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Cosmic cartography with UHECRs: Source constraints from individual events at the highest energies

Nadine Bourriche[a,*] **and Francesca Capel**[a]

[a] *Max-Planck-Institut für Physik, 80805 München, Germany*

E-mail: nadineb@mpp.mpg.de, capel@mpp.mpg.de

UHECRs at the most extreme energies provide strong constraints on their possible origins. They have a smaller horizon due to energy losses during propagation and are less deflected by intervening magnetic fields. However, studies searching for correlations with nearby sources are limited by the rarity of these events, and the suggested source catalogues often fall short in explaining their origins. We propose to use the reconstructed properties of individual detected UHECRs to map out three-dimensional constraints on the locations of their unknown sources. In this work, we focus on the recently published catalogue of 100 events with energies from 78 to 166 EeV recorded by the Pierre Auger Observatory and use CRPropa 3 to model all relevant propagation effects, including deflections in the Galactic and extra-Galactic magnetic fields. In deriving our location maps, we consider the reconstructed energies and arrival directions of events as well as results on the UHECR composition. We present constraints on the source locations for some of the most restrictive cases and demonstrate the impact of uncertainties in the reconstructed UHECR properties on these results. We also highlight possible astrophysical sources that are compatible with these regions and requirements. This complementary perspective lays the groundwork for building more physically-motivated source catalogues and statistical analyses in the future.

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1. Introduction

UHECRs are charged particles, protons, and heavier nuclei up to iron, that exceed energies of 10^{18}eV. Despite numerous attempts to identify their sources, the results are still inconclusive. Such searches face challenges due to the complex nature of UHECR propagation. In their journey from the source to Earth, UHECRs suffer from energy losses caused by photo-pion production, photo-disintegration, and pair production, as well as adiabatic losses. Moreover, their trajectory can be deflected by Galactic and extra-Galactic magnetic fields. The highest energy events have the advantage of being the most constraining, as they are less affected by magnetic fields, and they also must originate from the near Universe, since their detected energy implies smaller energy losses and a shorter traveled path.

Objects that have been suspected to accelerate UHECRs are starburst galaxies, active galactic nuclei, gamma-ray bursts and powerful supernovae, as well as tidal disruption events, pulsars and galaxy clusters or interacting galaxies (1). Some sources that have been found to correspond well with hotspots of possible arrival directions are Centaurs A, a radio galaxy, and two starburst galaxies, M83 and NGC 4945 (2).

The scope of this work is to use the properties of individually detected UHECRs to reconstruct a three-dimensional map of the location and distance of possible sources. We use the simulation framework CRPropa3 (3) to model all the relevant propagation effects and the deflections due to Galactic and extra-Galactic magnetic fields.

In the next step, we consider the two highest energy events detected by PAO (4). The source composition is restricted to a pure H, N or Fe composition. Using the studies of the relevant scenarios in CRPropa3 to motivate our priors on the distance, and the arrival directions as detected by PAO, we implement approximate Bayesian computation (ABC) to map out the directions and distances of possible sources that are consistent with the UHECR event data.

2. Methods

For the simulations performed with CRPropa3 to study the horizon distance, all energy loss mechanisms are included as well extra-Galactic and Galactic magnetic field. We choose a source with a power law energy spectrum with index $\Gamma = 2$ and a maximum source energy of $E_{\rm max} = 200$ EeV. For the minimum energy, we choose the threshold energy $E_{\rm th} = 166$ EeV. We model the EGMF as a random Gaussian field with a root mean square field strength $B_{\rm rms} = 1$ nG, minimum physical scale of turbulence $l_{\rm min} = 90$ kpc and maximum physical scale of turbulence $l_{\rm max} = 1000$ kpc, and a spectral index of $5/3$. For simplicity we only consider the regular component of the Galactic magnetic field.

Once we have a full picture of the journey of a charged particle from the source to the observer and the implied impact of the various assumptions on the horizon distance, we use the resulting information for the next step, where we aim to improve the connection between the CRPropa3 simulations and the observed UHECR data.

