



UNIVERSIDAD DE CONCEPCIÓN
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS

CONSTRAINING ASTROPHYSICAL SOURCES OF INTERMEDIATE-MASS ULTRA-HIGH ENERGY COSMIC RAYS

*Restringiendo las fuentes astrofísicas de los rayos cósmicos de ultra alta
energía de masa intermedia*

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Esta tesis está dedicada a mi familia, a mis amadas abuela Marcela y abuela Katy, que en paz descanse, y a mi esposo Kevin por su apoyo incondicional. A los rayos cósmicos y a Neil por encontrarlos y hacer posible mi viaje a Japón para participar en la ICRC2023.

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Resumen

Encontrar las fuentes donde se originan los rayos cósmicos de energías ultra altas (UHECRs), con energías mayores a 10^{18} eV, es difícil ya que sus trayectorias son deflectadas por los campos magnéticos Galácticos (GMF). Recientes interpretaciones de las lluvias de partículas (*air showers*) producidas por los rayos cósmicos sugieren un aumento gradual en la masa media de los UHECRs con la energía. La visión de décadas pasadas, UHECRs como mezcla de hidrógeno y hierro (con una composición relativa que varía con la energía), ahora se expande considerando composiciones de masas intermedias. Cabe destacar que mientras los UHECRs de H y Fe tienen recorridos libre medio (*mean free paths*) de ~ 100 Mpc, las composiciones intermedias tienen *mean free paths* de solo unas pocas decenas de Mpc.

En [Sotomayor Webar et al. \(2023\)](#) se realizaron simulaciones Montecarlo de las trayectorias de UHECRs con composiciones de H,O y Fe en 8 modelos de GMF para calcular las deflecciones de los UHECRs detectados por el Observatorio Pierre Auger y el Telescope Array. La distribución de las direcciones de llegada fuera de la Galaxia (corregidas por el GMF) de sub-muestras de UHECRs menos deflectados fueron correlacionadas con catálogos astronómicos. Se encontró una correlación con galaxias cercanas ($D \leq 20$ Mpc) cuando se consideraba una composición de oxígeno y el GMF model BSS de [Takami and Sato \(2010\)](#).

Este trabajo es la continuación del análisis realizado en [Sotomayor Webar et al. \(2023\)](#) usando oxígeno para obtener una distribución de las direcciones de llegada fuera de la Galaxia. Un análisis de máxima verosimilitud se ha considerado para comparar las distribuciones de UHECR con mapas de densidad compuestas por un modelo isotrópico y uno anisotrópico. El modelo anisotrópico considera las fuentes astrofísicas con un peso estadístico, proporcional a una propiedad relevante, multiplicado por un factor de atenuación siguiendo los resultados de [Allard et al. \(2008\)](#). Se propone un 'mapa de exposición extra-galáctico' para considerar las regiones magnificadas/suprimidas por el GMF. La distribución de UHECR fuera de la Galaxia al considerar una composición de oxígeno y el GMF BSS es consistente con la distribución de masa estelar y tasa de formación estelar en el universo cercano.

Abstract

Identifying the astrophysical source populations of Ultra High Energy Cosmic Rays (UHECRs), Cosmic Rays (CRs) with energy higher than 10^{18}eV (1 Exa eV or EeV), is difficult because UHECRs are deflected by the Galactic Magnetic Field (GMF). Recent interpretations of cosmic-ray-produced air showers with hadronic interaction models suggest a gradual increase in the mean mass of UHECRs with energy. The decades-old view of UHECRs being a mixture of ionized hydrogen and iron (with their relative composition varying with energy) has now expanded to consider intermediate nuclear compositions. In particular, while hydrogen and iron UHECRs have expected mean free paths of $\sim 100\text{Mpc}$, intermediate composition UHECRs have mean free paths of only 10s of Mpc.

[Sotomayor Webar et al. \(2023\)](#) used Monte-Carlo simulations of H, O, and Fe composition UHECR tracks in 8 proposed GMF models to estimate deflections suffered by the UHECRs detected by the Pierre Auger Observatory and the Telescope Array. They reported a strong association between the (GMF-deflection-corrected) arrival directions of 'least deflected' sub-samples of UHECRs with nearby ($D \leq 20\text{ Mpc}$) galaxies when considering an oxygen UHECR composition and the BS-S GMF model from [Takami and Sato \(2010\)](#).

This work is based on the analysis of [Sotomayor Webar et al. \(2023\)](#). We used an oxygen composition (a high-abundance intermediate mass species) for UHECRs, obtained out-of-Galaxy arrival direction distributions of these, and tested for correlations with the distribution of nearby extragalactic matter. A maximum likelihood analysis compares the UHECR distribution with smoothed density maps composed of an isotropic and an anisotropic component model. The anisotropic model accounts for the astrophysical sources weighted by relevant properties and multiplied by an attenuation factor following the results of [Allard et al. \(2008\)](#). We generate extra-galactic exposure maps that delineate the magnified/suppressed regions of the extragalactic sky in a given GMF model. The anisotropy of the out-of-galaxy UHECR distribution of oxygen composition UHECRs, in a BS-S model, is consistent with the (attenuated) density distributions of both stellar mass and star formation rates in the nearby universe.

