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Cosmic ray signatures in Paleo-detectors to investigate the past activity of our Galaxy

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Interactions between secondary cosmic rays and nuclei in natural minerals can leave tracks in the lattice due to nuclear recoils. These defects can be preserved up to the Gyr timescale, making these so-called "Paleo-detectors" useful "time machines" for the study of the history of astrophysical messengers such as cosmic rays, neutrinos or even dark matter. These "Paleo-detectors" feature huge accumulated exposure times even for small masses of material, making them long-term flux integrators of all radiation along the evolution of our planet. We present the case study of the Messinian salinity crisis, a period of draining of the Mediterranean Sea which is interestingly coincident with the estimated age of the Fermi Bubbles, around 5.5 Myr ago, when our Galaxy might have been active. Greatly increased cosmic ray acceleration near the Galactic Center could have left traces in the evaporites, mainly Halite, created with the evaporation of the sea and exposed directly to secondary cosmic rays. These mineral structures were then covered during the sudden reflooding of the Mediterranean basin 5.3 Myr ago; the cosmic ray flux information remained frozen due to the shielding of the massive body of water, possibly retaining information on the flux of particles at ground in that epoch.

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1. Introduction

The Paleo-detector technique [1] employs natural minerals to be used as solid state track detectors (SSTDs) for cosmic messenger such as neutrinos and dark matter and, as we propose for the first time in this contribution, ultra high energy cosmic rays (UHECRs). The technique is based on the phenomenon for which swift heavy ions that cross through a solid material, be it crystalline or amorphous, can create regions of damage of generally cylindrical shape. In the case of paleo-detectors, the damaging ions are the atoms composing the solid themselves: energetic penetrating particles can interact with the atoms, making them recoil with sufficient energy to dislodge them from the structure and damage it. These damages, which from now on will be referred to as *tracks*, are of semi-permanent nature, being erased only in the presence of an overwriting event that modifies the mineral structurally, such as mechanical breaks or changes induced by high temperature or pressure. The exact phenomenon that gives rise to the tracks is not yet understood: the two main proposals are the *thermal spike* model and the *ion explosion* model. The technique has been utilized for a long time, not for cosmic messengers but mostly for the observation of natural and induced fission tracks, i.e. tracks caused by energetic ions produced by spontaneous fission of Uranium, a common impurity in minerals; these fission tracks are commonly observed in Obsidian and Apatite, as shown in figure 1, after a chemical process called *etching*, which enlarges and highlights structural defects.

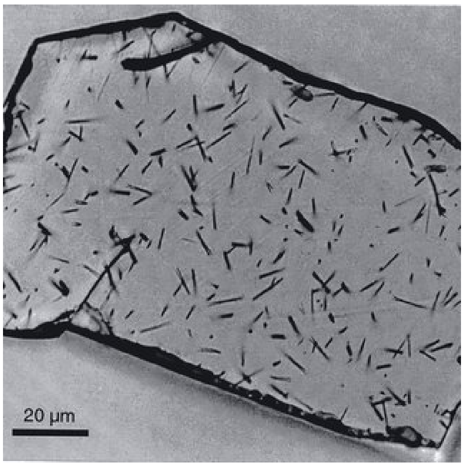

Figure 1: Etched fission tracks in an apatite grain from the Grassy Granodiorite of King Island, southeastern Australia. The tracks show their characteristic appearance as randomly oriented, straight-line etch channels up to a maximum length of around 16 μm.

Read-out methods for the tracks are various, depending on the scale of interest, the precision needed, the quantity of material to be analyzed and if etching is employed or not:

- Automated optical microscopy is a feasible technique for etched surfaces; it is widely used for fission tracks after chemical treatment, and could be suitable for paleo-detectors if the interesting tracks are similar in size or larger. The spatial resolution depends on the optics of the microscope.