ABC is a method of estimating the posterior distribution of a model parameter without needing a likelihood function. In cases where the likelihood function is too complicated to find analytically, we can replace it by producing artificial data sets via simulations. In this work, we consider three free parameters: the source distance, the galactic latitude and the galactic longitude. Our prior on this distance is uniform in the range $D_{\rm min}$ to $D_{\rm max}$. For hydrogen we consider $D_{\rm max}$ = 40 Mpc, for nitrogen $D_{\rm max}$ = 6 Mpc and for iron of $D_{\rm max}$ = 20 Mpc, $D_{\rm min}$ is always 1 Mpc. We chose the values with the help of the preliminary studies of possible horizons with CRPropa3, as described above, and we set the threshold energy at $E_{\rm th}$ = 153 EeV. Our other prior is on the position of the source, in galactic coordinates, which we are able to retrieve thanks to the arrival direction as detected by PAO and the backtracking. We then calculate the average total magnetic field deflection angle, $\theta_{\rm EGMF}$, using (5),

$$\theta_{\rm EGMF} \approx 2.3^{\circ} Z \left(\frac{E}{50\ {\rm EeV}}\right)^{-1} \left(\frac{B_{\rm rms}}{1\ {\rm nG}}\right) \left(\frac{L}{10\ {\rm Mpc}}\right)^{1/2} \left(\frac{1}{1\ {\rm Mpc}}\right)^{1/2} \tag{1}$$

and the result of the galactic backtracking, from which we obtain $\theta_{\rm GMF}$. We add 10% $\theta_{\rm EGMF}$ to have a wider prior and avoid underestimating the extra-Galactic deflections. Finally, we use a von Mises-Fischer distribution to sample source positions, where κ is a function of the total deflection angle and μ is the average direction of the particle after being backtracked. Once we have the position, we run a simulation. The output is a number of detected particles and their properties, such as direction, composition, and arrival energy. If the detected particles' energy is within $3\sigma_{\rm E}$, of that detected by PAO, given that $\sigma_{\rm E}$ = 13, and its arrival direction at the edge of the Milky Way (also obtained using the arrival direction as detected by PAO) is within $3\sigma_{\rm dir}$, given that $\sigma_{\rm dir} = 1^{\circ}$, the proposed source parameters are accepted, and otherwise rejected. We run our algorithm for as long as possible, given our computational constraints, and obtain combinations of possible source positions and distances. Our approach has similar goals to that described in (12) but takes a complementary data-driven focus.

3. Results

Figure 1 summarises the results of the ABC algorithm for source directions. It shows the sky map, in galactic coordinates, of accepted source positions for the two highest energy events detected by PAO with energies of $E_1 = (166 \pm 13)$ EeV and $E_2 = (165 \pm 13)$ EeV. We see that iron, with its larger charge, is significantly more affected by the galactic magnetic field than hydrogen and nitrogen. Its position before and after entering the Milky Way are separated by several degrees, as shown in Figure 2a and Figure 2b. Moreover, while the accepted source positions for nitrogen and hydrogen are rather localised, for iron, the distribution is wider. We could also constrain the range of distances at which the possible sources are. In Figure 3, we show the proposed and accepted source distances for each of the three composition cases considered. The results are coherent with the findings of the preliminary work on the GZK horizon, and it is confirmed that nitrogen has the smallest horizon, ≈ 3 Mpc.

