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Astroparticle physics obtaining more attention from a new type of audience

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Abstract. Cosmic-ray muography is a group of density-imaging techniques based on directional measurements of muon attenuation in liquid or solid media. The foundations of this emerging multidisciplinary research field were already laid in the 1950s-1970s, but the number of applications and research publications has witnessed a constant increase only in the last 15 years. We describe here what is currently happening on different fronts, where we may go next, and what this means for astroparticle physicists.

1. Introduction

High-energy physics (i.e., astroparticle and particle physics) is experiencing a peculiar twist of events as its research draws more attention than, perhaps, ever before. Science magazines and online science popularizer sites have lately contained numerous news articles of the recent measurement of the muon's anomalous magnetic moment [1], discussing the nature of the experiment and the impacts of the result for new physics and the Standard Model. In addition, muons have acquired much interest lately from geoscientists and engineers working in research and applications that coincide with subject matters overlapping with astroparticle physics. In this case, however, the reason behind the newly grown interest lies in how atmospheric muons can be used as radiographic probes of density variations in geological materials and, in some cases, buildings and manufactured constructions. Various names exist for the method group that utilizes muons for these purposes. We apply the word *muography*, an umbrella term for various techniques applying muons for imaging [2]. The different techniques include muon radiography and tomography and time-lapse (or time-sequential) variants of the same.

In this work, we summarize why muography is currently experiencing a period of unprecedented growth, how we got here, what is currently happening on different fronts, where we may go next, and what this means for astroparticle physicists.

2. Muography in brief

The various forms of muography are easiest to explain by an analogy to X-ray methods. Indeed, muon radiography and muon tomography share many principles with X-ray radiography and X-ray tomography, respectively. The shared similarities include the principle upon which the density image reconstruction is based: i.e., the directional attenuation of the radiation of interest. There are, nevertheless, also significant dissimilarities, such as the fact that in muography, radiation does not need artificial generation. Also, the observation scale is up to three magnitudes bigger in muography, which allows imaging of solid objects as large in diameter as 2 km or more, although, on such a scale, data collection is time-consuming. In the vertical direction, muography can be applied in depths below 1 km, but it is clear that the deeper one seeks to apply muon detectors, the more time one needs (up to years) for collecting adequate statistics for high-resolution imaging. However, to overcome the quickly diminishing muon flux, the detectors could be built larger, and their sheer numbers multiplied. These technical means may improve muography's feasibility in depths where deeper mining, for example, is actively going [3].

We have included only some references. A reader looking for more comprehensive reviews on muography, muon detectors and their most common forms and applications are directed to the first book wholly dedicated to muography [4].

2.1. Early days
The mutual story of muons, engineers and geoscientists started as the first experiments with muon imaging were conducted in Australia in the 1950s [5]. In the late 1960s, Alvarez et al. [6] studied a pyramid in Egypt with muons. The first theoretical examinations for applying muons for mining industry applications were proposed in the late 1970s [7]. A more detailed summary of the early days of muon imaging is provided, for example, in [8].

2.2. Current period
Very little happened in the story of muography in the 1980s to 1990s. In retrospect, the current period began when the researchers commenced experimental imaging of volcanoes in Japan in the 2000s [9]. The number of applications and research publications has witnessed a constant increase ever since, as shown, for example, by [8].

As discussed in the next section, muography has been applied or proposed for a significant number of geological, geophysical, geotechnical and engineering applications. The researchers and end-user working in these fields are often crossing boundaries due to the interdisciplinary requirements of their respective disciplines. Occasionally, this means that they read and actively refer to the works published by astroparticle physicists. This new audience of cosmic rays, Extensive Air Showers, and muon propagation models and simulations comprises geologists, geochemists and geophysicists, and various engineers, none of whom have been traditional consumers of astroparticle physics literature. Indeed, these scientists and astroparticle physicists do not naturally interact, or that has been the case until now. Below we examine this development and its main drivers in more detail.

2.3. Growth drivers for muography
The corresponding author of this work is a geologist by education and yet in the process of crossing the barrier between two branches of science that have not traditionally crossed the paths too often (the radionuclide dating has been one of the major exceptions). This particular personal journey may not yet be a tip of an iceberg, but it is, at the very least, an example of a new tendency of cross-pollination between disciplines. In this case, the driving force is muons and muography, the rapidly evolving application of muons in a wide range of disciplines. Nevertheless, cross-pollination between disciplines is a common thread in current science and positively links to scientific impact and productivity [10].

Muography has been primarily applied in the fields of volcanology [11–15], archaeology [16] and civil engineering [16,17]. The disciplines and applications in which muography has been applied also include many geoscience applications [18–22]. Muography outside Earth has also been proposed for Mars [23,24], Moon [24–27] and asteroids [28,24]. On Earth, muography is currently piloted or proposed in multiple mineral exploration and mining applications [2,19,29–32], but it may still take a few years before we see more papers on these studies (hence, we are forced to refer to several conference works). In addition, many other applications have been proposed, such as borehole muography in continental scientific boreholes [33], geothermal exploration [34,35] and weathering studies [31,32], and it is likely only a question of when rather than if they are piloted. From these examples, it becomes evident that the need for muography is real.