- Small Angle X-ray scattering (SAXs) tomography, achievable at a synchrotron facility. It allows for 3D bulk imaging of materials with a resolution of $\approx$ 15 nm. It is unclear if the contrast of the tracks is enough to be seen by this technique.
- Helium Ion Beam Microscopy (HIBM), which allows to read out an extremely thin ($\approx$ 100 nm)slice of a sample with an impressive resolution of $\approx$ 1 nm. A 3D reconstruction of the sample is achievable by ablating each layer after readout using a laser beam, but this possibility is only obtainable for smaller sample and is an obviously destructive technique.

The exploitation of natural minerals as SSTDs for the search of rare particles and exotic interactions is an idea which by now has accrued a sizeable history, at least as a proposal. The first mentions, in the 1960s, theorized the possibility of searching for magnetic monopoles trapped and accumulated during Myr timescales in ferromagnetic materials [2]. In the same field of research and time period, subsequent papers a different approach is presented, in which tracks, in that case left by throughgoing monopoles, are mentioned for the first time. Related ideas proposed searches for Fullerenes (C_{60}) created by ionizing particles in geological samples [3], or radioactive and rare isotopes resulting from supernovae and other catastrophic cosmic events. The first usage of tracks for WIMP interactions was published by Snowden et al. [4], using muscovite mica as a target sample.
With enormous progress both in read-out technologies and theoretical and empirical knowledge of possible messengers detectable. As the tracks, in absence of catastrophic events, remain frozen in the mineral for up to the Gyr scale, interactions from many different cosmic messenger, even if rare, pile-up over the years accumulating an impressive exposure that can be equivalent to that of man-made experiments aimed at the detection of the same particles or interactions. The main caveat remains the identification and/or shielding from the backgrounds that can muddle the signal of choice.

2. Proposed signals in paleo-detectors

The following is a list of possible sources of signal that could be investigated using paleo-detectors

WIMP dark matter

Weakly interactic massive particles, or WIMPs, currently represent the most substantiated dark matter candidate, and the most used as target in DM direct detection experiments. The largest active experimental effort for direct detection of DM is based on the search for nuclear recoils induced by WIMPs, with a possible signal consisting in an annual or diurnal modulation. The only reported signal consisted with DM is the detection of an annual modulation by the DAMA experiment; this result is however very controversial and in tension with other experiments.
The paleo-detector technique would use the same approach as traditional man-made experiments for DM detection, i.e. looking at the effects of nuclear recoils, the tracks. Paleo-detectors are particularly well suited for particles of masses below 10 GeV, and, together with the large exposure if the suitable mineral is available, can have the advantage of being able to study the temporal

dependance of the signal on the Myr-Gyr scales, to help differentiate a possible DM detection from backgrounds.

Solar neutrinos

One of the most interesting open question in solar physics is the solar metallicity problem, the abundance of elements heavier than Helium in the Sun. Measuring the evolution over Gyr of the metallicity can give a very important insight on the Solar Standard Model and stellar evolution models. The paleo-detector technique is currently the only possibility to access this information. The main proposal is focused on the detection of ^8B neutrinos, which have high energy ($\approx 10MeV$) and a strong dependence on the solar core temperature, making them easier to detect and more insightful on the internal processes.

Supernova neutrinos

Most of the energy released during core collapse supernovae, in fact over 99%, comes in the form of neutrinos, typically in the MeV energy range. The neutrino emission for supernovae has up to now been studied only during the explosion of SN1987a, but the absence of more recent events in the Milky way or vicinity has hindered further studies. Paleo-detectors should be sensitive to two aspects of supernova emissions: galactic events and diffuse supernovae background.
A Galactic event, especially if close to the Solar System, could leave a visible trace, identifiable as a in increase in the number of tracks in samples older than the supernova, if compared to younger minerals. This can be exploited both to look for the signature of a specific event, i.e. by taking material from two samples that are of similar age but with a CCSN happening between the formation of one and the other, thus constraining in time, and possibly space, the event; on the other hand, the technique could be used to extract information about the rate of supernovae in the Milky way, measuring the absolute rate and its time variance in the last Gyr, which should reflect the evolution of the star formation rate. Also the extragalactic component of supernova neutrinos, also known as the diffuse Sn background, even if subdominant in flux, could be visible using paleo-detectors, and its history and time evolution could give insight on star formation rate in cosmological terms.