4. Discussion

Under the assumptions made on the source properties, from our results, we can infer that for UHECRs that have energies exceeding hundreds of EeV, the sources must be very close, with $D_{\rm max}$ < 35 Mpc. In particular, if we anticipate to see heavier nuclei. This is to be expected

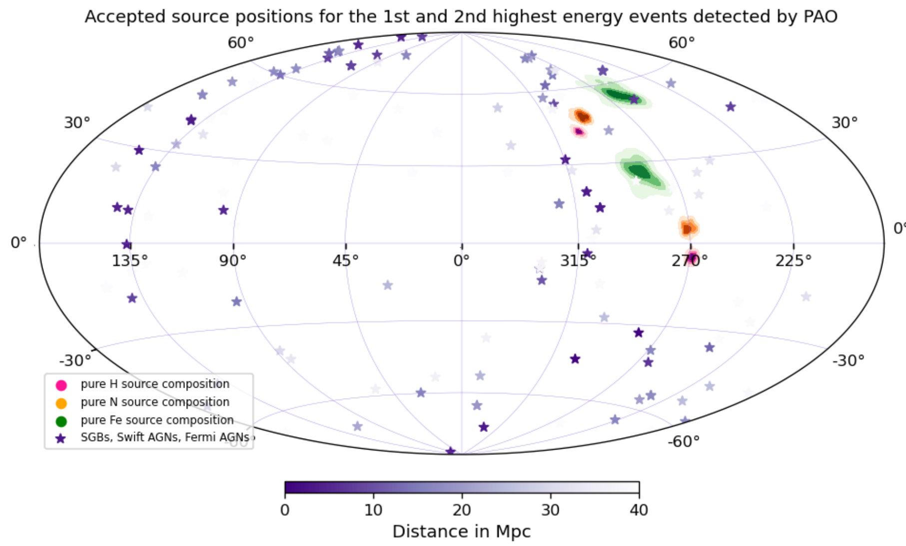
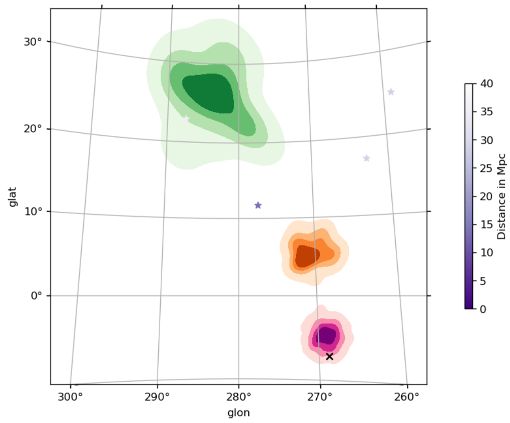


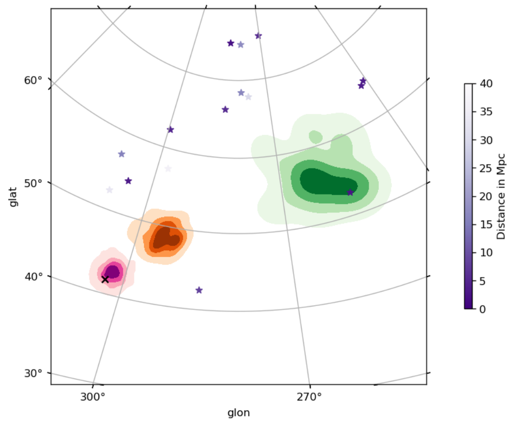
Figure 1: Map in galactic coordinates of the accepted source positions of the first and second highest energy events detected by PAO. In green are the accepted source positions assuming a pure source composition of iron, in orange a pure source composition of nitrogen and in pink a pure source composition of hydrogen. The purple stars mark the position of some of the closest SBGs and AGNs. The darker the star, the closer it is.

since heavier nuclei have smaller loss lengths compared to protons. Nitrogen, especially, has a weak binding energy, making it more prone to photodisintegration; iron is less affected since it is the most stable nucleus. It remains unclear exactly how the composition changes as the energy increases. The composition is quite hard to determine since it is not measured directly, but derived from the mean and the dispersion of the depth of the shower maximum. It also depends on which hadronic interaction model is used. If we were to consider the PAO results, we would expect intermediate masses at arrival, with also a contribution from protons and iron nuclei (6), suggesting an intermediate to heavy source composition. We showed that if this is the case, there must be sources that are in our nearby Universe. In particular, for a nitrogen dominant source composition $D < 3$ Mpc, this restricts us to the local group of galaxies, which would imply that the possible source classes could be limited to, e.g., GRBs (7).