Muography-based characterization of material densities can obtain many forms. It can be carried out with many types of gaseous, scintillation, and nuclear emulsion detectors (e.g., drift chambers, micro-mesh gaseous structures, resistive plate chambers, multi-wire proportional chambers, and Cherenkov telescopes [4]. Some detectors are mobile, some transportable, and some stationary. Some detectors are meant to be used in stable conditions, whereas in some cases, the application dictates that the detector must be robust and of high endurance. The latter is especially true for long-term monitoring campaigns. Most of the varied detector types can be deployed in multiple environments (e.g., within buildings, on the ground, caves, and tunnels), some even underwater (e.g., borehole detectors). As the number and nature of muography applications expand, the cumulative field experiences will aid in making detectors ever more robust, automatic, and hopefully, easier to use. Hence, the feedback from the end-users to muography method developers, simulation software developers and especially muon detector designers forms a sort of backflow of information from non-physicists to astroparticle physicists. It is hard to foresee why this would not benefit astroparticle physics too.

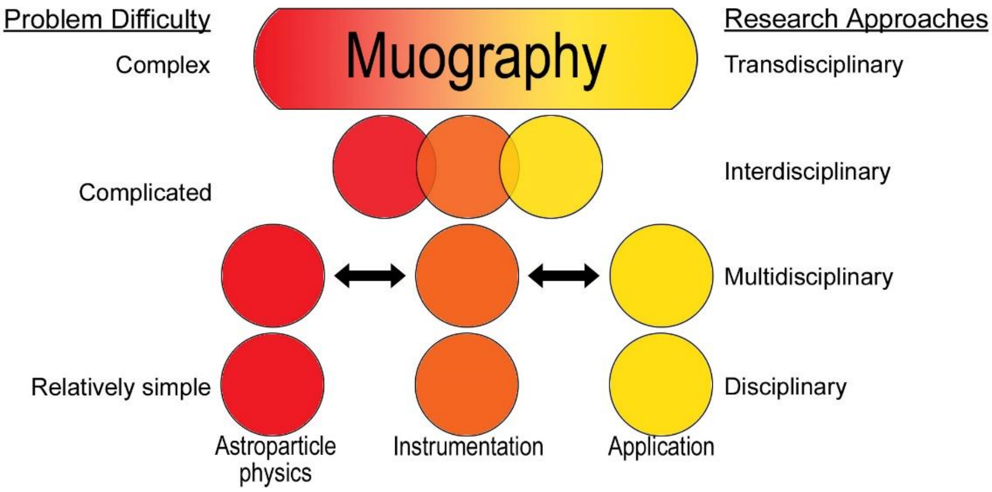

Figure 1. A schematic presentation of the interdisciplinary to transdisciplinary nature of muography.

The cross-pollination between the different disciplines establishes muography not only a highly multidisciplinary but also an interdisciplinary if not transdisciplinary field of research (Fig. 1). It also aids in enlarging and widening the audience base of astroparticle physics. At the first stage, this new group of researchers gets familiarized with the phenomena primarily researched by astroparticle physicists, such as EAS and the laws governing the propagation of high-energy muons in materials of different densities and chemical compositions. In the next stage, a section of those who benefit most from the new applications stemming from astroparticle physics start research of their own, most likely for filling gaps in our shared knowledge. These types of activities are already proceeding as demonstrated, for example, by statistics regarding muography-related publications first-authored or participated in by the non-physicist researchers and end-users of the new technologies and methods. Such a development expands the muography community both in numbers and multidisciplinarity. Even though such new research may not automatically be of great interest to astroparticle physicists, it is likely fruitful in the long run as some research topics are hard to carry out without specialized skills and expertise in these other disciplines (e.g., muon propagation and energy loss in real-world rocks). In the short term, however, the best value proposition for astroparticle physicists is that their research is becoming more and more referenced by authors who are non-physicists and in journals that astroparticle physicists do not necessarily follow (e.g., geoscience journals). It is also likely that this new pool of researchers increases the total reference counts of some astroparticle physics publications.

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3. Conclusions

It has been shown that muography is a discipline that asks for collaboration between numerous research fields before it can reach its potential and finds its place in the toolbox of applied sciences. This alone promotes spillover of particle physics to disciplines that rarely converge. Moreover, as the detector developers are commonly astroparticle, particle or nuclear physicists by education, and as they generally are also those who apply their detectors in the field, most case study papers contain and will likely continue to contain references to the astroparticle physics papers. Such a development is easy to predict as muography is multidisciplinary, interdisciplinary and transdisciplinary and often requires simulation toolkits and codes such as CORSIKA, GEANT4 and FLUKA. On these bases, we can conclude that astroparticle physics is obtaining more attention from a new type of audience.

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