Keywords – Ultra High Energy Cosmic Rays (UHECRs), Nearby Galaxies, Galactic Magnetic Fields

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Chapter 1

Thesis outline

This chapter briefly describes the 'big picture' and the principal motivations of this thesis.

Cosmic rays are particles with energies between $\sim 10^6$ and 10^{21} eV (Kotera and Olinto, 2011); for energies greater than 10^{18} eV they are called ultra-high-energy cosmic rays or UHECRs. Since the discovery of UHECRs, their origin or nature has not been confirmed. The state-of-the-art understanding is that they are composed of completely ionized nuclei generated in highly energetic extragalactic astrophysical sources. Along their journey, they suffer various types of interactions that affect their composition and energy. Also, being charged particles, they suffer trajectory deflections due to extra-galactic and Galactic magnetic fields (GMF).

Their origins remain a mystery even after decades of observational and theoretical efforts. Understanding UHECRs allows us to comprehend interactions and accelerators in the Universe that reach energies that greatly exceed those attainable at any human-made accelerator.

A UHECR passing through the Earth's atmosphere can be detected since it interacts with atoms and molecules in the air, producing cascades of secondary particles called extensive air showers (EAS). The two large currently operating UHECR detectors, from which I have used data on arrival directions and energies, are the Pierre Auger Observatory (PAO) and the Telescope Array (TA).

The arrival directions of UHECR appear to be anisotropic, and many studies have investigated this anisotropy and attempted to correlate it with astrophysical

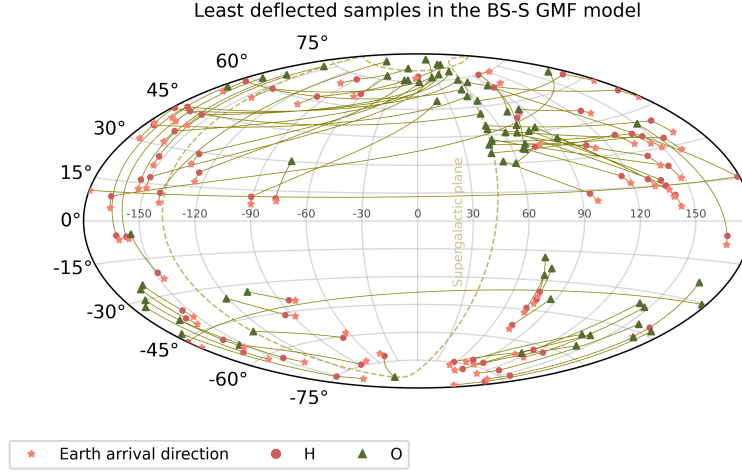


Figure 1.0.1: An example of 'least deflected' UHECRs arrival directions before (orange stars) and after correction for deflections in a BS-S GMF for H (red circles) and oxygen (green triangle) compositions. An Aitoff projection in Galactic coordinates is used. Note the alignment of oxygen (green triangles) deflection corrected positions with the supergalactic plane in the northern Galactic hemisphere. The angular deflections range from near-zero to a few tens of degrees for H, and many tens of degrees for O, as compared to the few degrees uncertainty of telescope-measured arrival directions. Figure adapted from [Sotomayor Webar et al. \(2023\)](#)

sources. A relevant work that motivated this thesis was done by [Sotomayor Webar et al. \(2023\)](#) (e.g., Figure 1.0.1), who found a strong association between the (GMF-corrected) arrival directions of 'least-deflected' UHECRs with nearby galaxies when considering an oxygen composition.

The methodology of [Abreu et al. \(2010\)](#) has also become a guide for the work presented here. They used the UHECR data from the PAO collected between 1 Jan 2004 and 31 Dec 2009 (periods I+II in their paper) to perform statistical tests on smoothed density maps created with galaxies selected by hard X-ray emission (Swift-BAT catalog) and infrared (IR) emission (2MASS Redshift Survey or 2MRS catalog). The method implemented consists of creating smoothed density maps for an isotropic model, the nested hypothesis, and an anisotropic model composed of the astrophysical sources. The anisotropic map uses a Fisher function centered on each source to model the distribution of the fluxes in a certain anisotropic model. Then, a maximum likelihood ratio test between the two hypotheses is computed using the likelihood that considers the probability in the direction of the UHECRs obtained from the smoothed density map. The likelihood ratio test

is computed for each combination of anisotropic fraction and search radius of the Fisher Function until finding the parameters that make the best correlation.

