

A Bayesian source association analysis of UHECRs: Impact of the Galactic magnetic field and composition

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Abstract. We present a statistical analysis of the association between UHECRs and proposed astrophysical sources. Our approach is based on the Bayesian hierarchical framework presented in Capel & Mortlock 2019, but with notable extensions. Using CRPropa3, we now include the lensing effect of the Galactic magnetic field and explore the impact of heavier compositions. This analysis directly connects to the physics of UHECR propagation so that each detected event is allowed different possible deflections and energy-loss horizons based on its measured energy, arrival direction and the corresponding uncertainties. In this way, we can easily interpret the connection to proposed sources in a physical way. We verify our approach using simulated data and then present our results with views of the Northern and Southern skies thanks to publicly available data from both the Telescope Array experiment and Pierre Auger Observatory.

1 Introduction

The quest to determine the origins of ultra-high-energy cosmic rays (UHECRs) is an ongoing problem, due to the complex physical processes involved in their injection, acceleration, and propagation, as well as the technical challenges in their detection. In particular, point-source analyses cannot accurately determine the sources of UHECRs due to their rigidity-dependent deflections from the extra-Galactic and Galactic magnetic fields (EGMF and GMF, respectively). While several attempts have been made to associate sources with UHECRs through their detected positions, no consensus for exact sources have yet been established (see recent reviews, e.g. Anchordoqui 2018 [1] and Batista et al. 2019 [2]).

Due to the large number of parameters and uncertainties involved, it is challenging to construct a comprehensive statistical model from UHECR observations. Nevertheless, this can be approached within the framework of Bayesian hierarchical modeling. Earlier work has made progress in this direction, with Watson [3], Soiaiporn [4], and Kanin & Mortlock [5] developing Bayesian models that focused on using the UHECR arrival directions. Capel & Mortlock 2019 (CM19 hereafter) [6] extended these models by presenting a joint model including both UHECR energies and arrival directions, yielding a source association fraction of up to ~ 0.2 with a set of starburst galaxies proposed from Ref. [7] (SBG hereafter) and the

public UHECR events from the Pierre Auger Observatory (PAO) [8] as reported in Ref. [9] (PAO14 hereafter).

In this paper, we report on the progress in quantifying the impact of the GMF and UHECR composition on source-UHECR associations by further developing the joint model presented in CM19. In Section 2 and 3, we describe the physical and statistical model used to include GMF and composition effects and to perform the Bayesian source association analysis. In Section 4, we apply our model to the PAO14 data and to the public data from the Telescope Array experiment (TA) [10] reported in Ref. [11] (TA15 hereafter) with the SBG catalogue as above. We show the individual source-UHECR association probabilities and also the posterior distribution of the source association fractions to describe the impact of the GMF and composition. In Section 5, we discuss our obtained results. Finally, in Section 6, we summarize on the current status of our work and outline plans for the future. The package used in our work is available online.¹

2 The Physical Model

The model is based on the physical model presented in CM19.

2.1 Source

We assume a population of steady-state sources with equal particle luminosity Q such that the UHECR flux $F_k = Q/4\pi D_k^2$ only depends on the source distance D_k for each

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¹<https://github.com/cescalara/fancy>

source k . We assume that the sources produce UHECRs of the same composition with a power law spectrum, $dN/dE \propto E^{-\alpha}$, where α is the spectral index. We also include an isotropic background flux F_0 for UHECRs that originate from sources not present in the considered catalogue.

2.2 Energy Losses

As an intermediate stage in our approach, we describe the energy losses that the UHECRs undergo through their propagation using the loss length. Under the continuous energy loss approximation, we evaluate the arrival energies of the UHECRs by the following first order differential equation:

$$\frac{dE}{dz} = -\frac{E}{L_{\text{loss}}(E, z)} \quad (1)$$

where z is the redshift of the UHECRs and the loss length $L_{\text{loss}}(E, z)$ is described by losses due to photopion production (β_π), electron pair production ($\beta_{e^\pm}$), adiabatic expansion of the universe (β_{adi}) and photodisintegration (β_γ) processes:

$$L_{\text{loss}}^{-1}(E, z) = \frac{dt}{dz}(\beta_\pi(E, z) + \beta_{e^\pm}(E, z) + \beta_{\text{adi}}(E, z) + \beta_\gamma(E, z)). \quad (2)$$

Note that, unlike CM19, which assumes a pure proton UHECR composition, we consider photodisintegration processes as they are relevant for UHECR compositions with $Z > 1$. A preliminary implementation of this is performed using the loss length as given in the propagation modules provided by CRPropa3 [12]. It is assumed that the energy loss rate is described by the average number of nucleons lost for all possible disintegration channels.

