidirectional). The acquired waveforms are digitized to 12 bits at 3.125 Msps, with GPS absolute time accuracy. All detectors are controlled by a Main PC with a Wi-Fi router, which serves both as a command device and a local storage. The Main PC can be accessed remotely. The whole set-up, except the radio receiver, is housed inside an Al water-tight case, allowing for a convenient transportation in case of relocation of the experiment.

Fig. 2 – Up: the ESTHER set-up installed at the Citelli Refuge. Right: a close-up of the ESTHER detectors and antenna enclosed in the aluminum case.

WORKING PRINCIPLE

The ESTHER set-up includes a Main PC with internet connection and local storage, which can be accessed remotely. This allows to remotely manage all detectors, control their proper functioning, and download the data acquisitions.

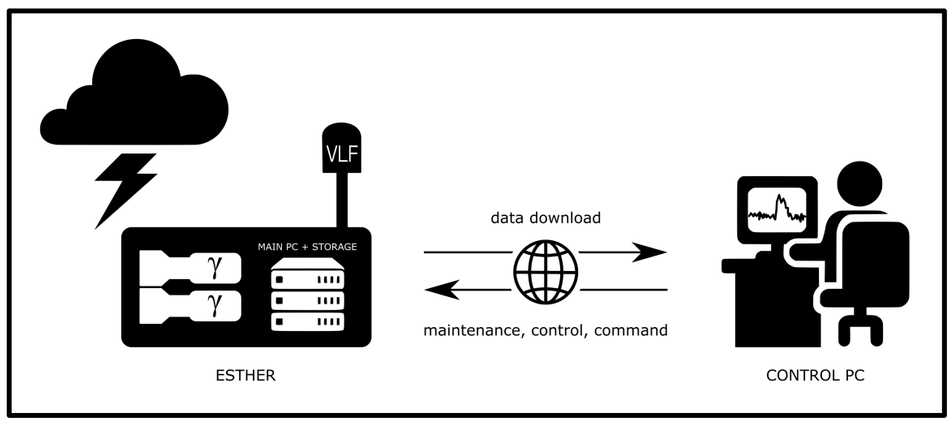

Fig. 3 – Basic working principle of ESTHER. All detectors can be remotely managed by using a local Main PC with Wi-Fi internet connection, that also serves as local storage for the acquired data.

LIGHTNING ACTIVITY AT MT. ETNA

An extensive analysis of the flash rate recorded at Mt. Etna in the last 8 years pointed out that the mountain top is interested by strong lightning activity, especially in summer [*Ursi et al.*, 2023]. In particular, the largest fraction of discharges cluster right above the main volcano craters, where the frequent presence of volcanic ashes possibly locally increases the electrical conductivity, under conditions of humid air typical of thunderstorms, making that region a natural trigger for lightning. Moreover, as for other volcanoes around the world, Etna has been documented to produce volcanic lightning (last times in 2015 and 2022).

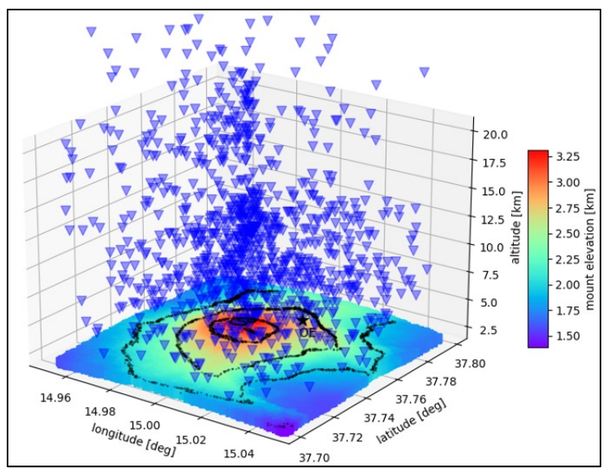

Fig. 4 – Distribution of intra-cloud flashes occurred on Mt. Etna, showing a thick column of events right above the main craters, possibly favored by the frequent presence of humid volcanic ashes.

