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A strong dependence of the radio emission of air showers on X_{max} and primary composition

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It is well-known that the composition of the cosmic ray primary particle changes the characteristics of the air shower it induces, most notably the average atmospheric depth of the shower maximum (X_{max}). Showers induced by heavy primaries, such as Fe, develop faster and thus higher in the atmosphere than those induced by their lighter counterparts, like protons. This changes the observables of the shower, such as its radio emission detected at ground level. Traditionally, X_{max} is used as a surrogate for composition: X_{max} reconstructions are used to infer the average composition of a given cosmic ray flux.

In this work we describe a historically overlooked strong X_{max} dependence of the measured electric field amplitudes at ground level, even accounting for intrinsic differences in the electromagnetic (EM) energy of the showers due to different primary compositions, which would also affect these amplitudes. This strong composition dependence can be used, in a novel way, to directly infer the cosmic ray primary composition not only as an average for a flux, but also on an event-by-event basis, bypassing any X_{max} reconstructions and using comparisons to simulations or machine learning (ML) methods instead.

This X_{max} dependence can be understood in terms of two competing scalings of the measured electric field: One that goes with $(1/\rho)^J$, where ρ is the air density at X_{max} and J is a zenith dependent non-linearity factor. This density scaling decreases the geomagnetic emission of deeper, higher X_{max} showers. The other scaling goes with $(1/R)$, where R is the distance from X_{max} to the core of the shower at the ground, and instead increases the measured electric field of deeper showers. At lower zenith angles, the $(1/R)$ scaling is stronger and leads to larger measured electric fields in the case of the deeper showers induced by lighter primary compositions. The picture at higher zenith angles, i.e., at lower densities, is more nuanced and is highly affected by the geomagnetic field. In this region, the deflections due to the Lorentz force are much larger and increase the perpendicular momenta of $e^{\pm}$ in the shower, which would tend to increase the radio emission. However, these larger deflections also increase the time delays between the particle tracks in the shower, decreasing the coherence of the radio emission. This loss of coherence is highly dependent on the strength of the geomagnetic field and can slow down, or even reverse the increase of the radio emission with decreasing air density. This coherence loss is represented by the non-linearity factor J, which governs if lighter primary compositions will induce higher or lower fields than heavy primaries at these higher zenith angles. Understanding the characteristics of these very inclined showers is crucial for future experiments, such as GRAND.

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