2.3 EGMF Deflections

The magnetic deflections from the EGMF experienced by a UHECR with energy E , charge Z , travelling at a distance D from Earth are described by an analytical approach, with a root-mean-square (RMS) angular scale as such:

$$\bar{\theta} \approx 2.3^\circ Z \left(\frac{E}{50 \text{ EeV}} \right)^{-1} \left(\frac{\bar{B}}{1 \text{ nG}} \right) \left(\frac{D}{10 \text{ Mpc}} \right)^{1/2} \left(\frac{l_c}{1 \text{ Mpc}} \right)^{1/2} \quad (3)$$

where $\bar{B}$ is the RMS EGMF strength and l_c is the field coherence length [4].

2.4 Detection

As in CM19, we model the detected energies $\hat{E}$ from a Gaussian distribution, given the reported reconstruction uncertainty f_E and "true" arrival energies E . Similarly, we model the detected arrival directions $\hat{\omega}$ using a von-Mises-Fisher (vMF) distribution [13] as in CM19:

$$p(\hat{\omega} | \omega, \kappa_d) = \frac{\kappa_d}{4\pi \sinh \kappa_d} \exp(\kappa_d \hat{\omega} \cdot \omega) \quad (4)$$

where ω is reported "true" arrival direction and κ_d is the concentration parameter, inversely related to the angular reconstruction uncertainty σ_ω . The exposure of PAO and TA is calculated using the formalism provided in CM19.

2.5 GMF Deflections

Unlike CM19, which describes both EGMF and GMF deflections using Eq. 3, we use a backtracking approach to describe the GMF deflections. We backtrack each UHECR with a detected arrival direction $\hat{\omega}$ (sampled by Eq. 4) using CRPropa3, assuming a GMF model postulated by Jansson & Farrar [14] (JF12 hereafter). Fig. 1 shows the skymap of the deflected UHECRs from the TA15 dataset [11] using this approach, assuming a composition of protons.

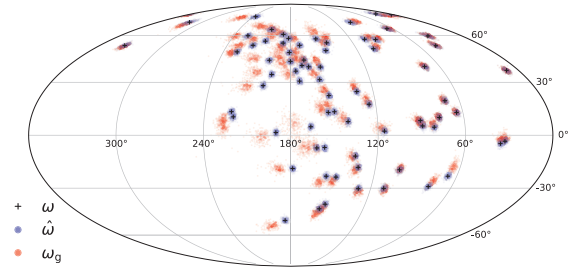


Figure 1. Skymap of deflected UHECRs (ω_g , red) using our approach, assuming all UHECRs are protons. The true arrival directions (ω , black) provided from the TA15 dataset are sampled via Eq. 4 ($\hat{\omega}$, blue) and then deflected under the GMF model from JF12. The skymap is in galactic coordinates with the Galactic anti-center at the origin.

From the arrival direction at the galactic boundary ω_g , we can extend the vMF distribution in Eq. 4 by replacing κ_d with a modified parameter κ_{GMF} , which now includes the effects of the GMF. The concentration parameter κ_{GMF} is determined by numerically solving

$$\int_{\Omega} d\omega p(\omega_g | \hat{\omega}, \kappa_{\text{GMF}}) = \frac{1 - e^{-\kappa_{\text{GMF}}(1 - \hat{\omega} \cdot \omega_g)}}{1 - e^{-2\kappa_{\text{GMF}}}} = P \quad (5)$$

where Ω is the cone of solid angle subtended by the contour of the region containing $P = 0.683$, analogous to the "1 σ " region of a Gaussian distribution [4]. The new concentration parameter κ_{GMF} is then considered in the likelihood function for the arrival directions, which takes into account the GMF deflections by modifying the width of the distribution (see Sec. 3).