Atmospheric neutrinos

Atmospheric neutrinos are produced by the decay of pions and kaons that are created in the cascade of particles known as *extensive air shower* (EAS) that is the result of interactions between primary cosmic rays and molecules and atoms in the Earth's atmosphere. The other particles composing the shower are mostly absorbed by the atmosphere and the first layer of soil. Neutrinos on the other hand are much more penetrating, and could be a source of tracks for paleo-detectors. This fact could be exploited to study the history and evolution of secondary and, as a reflection, primary cosmic ray flux evolution. Another important case for studying the impact of atmospheric neutrinos is the fact that they are one of the primary backgrounds for other neutrino analyses.

Secondary cosmic rays

Apart from atmospheric neutrinos, the most penetrating component found in EASs are high energy muons, followed by a scarce number of neutrons and pions that reach the ground. These components can inuce recoils that produce tracks, and as such are considered a background for all other paleo-detector signals. In fact, they are the main reason for which most paleo-detector searches for DM or neutrinos propose to excavate the samples from below large rock overburdens. Aside from the interest of studying the most prominent background for other signals, secondary cosmic rays and especially muons can be treated as particles of interest, with similar goals and possibilities to atmospheric neutrinos, consisting mainly in the study of cosmic ray flux history and searches for past bursts.

The main common background for all uses of paleo-detectors is natural radioactivity, in particular in the form of α particles from the decay chain of U and Th, as well as neutron tracks from (α, N) reactions and spontaneous fission.

Using the `python` package `paleopy` [9] we calculated the track length spectra in Halite for the sources of background, i.e. atmospheric neutrinos, solar neutrinos, the diffuse supernovae neutrino background, geoneutrinos, neutrons and fragments from the spontaneous fission of ^{238}U, by using the framework implemented in the package for Dark Matter searches. We added the signal obtained from the muonic component of the secondary cosmic ray spectrum, computing the energetic spectrum of the recoils (for Na, CL and fragments) induced by the observed spectrum of muons at sea level [] using Geant4 [6]. The result is shown in figure 2.

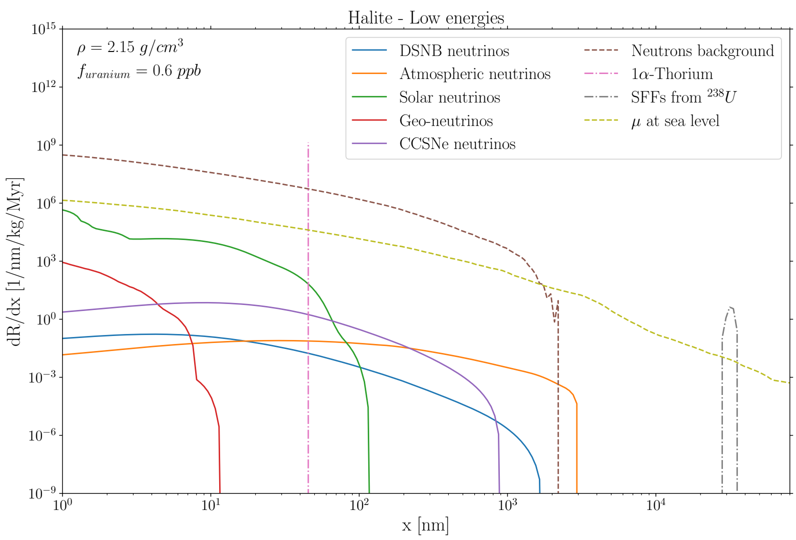

Figure 2: (Preliminary) Differential track length spectra in halite for all the sources of background and the signal computed in the All Energies scenario