A major motivation for this thesis is that recent interpretations of cosmic-ray-produced air showers with hadronic interaction models suggest a gradual increase in the mean mass of UHECRs with energy, specifically, the results from the Pierre Auger Observatory and the Telescope Array that found an increase in the mass, with a mean baryonic number $A \approx 14 - 20$ at ≈ 40 EeV (201 (2016); Aab et al. (2017a); Abbasi et al. (2016)).

This thesis aims to find a distribution of astronomical sources, weighted by properties that can be considered proportional to their UHECR flux, that are consistent with the anisotropies of the out-of-galaxy UHECR arrival direction distribution.

The first part of this thesis involves simulating UHECR trajectories to obtain GMF-deflection-corrected arrival directions. This is done both for grids of arrival directions and for the sample of Earth-arrival directions and energies of 303 UHECRs detected by the Pierre Auger observatory and the Telescope Array (same sample as in Sotomayor Webar et al. (2023)) considering an oxygen composition.

The second part of this thesis consists of comparing astronomical samples and UHECR arrival directions through a likelihood ratio test between two hypotheses, isotropy and anisotropy. The anisotropic model considers the different astronomical catalogs weighted by relevant properties that are multiplied by an attenuation factor, which compensates for energy loss during the extragalactic travel path, expected for oxygen composition UHECRs.

The contents of the thesis are organized as follows. Chapter 2 presents an introduction and a theoretical background on UHECRs. Chapter 3 presents the theoretical background of the backtracking and the maximum likelihood ratio tests used. Chapter 4 presents our construction of 'extragalactic exposure maps' for different compositions and GMF models, Chapter 5 presents our methodology for statistical correlations, and Chapter 6 presents our results and analysis. Finally, a discussion in Chapter 7 closes this thesis.

Chapter 2

Introduction

This chapter presents an introduction to, and historical context of, cosmic rays, the experiments used to study UHECRs, and current progress in revealing the composition and origin of UHECRs.

2.1 Cosmic Rays

In 1912, Victor Hess was the first to conclude that ionizing radiation increases with altitude using measurements in balloon-based ionization detectors (see [Hess \(2018\)](#) for an English translation). He concluded that the ionizing radiation had an extraterrestrial origin instead of an origin due to radioactive elements from the ground. The first interpretation of this unknown radiation was gamma-ray radiation, which was the most penetrating radiation known at the time. Jacob Clay found a lower cosmic ray ionization near the equator that was first attributed to atmospheric effects ([Clay, 1927, 1928, 1930](#)).

[Bothe and Kolhörster \(1929\)](#) proved that CRs are charged particles because magnetic fields deflect their trajectories. They provided the interpretation of the dependence between the latitude and the cosmic ray intensity anisotropy induced by the Earth's magnetic field. The measurements of [Clay and Berlage \(1932\)](#) and [Compton \(1932, 1933\)](#) confirmed this explanation through a geomagnetic effect compatible with the idea that this radiation consists of charged particles.

[Störmer \(1930\)](#) reproduced the trajectories of charged particles in a magnetic dipole, relevant for the interpretation of Compton's work on the latitude effect as

well as the asymmetry in cosmic ray intensity in the East-West direction depending on the sign of the charged particles.

2.1.1 Galactic Cosmic Rays

Galactic Cosmic Rays (GCRs) have energies below 10^{15-17} eV. As they propagate, GCRs undergo nuclear interaction with interstellar gas, producing secondary particles by spallation. The original GCR, before suffering nuclear interactions, is referred to as the 'primary cosmic ray'.

Direct detection of primary GCRs is interpreted after accounting for secondary spallation produced during propagation in the Milky Way. Measurements of GCR energies and compositions suggest that they were accelerated from material of the interstellar medium (ISM) mixed with stellar wind material expelled by supernovae. There is evidence for a GCR origin in super bubbles from Wolf-Rayet stars (W-R); data are consistent with a GCR source composed of 80% solar system and 20% W-R material (Binns et al., 2005), this origin is a widely accepted mechanism to explain the isotopes of C, O, Ne, Fe for which there is a large difference of isotopic composition compared to Solar System abundances. The composition of the GCRs after secondary spallation is generally similar to that of the solar photosphere or meteorites (Grenier et al., 2015).

Grenier et al. (2015) summarized the cosmic-ray composition and spectra results between 2008 and 2014, and The Cosmic-Ray DataBase (CRDB) contains experimental data of GCRs compiled from various studies, with energies ranging from 10^6 to 10^{21} eV for different species, such as lepton, nuclei, and anti-nuclei. The data from this study and the literature are available to the community ¹ (Strong and Moskalenko, 2009).

2.2 Ultra-high Energy Cosmic Rays

Nominally, CRs with an energy higher than 10^{18} eV (1 Exa eV or EeV) have been called ultra-high-energy cosmic rays (UHECRs). However, in this work, UHECRs are defined as CRs with an energy higher than 40 EeV. Since their discovery in 1963, starting with an energy of 10^{20} eV (Linsley, 1963) and reaching a peak of

¹<https://lpsc.in2p3.fr/crdb/>

3.2×10^{20} eV in the Fly's Eye experiment in 1991 (Bird et al., 1994), the origin of the highest-energy cosmic rays remains unknown, as does the physics governing their acceleration. The data and theory provided by the study of UHECRs make it difficult to make absolute deductions, necessitating the assembly of areas such as plasma physics, astrophysics, and multi-messenger astronomy.