3 The Statistical Model

We use a Bayesian hierarchical model with Stan, a state-of-the-art platform for statistical modeling and computation [15]. The parameters are fitted using a Markov Chain Monte Carlo sampling method with the Hamiltonian Monte Carlo algorithm. Through this approach, we

can encompass more propagation physics into our model and construct a “bubble” of possible origins for each UHECR based on its energy and arrival direction.

3.1 Likelihood Function

In our analysis, we follow the likelihood function as presented in CM19. However, to take the GMF deflections into account, we replace the concentration parameter κ_d by κ_{GMF} , which now includes the effects of the GMF deflections. This is reflected in the probability distribution that describes the probability of observing a UHECR with arrival direction $p(\hat{\omega} | \bar{\omega}_k, \bar{\theta})$ (Eq. (A5) in CM19), which is subsequently contained in the likelihood function. In doing so, we assume that the detection uncertainties are smaller than the impact GMF deflections, which holds for the cases considered here.

3.2 Priors

To describe a more accurate representation of the EGMF strength, we consider a narrower prior for $\bar{B}$ compared to CM19. In our analysis, we consider a normal prior with $\mu_{\bar{B}} = 1$ nG with a spread of $\sigma_{\bar{B}} = 3$ nG, motivated by observational constraints on the EGMF strength, e.g. Refs. [16, 17]. The same weakly informative priors as in CM19 are used for the other highest-level parameters (α , Q , and F_0).

4 Results

We apply our Bayesian hierarchical model for the PAO14 and TA15 datasets independently and evaluate the association probabilities as in CM19 using the SBG catalogue. In Fig. 2, we show the posterior distribution for the source association fraction of UHECRs with the PAO14 and TA15 dataset as mentioned above, considering four different configurations:

- (a) A pure proton composition, assuming a joint GMF + EGMF magnetic field, following the configuration used in CM19
- (b) A pure proton composition with the GMF deflections as done in this work
- (c) Same as (a) but for a pure nitrogen composition
- (d) Same as (b) but for a pure nitrogen composition

We note that the obtained nitrogen results are preliminary at this stage of our project, as we have not thoroughly considered for further physical effects such as the evolving composition throughout propagation. Here, the source association fraction is defined as the fraction of the flux of UHECRs that are associated to a particular source catalogue such that

$$f = \frac{\sum_k F_k}{F_0 + \sum_k F_k}. \quad (6)$$

In Fig. 3, we show the skymap presenting the individual source-UHECR association probabilities for each

dataset, assuming a pure nitrogen composition and including the effects of the GMF deflections from this work (as in case (d) from above). The dominant sources, i.e. those with the highest source association probabilities, are NGC4945, M83, and NGC253 for the Southern sky and M82, IC342, and NGC6946 for the Northern sky.

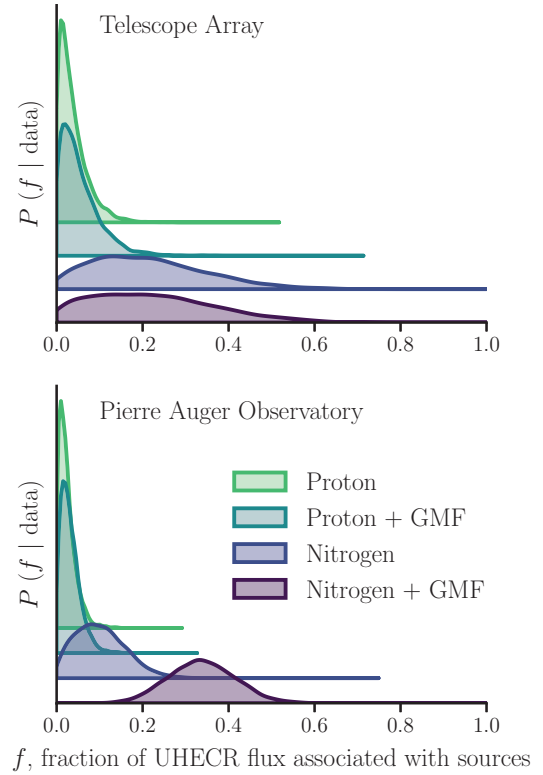


Figure 2. Posterior distribution of the source association fraction for TA15 (top) and for PAO14 (bottom). We evaluate the associations with the SBG catalogue for both datasets. The source fractions are determined assuming proton and nitrogen compositions and also with and without the effect of the GMF deflections mentioned in this work, as shown in the legend.