3. Choice of mineral

To be suitable paleo-detector candidates, minerals must satisfy important criteria regarding their composition, geological history and location in the Earth's crust. As a rule of thumb, minerals should be composed of insulating or mildly semiconductor elements, with resistivity larger than 2000 Ωcm to make the track formation mechanism possible. Moreover, as reported, the largest common background comes from natural radioactivity, composed by fission fragments and radiogenic neutrons from (α, N) and fission; thus it is important to pick the minerals with the lowest

uranium content possible. The best sources for obtaining sampels with low Uranium content are the mantle, which averages 0.1 ppb, but is extremely hard to reach, and evaporites from seawater, that range between 0.1 and 10 ppb, orders of magnitude purer than the Earth's crust, which averages 0.1 ppm.
The radiogenic neutron background is strongly attenuated if the mineral contains Hydrogen, due to the large energy loss that neutrons undergo in a single interaction with a Hydrogen nucleus. Minerals containing it are thus preferrable.
Due to their strong flux and much higher cross-section, the non-neutrinic component of EASs is a strong background for dark matter or neutrino searches; for these purposes minerals have then to be extracted from at least an equivalent overburden of 5000 m of rock, obtainable only in borehole probes for petroleum excavations. Paleo-detectors for studies on secondary cosmic rays can instead be sourced from shallower sections of the crust, selecting material mostly based on its history of exposure, i.e. if the mineral in question was completely exposed to the cosmic ray flux for a period of time and then buried under an absorbing material, trapping and preserving the information on the past flux in its structure. A specific serendipitous case in this direction is presented in the next section as a case study.

4. A case study: the Messinian salinity crisis and the Fermi Bubbles

At the end of the Miocene, more precisely between 5.97 and 5.33 Ma, a series of tectonic processes dramatically altered the Mediterranean Basin, closing the entrance to waters from the Atlantic Ocean and transforming it into a gigantic saline basin. This event is known as the *Messinian salinity crisis*. As water desiccated, during a relatively short timespan of 700 years, salts and minerals diluted in it began coalescing and forming crystalline conglomerates known as evaporites. The main evaporite minerals formed in this process were Gypsum ($CaSO_4 2(H_2O)$) and Halite (NaCl) (figure 3). Around approximately 5.33 Ma, in the early Lower Pliocene, the Strait of Gibraltar reopened, flooding the basin in an event knwon as the Zanclean Flood, and the evaporites were submerged in the span of $\approx$10 years.

Coincidentally, the time period of the Messinian salinity crisis is coeval with the proposed birth of the Fermi bubbles, two large large lobes of magnetized plasma observed in γ and X-rays by the Fermi and ROSAT satellites respectively. These Galactic structures could be explained as the signature of a past AGN-like activity of the Milky Way.
We set out to test if evaporites, and in particular Halite which is easier to extract, formed in the Mediterranean during the Messinian salinity crisis, could be used as paleo-detectors to extract information about the flux of high energy cosmic rays in the period of time close to the birth of the Fermi bubbles.
To do so we simulated the emission from the Fermi bubbles, assuming a period of emission starting 6 Ma and lasting 1 Myr. Protons with energies above 10 TeV and distributed according to the expected power-law spectrum of comsic rays were generated at the borders of the bubbles, schematically represented by two ellipses protruding from the Galactic Center; using `CRPropa` [8] they were propagated to Earth in the galactic magnetic field model proposed by Jansson and Farrar. Simulations were obtained with three dfferent scenarios, based on comic ray energy: *ballistic*, for the highest energies which are weakly affected by the magnetic field, *semi-ballistic* for intermediate