In our work, if we assume that the composition is dominated at arrival by the mass group $A > 28$, meaning having mostly iron nuclei at the source, we find that the accepted source positions match some of the sources from the catalogs that we used, including SBGs (8), Fermi AGNs (9) and Swift AGNs (10). In the case of the first event, this source is NGC 3783 which is a Seyfert 1 galaxy. Seyfert galaxies have been postulated to be possible UHECR accelerators (13). However, it is too far, $D > 30$ Mpc and not within the horizon that we find for $A > 28$, which is $D \approx 13$ Mpc. It is worth mentioning that the first event was detected coming from the direction of the galactic plane. Given how bright the galactic plane is, it is difficult for instruments to detect extra-Galactic

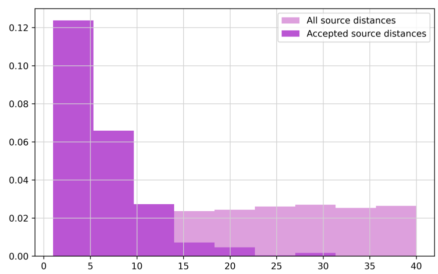


(a) Zoom on the first highest energy event detected by PAO.

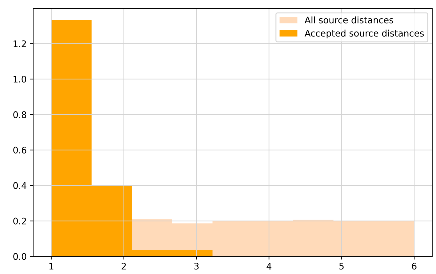


(b) Zoom on the second highest energy event detected by PAO.

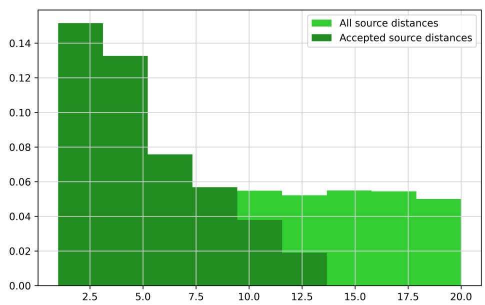
Figure 2: Zoom on the first and second highest energy events detected by PAO, the black cross indicates the position of the events as measured by PAO.



(a)



(b)



(c)

Figure 3: Histograms of the accepted vs all source positions for a pure H (3a), N (3b) and Fe (3c) source composition.

objects at those latitudes.

Regarding the second event, assuming a pure iron source composition, the matching source is NGC 3521. Starburst galaxies similar to NGC 3521 have long been suspected to be sites of UHECRs acceleration (1), moreover given that it is at a distance of D ≈ 6.84 Mpc (8), it is within our maximum possible source distance for iron D ≈ 13.5 Mpc.

We note that we have modified our results following ICRC 2023 after noticing an inconsistency with the coordinate transforms.

5. Conclusions

If arrival compositions similar to the ones predicted by PAO are assumed, NGC 3521 could potentially be an interesting candidate for UHECRs acceleration. Its astrophysical classification as a starburst Galaxy indicates that it could be capable of high-energy acceleration, and it is also consistent with the predicted distance and position, assuming a heavier source composition. What is certainly a more physical assumption is to consider a mixed source composition, with different fractions of the five main elements, which will be explored in future work. Also, a higher maximum source energy will be explored, since there are theoretical clues that there are astrophysical objects that can reach $E_{\max} \approx 1000$ EeV (7), which would widen the horizons and allow us to consider sources that are further away. We plan to introduce more free parameters, such as the spectral shape, as it will allow us to learn more about the type of sources and the acceleration mechanisms at play, as well as explore more sophisticated methods to overcome the computational constraints. We plan to extend this approach to all of the 100 highest energy events detected by PAO, expecting to investigate further known source candidates such as Centaurus A, M83 and NGC 4945, as well as potentially explore previously overlooked astrophysical objects, like NGC 3521.

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