The composition and sources of the UHECRs remain unknown. Evidence points to fully ionized atoms that energetic astrophysical objects have accelerated until these nuclei reach very high energies. However, whether they are dominated by high, intermediate, or low masses remains a dilemma.

2.2.1 Energy spectra

The energy spectra of cosmic rays cover a wide range of energies, from 10^6 eV to 10^{21} eV, which can be approximated by a combination of power laws. Figure 2.2.1 shows the energy spectrum of cosmic rays above 10^{14} eV. Several features are notable, such as the 'knee' at $\sim 10^{15.5}$ eV and the 'ankle' at $\sim 10^{18.7}$ eV, where extragalactic cosmic rays are believed to begin to dominate (Abbasi et al., 2018a). Between 10^{15-17} eV there is a potential transition between a galactic and an extra-galactic origin of cosmic rays if a mixed or iron (Fe) composition is assumed, or caused by propagation losses due to pair production if UHECRs are primarily protons. Another possible explanation is an increasing mass composition from a few EeV to 40 EeV (Allard et al., 2008).

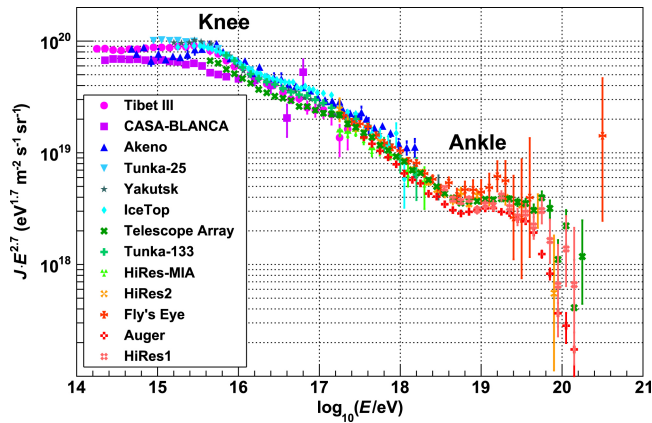


Figure 2.2.1: Cosmic ray spectrum measurement from different experiments. Above the knee, the flux appears to decrease more steeply until the ankle, where it flattens again. A flux suppression at the highest energies is also seen. Figure from Abbasi et al. (2018a)

2.2.2 GZK effect

In particular, the CR flux is suppressed above $\sim 10^{19.8}$ eV due to interactions between CRs and cosmic background radiation, known as the Greisen-Zatsepin-Kuzmin (GZK) effect (Abbasi et al., 2018a). This effect produces a cutoff in the proton CR spectrum since cosmic background radiation photons interact with cosmic rays, triggering the pion photoproduction processes and, as a result, the proton UHECRs lose energy ($\sim 20\%$) (Greisen, 1966; Zatsepin and Kuz'min, 1966).

The Fly's Eye Cosmic Ray detector data confirmed a suppression in the CRs spectrum at 60 EeV (Abbasi et al., 2008), independently Pierre Auger Observatory at 40 EeV (Abraham et al., 2008), and later the Telescope Array at ~ 32 EeV (Abu-Zayyad et al., 2013). To describe the changes in the CR flux with energy through models, the maximum injection energy of their astrophysical sources, composition, acceleration, interactions with interstellar medium, and magnetic fields must be considered.

2.2.3 Sources and acceleration

The Larmor radius of a highly relativistic particle is given by $r = \epsilon / (ZeB)$, with ϵ the energy of the particle, Z its charge number, e the charge of the proton, and B the magnetic field containing it. When a UHECR undergoes circular rotation in the GMF, the Larmor radius is larger than the thickness of the Galaxy, so UHECRs should not be confined in the Galaxy, sustaining their extragalactic origin (Kotera and Olinto, 2011).