OBSERVATIONS: DETECTION OF AN INTENSE POSITRON BURST

Up to now, ESTHER collected a continuous datastream covering 4 months, from May 24th to September 23rd, acquired in the first installation site (Citelli Refuge). In this time frame, it experienced a total of 22 days of thunderstorms at the installation site. For all these thunderstorms, ESTHER revealed typical gamma-ray signatures of ^{222}Rn washout/rainout processes. Moreover, during summer 2024, ESTHER experienced several days interested by intense volcanic eruptions, which may have produced interesting spectral signatures in the data, currently under analysis.

On 22 July 2024, during an intense thunderstorm taking place right above the experimental set-up, the ESTHER detectors revealed a gamma-ray event lasting about 6.5 minutes, composed of an initial weak possible gamma-ray glow, a following shallow prolonged emission, and a final intense burst lasting ~40 s, this last exhibiting a remarkable 511 keV emission. The final burst released more than 16% of its total counts within 511±25 keV, exhibiting a count rate, in that very energy range, 5 times higher than that typically encountered in the background. This episode could be the result of the annihilation of positrons produced in the parent thundercloud, either during relativistic runaway processes (RREA) or photonuclear reactions. Some possible scenarios that could have led to the production of this event are currently under investigation.

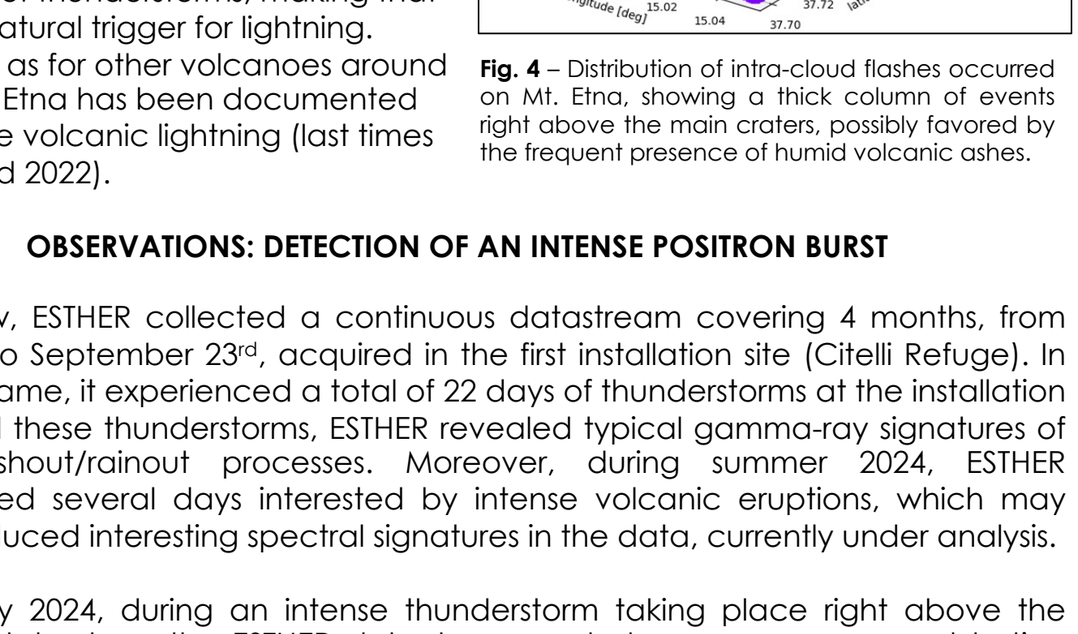

Fig. 5 – Left: light curve of the event detected on 22 July 2024. The most intense episode is highlighted in red. Right: energy spectrum of that episode, where it is clear a remarkable emission in the 511±25 keV energy range, possibly produced by positron annihilation.

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*alessandro.ursi@inaf.it