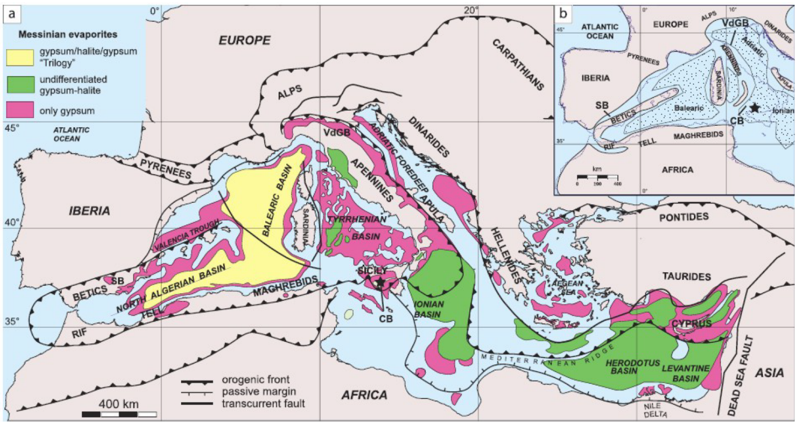

Figure 3: a) Map of the Messinian evaporites in the Mediterranean. The term "trilogy" indicates the threefold deeper succession of Western Mediterranean that, based on seismic, includes a halite unit sandwiched between two gypsum units. B) Paleocenaographic map of the Western Mediterranean basins during the Messinian salinity crisis, showing the main evaporite depocentres (dotted areas). Emerged areas are in gray. Dotted line is the modern coastline. From [7]

energies that are affected but not completely isotropicized, and *diffusive*, in which particles propagate through random walk.

The spectrum at Earth obtained by the simulations is shown as dots in figure 4, in which it is also compared to the expected spectrum of cosmic rays shown as a solid line. It is interesting to note the dip in flux in the energies corresponding to the *semi-ballistic* regime, between 100 PeV and 6 EeV, caused by the magnetic field blocking cosmic rays from reaching the galactic disk. Also shown in the plot, as coloured bars around the dots, are the delays experienced by the particles when comapred to photons; this is a parameter of paramount importance in our analysis, since, if too delayed, cosmic rays could reach the Earth after the Zanclean flood, when the evaporites are already shielded. It is evident from the plot that in the ballistic regime the time delays are negligible, while particles in the diffusive regime are mostly trapped in the galaxy for too long to be part of the signal, condition represented by the color orange in the bars.

In the eventuality of active acceleration of UHECR in the Fermi bubbles, the integrated flux would be orders of magnitude larger than the observed one, due to the much smaller distance to Earth with respect to all the currently proposed sources. The muon-induced track length spectrum could then be orders of magnitude higher than the one shown in figure 2, especially in the high-length region.

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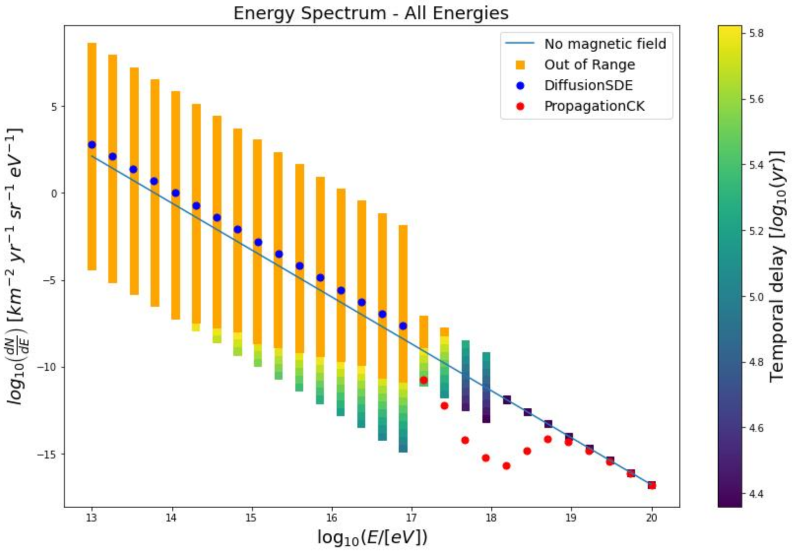

Figure 4: Comparison between the expected spectrum and the energy spectrum obtained from the CRPropa simulation using two different propagation models: PropagationCK (red dots) and DiffusionSDE (blue dots). The vertical banners represent the 5σ interval of the arrival time distribution.

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