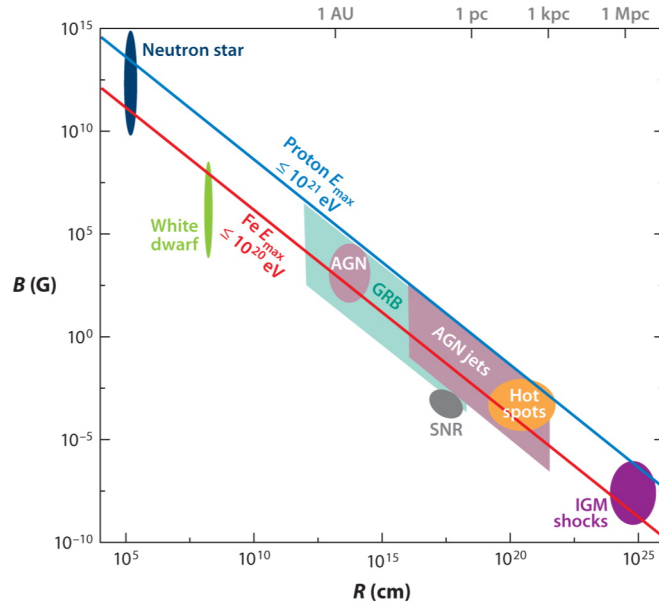
The Larmor radius provides a condition for the maximum rigidity of the UHECR source defined as $R = \epsilon_{max} / Ze$, which becomes an intrinsic quantity of the source, but also the increase in the mass of the UHECR composition restricts the maximum rigidities of the sources.

The maximum energy that a CR can reach in this acceleration is the basis of a criterion for candidate sources: the source extension R_s should be smaller than the Larmour radius. The process in which the particle leaves the source and is unable to gain more energy is described by the Hillas criterion (Hillas, 1984), which follows:

$$\epsilon_{max} = ZeBR_s \quad (2.2.1)$$

where R_s is the size of the source (Kotera and Olinto, 2011). This equation does not consider the time dependence of the source environment or the relativistic outflows.

Neglecting the energy losses, only R_s and B describe the source, showing the relationship between the magnetic field and the size of the source. Figure 2.2.2 shows a Hillas diagram in which different astronomical sources where particle acceleration may occur are plotted.



Kotera K, Olinto AV. 2011.

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Figure 2.2.2: Updated Hillas (1984) diagram. Protons can be trapped above the dark blue lines until they reach energies above $E_{max} = 10^{21}$ eV. Above the red line, iron nuclei can be confined to energies above $E_{max} = 10^{20}$ eV. Candidate sources are shown with uncertainties. Figure from Kotera and Olinto (2011).

Diffusive shock acceleration (DSA) or first-order Fermi acceleration is among the soundest CR acceleration mechanisms at high energies. The B field in the Hillas criterion is related to an electric field in a plasma that can suffer differential motions in which particles can gain non-thermal energy; this process occurs gradually and stochastically.

The most famous example of first-order Fermi acceleration is shock acceleration, in

which particles crossing a front shock gain momentum proportional to $\beta = \frac{v}{c}$, with v the velocity of the shock wave and c the velocity of the particle. The dissipation of cosmological shock waves leads to thermal energy, and part of the shock is converted to cosmic ray energy via DSA (Matthews and Taylor, 2023). On the other hand, the second-order Fermi acceleration refers to the CRs gaining energy by collisions against the magnetic field of magnetized clouds in the interstellar space of galaxies, and the fractional energy gained per scatter is proportional to β^2 (Fermi, 1949).

2.2.3.1 Origin in astrophysical sources

Evidence points to nonthermal particle energization processes that occur within and around cosmic structures such as galaxy clusters (Ryu et al., 2003). Jets from an AGN can travel hundreds of kpc into the environment, forming giant radio galaxies such as Centaurus A and Fornax A, which show bright hot spots at the end of the jets, where termination shocks are produced (Matthews et al., 2018). UHECRs acceleration above approximately 1EeV can be produced in the large-scale shock of superwinds from nearby starburst galaxies, a that model appears to be consistent with the spectrum observed by The Pierre Auger Observatory (Anchordoqui, 2018). Gamma-ray bursts (GRBs), pulsars, magnetars, and black holes are also candidates for UHECR acceleration sources (Matthews and Taylor, 2023).

2.2.3.2 Origin in dark matter?

The nature of Dark Matter (DM) is still unknown, it is considered to be nonbaryonic and nonrelativistic. The Standard Model (SM) of particle physics needs to be expanded to explain observations. One of the possible extensions of the SM proposes that DM is formed by a nonbaryonic new particle called the weakly interactive massive particle (WIMP) that decays or annihilates in SM particles. The decay of WIMPs can produce gamma rays and cosmic rays, among other products, which may be detectable (Porter et al., 2011).

2.2.4 Propagation

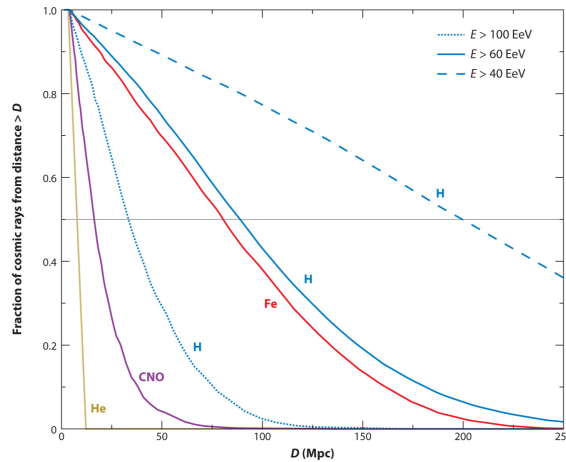
There are different processes that UHECRs undergo through their propagation from their source to Earth. In the intergalactic medium, UHECRs are affected

not only by the CMB but also by infrared, optical, and ultraviolet (IR/OPT/UV) backgrounds, which affect the propagation of compound nuclei and the production of cosmological neutrinos, as well as by cosmological expansion, producing energy losses.