5 Discussion

We observe that, with a pure proton composition, the posterior distributions in Fig. 2 are peaked at source fractions close to zero, contrary to the results of CM19. This implies that the narrow priors on the EGMF significantly affect the source-UHECR associations, possibly due to the smaller width of the vMF distribution described by $p(\hat{\omega} | \bar{\omega}_k, \bar{\theta})$. We also observe that, with protons, the effects of the GMF deflections do not impact the source association probabilities significantly for both datasets. This is due to the small nuclear charge of protons, which experience fewer deflections from both the EGMF (as seen in Eq. 3) and the GMF due to their Z -dependence.

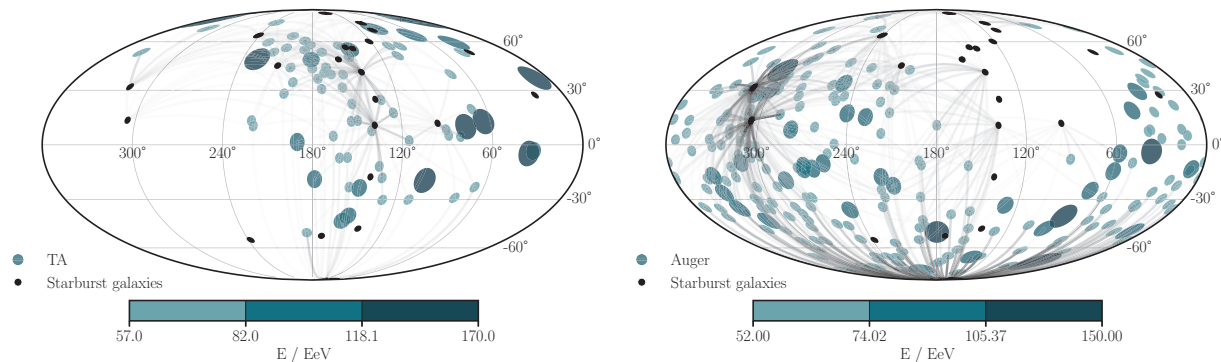


Figure 3. Skymaps of individual source-UHECR association probabilities (represented as weighted lines) for the TA15 (left) and for the PAO14 data (right), scaled by their energies (blue). We consider the SBG catalogue and a pure nitrogen composition and further consider the effects of the GMF deflections implemented in this work for both datasets. Coordinates are given in Galactic coordinates with the Galactic anti-center at the origin.

In general, we observe that the source-UHECR associations increase by including the effects of the GMF deflections with a larger nuclear charge. Fig. 2 shows that by considering a pure nitrogen composition, the posterior distributions for the source fraction are small near zero and average at $f \sim 0.2$. This is most likely due to large deflections from both the GMF and EGMF. As both deflections depend on Z , a higher nuclear charge will deflect the UHECRs more strongly, increasing the width of the vMF distribution and subsequently allowing for more sources to be associated. This effect is also observed in the skymaps in Fig. 3, as sources outside the field of view of each observatory are associated with the UHECRs in each dataset. Such results may change if we instead replace the vMF distribution by a new distribution at the galactic boundary, which is currently under investigation.

6 Conclusion

In our work, we aim to quantify the impact of GMF deflections and UHECR compositions on source-UHECR associations. We perform a preliminary implementation of the GMF deflections and UHECR composition into the joint Bayesian hierarchical model proposed by Capel & Mortlock 2019 [6] with CRPropa3. We evaluate the source-UHECR associations for the PAO14 and TA15 datasets using the SBG catalogue. For a pure proton composition, the source fraction distribution show that the effects of GMF deflections do not impact the source associations strongly. However, the source-UHECR associations, in general, increase when we consider the GMF deflections from this work with a higher nuclear charge, as observed by the source fraction distribution and the skymaps showing the source association probabilities. We plan to more accurately model the UHECR propagation for nuclei by considering the photodisintegration of the nuclei throughout their propagation.

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