Processes such as accretion, fueling, and triggers of star formation in which UHECRs are accelerated are intrinsically related to time variability, which is an inherent part of UHECR studies. Also, UHECRs after leaving their source can be 'echoed' or scattered off magnetic fields close to their originating source.

2.2.4.1 UHECR horizons

It should be considered that, depending on the energy range, there are different dominant photo-disintegration processes between the CRs and photons of IR/OPT/UV backgrounds. The dissociative effects on trans-GZK CRs are shown in Figure 2.2.3, showing the fractions of CRs arriving on Earth, depending on their original energies and compositions.

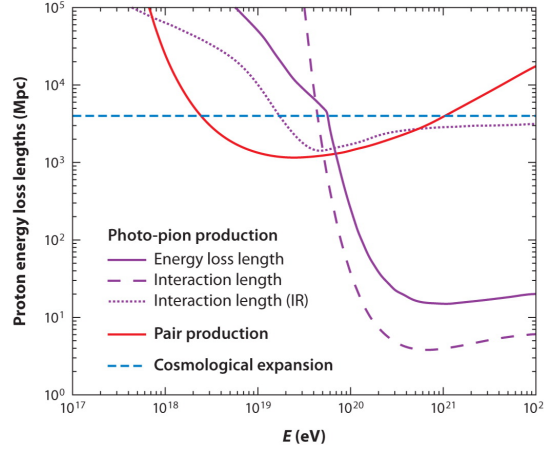


 Kotera K, Olinto AV. 2011.
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Figure 2.2.3: Fraction of cosmic rays that survive after traveling a distance D (Mpc) for different compositions (H, He, CNO, Fe) with energies over 60 EeV. The horizontal gray line shows where 50% of a species can survive. Figure from [Kotera and Olinto \(2011\)](#)

UHECR sources should be within a horizon called the GZK sphere (which implicates all the processes mentioned), which involves a distance scale where matter is inhomogeneously distributed. If UHECRs are composed mainly of protons with energies higher than 60 EeV, they suffer from flux suppression

and changes in composition by interaction with backgrounds that lead to pion production or pair production. Figure 2.2.4 shows the proton energy loss lengths. The distance cut-off was estimated to be approximately 100 Mpc for proton/iron and 20 Mpc for carbon/nitrogen/oxygen if $\approx 50\%$ of CR survived (Kotera and Olinto, 2011).



 Kotera K, Olinto AV. 2011.
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Figure 2.2.4: Proton energy loss lengths for photo-pion production and electron-positron pair production due to the interaction of protons and background photons. The dashed blue line indicates the losses due to cosmological expansion. Figure from Kotera and Olinto (2011).

2.2.4.2 Galactic and extra-galactic magnetic fields

Deflections by intergalactic magnetic fields (IGMF) are expected to be weak, the upper limit has been constrained with different methods, for example, considering the astrophysical sources correlated with the CR arrival direction reported by PAO the upper limit reaches the value of $B < 0.7 - 2.2 \times 10^{-10}$ G. In this study, the source of uncertainty is the unknown mass composition of cosmic rays (Bray and Scaife, 2018).

Meanwhile, Galactic magnetic fields that reach $\sim 1 \mu\text{G}$ are expected to produce significant and ordered deflections in the CR trajectories. Specifically, at UHECR energies, angular deflections due to the GMF span a range from near zero to a few tens of degrees for H, increasing to hundreds of degrees for Fe, compared to a few degrees of precision in the arrival direction (for example, Takami and Sato (2008); Nagar and Matulich (2010); Jansson and Farrar (2012); Sotomayor Webar

et al. (2023)).

2.2.4.3 Echoed UHECRs

A model for intermediate UHECR anisotropies in the UHECR arrival directions considers that UHECRs are accelerated by powerful outbursts in nearby sources and then UHECRs 'echo' or scatter off the circumgalactic medium of star-forming galaxies, for example, resulting in arrival directions correlated with star-forming galaxies even though these are not the initial sources. Different compositions are expected from an echoed wave in comparison to a direct wave because propagation depends on rigidity and each composition has its loss length (Bell and Matthews, 2022).

2.3 UHECR indirect detection experiments

Measurements of *extensive air showers* (EAS) showed that CRs produce showers of secondary particles when they interact with the atmosphere (e.g. Rossi, B (1934) and Auger et al. (1939)). The study and use of EAS made the discovery of elementary particles possible. Through the photography of cosmic rays in a cloud chamber under the field of a magnet, the positron was discovered (Anderson, 1932). Likewise, the muon was discovered with cloud chamber photography by Anderson and Neddermeyer (1936); Neddermeyer and Anderson (1937). Furthermore, with the study of cosmic ray tracks, strange particles, and charged pions were discovered between 1947 and 1950 (Watson, 2019).

The study of elementary particle physics transitioned from cosmic rays to dedicated particle accelerator laboratories in the early 1950s, while cosmic ray research shifted its focus towards astrophysics (Israel, 2012).

Above 10^{14} eV, the cascades of secondary particles or EAS are the only way to detect UHECRs from Earth. These can be detected by both their fluorescent light in the atmosphere and with ground surface detectors, which allows the derivation of the energy and arrival direction of the original UHECR, and potentially its composition.

Some of the experiments that have collected data in the UHECR energy range are the Akeno Giant Air Shower Array (AGASA) experiment, which detects the

shower of particles using surface detectors spread over a wide area (Chiba et al., 1992), and the High-Resolution Fly’s Eye Cosmic Ray detector (HiRes), which uses fluorescence detectors to detect air fluorescence light along air shower tracks (HIRES Collaboration, 2001). On the other hand, the Telescope Array Experiment (TA) (Abu-Zayyad et al., 2012) and The Pierre Auger Observatory (PAO) (Pierre Auger Collaboration, 2015) use both detector techniques.

There are other experiments, such as the Extreme Universe Space Observatory (Catalano et al., 2003) to observe the scintillation light and the Cherenkov light reflected by the sea, land, or clouds from space with a monocular telescope attached at the International Space Station. However, the UHECRs in this work are restricted to those from the TA and PAO experiments as they provide the largest individual samples with precise arrival direction and energy estimates.

2.3.1 Pierre Auger Observatory Hybrid event reconstruction

A powerful technique to measure mass-sensitive features in EAS is the fluorescence technique, as in the case of the Telescope Array Experiment (TA) and the Pierre Auger Observatory (PAO), which are composed of fluorescence-telescope detector (FD) stations and surface detector (SD) stations. In the case of PAO, the SD is composed of a baseline array of water Cherenkov stations, whereas the TA SD stations use scintillator detectors. When EAS are detected with both SD and FD, they are called golden hybrid events, which relate the shower size from SD with the shower energy of the FD.

2.3.1.1 Fluorescent detector

For example, the hybrid event reconstruction in the PAO consists of obtaining the energy and an arrival direction for a shower from the FD, based on the sizes and times of the signal registered. For geometry reconstruction, the pixels of an FD are triggered by the shower front, and the signal for pulse start and stop times with signal-to-noise ratio above some threshold are chosen.

The shower detector plane is a plane that contains the shower front axis and the triggered FD. The projection of a shower in the telescope evolves along the shower detector plane, and each pulse is associated with an angle to the horizontal axis of

the telescope. The time when the shower front on the SD meets the shower axis is restored and an angle is associated. Later, the light deposited as a function of time is converted to energy. The Cherenkov light and the fluorescence light are related to the energy deposited (by a linear set of equations), and then a shower profile is derived. The full longitudinal energy profile and its maximum at depth X_{max} are computed (see page 59 of [Pierre Auger Collaboration \(2015\)](#)).

2.3.1.2 Surface detector

In the case of the SD, an approximation of the shower arrival direction is obtained by fitting the times of arrival of the signals received by each SD station to a plane front. If an event triggers enough stations, a concentric spherical model is used (see Figure 2.3.1). A specific function is used to describe the lateral distribution function of the signal on the ground. Finally, the shower arrival direction is obtained with the shower arrival origin from the geometrical reconstruction and the shower impact from the lateral distribution function.

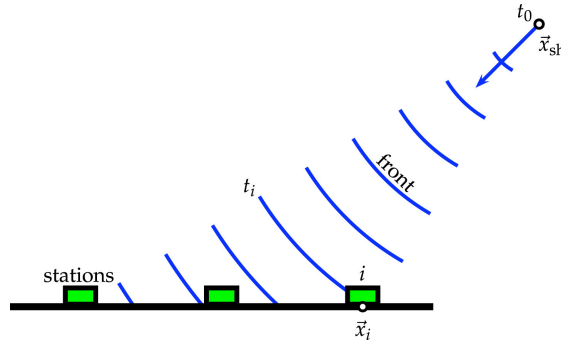


Figure 2.3.1: Reconstruction of the shower geometry using SD stations. The arrival direction is derived by fitting the start times of the signals at the SD stations to a concentric-spherical model.

The air showers detected independently with both the SD and FD (so-called hybrid events) are used for cross-calibration. Hybrid events with a zenith angle of less than 60 degrees are used to relate the shower size of the SD to the energy of the FD. An example of a hybrid event reconstruction observed by four telescopes is shown in Figure 2.3.2, in which the individual geometry reconstructions are shown as black lines. The energy scale derived with the hybrid method can be applied to all showers detected only by SD (see Sections 10 and 11 [Pierre Auger Collaboration \(2015\)](#) for details).

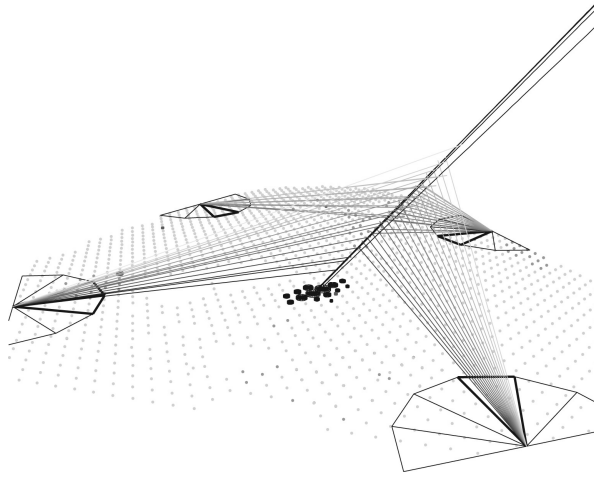


Figure 2.3.2: Reconstruction of a hybrid event. Figure from [Pierre Auger Collaboration \(2015\)](#).

2.3.2 Air shower components

The cascade of particles has an electromagnetic and a hadronic portion. For example, the decay of a π^0 into two gamma rays; these photons in the electric field of a nucleus will produce electron pairs. The electron pairs will produce photons through bremsstrahlung (electrons or positrons are accelerated in the electric field of some nucleus) ([Watson, 2019](#)).

The energy loss of the electron is a stochastic process. A simple cascade model, termed the Heitler model, of an electromagnetic shower is shown in panel (a) of [Figure 2.3.3](#), in which a particle with original energy E (electron) leads to two new particles, each electron of the pair taking energies $E/2$ when traveling a distance λ , equal to the mean free path of pair production. The process continues to divide the energy into equal parts in each node until the energy loss rate via bremsstrahlung falls below the energy loss rate via pair production. If this happens after depth X , the number of track segments and the depth at which the shower reaches the maximum can be calculated. The change of the shower maximum with energy is called the 'elongation rate' (X_{max}); this model relates X_{max} to the primary energy E . At UHECR energies, X_{max} allows constraints on the primary composition of UHECR through the change of X_{max} with energy called ' $\langle X_{max} \rangle$ ', which scales as $\log(E/A)$, where A is the atomic mass. Heavier primary particles are expected to have shorter $\langle X_{max} \rangle$ values than light primaries ([Watson, 2019](#)).

On the other hand, the hadronic portion of the cascade, produced by a proton

or nucleus, feeds the electromagnetic one. This process is more difficult to describe and model since it involves parameters that have large uncertainties at these energies (e.g., cross-section and inelasticity). A model has been made by [Matthews \(2005\)](#) and is shown in Panel (b) of Figure 2.3.3. In this description, the first collision produces π^0 (which decays into gamma rays, as was shown) and $\pi^{+/-}$. Charged pions travel and interact to form new generations of pions until their energies decrease to a critical value where their decay into muons is more likely ([Watson, 2019](#)).

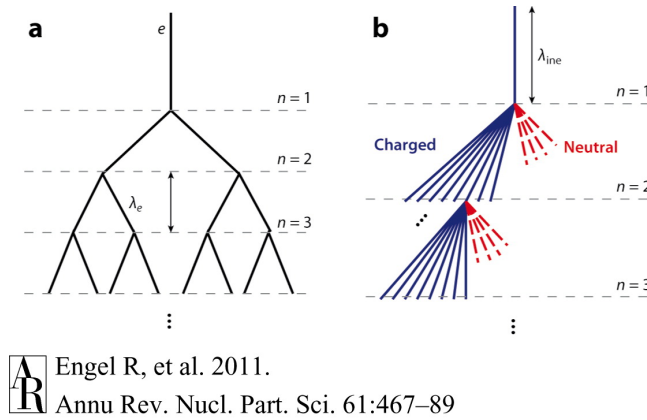


Figure 2.3.3: (a) Model of an electromagnetic shower. (b) A hadron induces a shower's hadronic components, in which dashed lines represent trajectories of neutral particles and solid lines of charged particles. Figure from [Engel et al. \(2011\)](#).

2.4 Results from UHECR observations

2.4.1 UHECR Spectra

It should be noted that the UHECR energy spectrum of CRs measured by the PAO and TA observatories agree in all the common regions in the sky, but above 10^{19} eV (at and beyond the 'flux suppression') the spectra of PAO and TA show a relative shift in energy on the order of 20% per decade, which remains even after rescaling the energies by 5.2% ([The Telescope Array Collaboration and The Pierre Auger Collaboration, 2018](#)). In addition, the UHECR energies were rescaled by 10% per decade ([AbuZayyad et al., 2019](#)), see Figure 2.4.1.

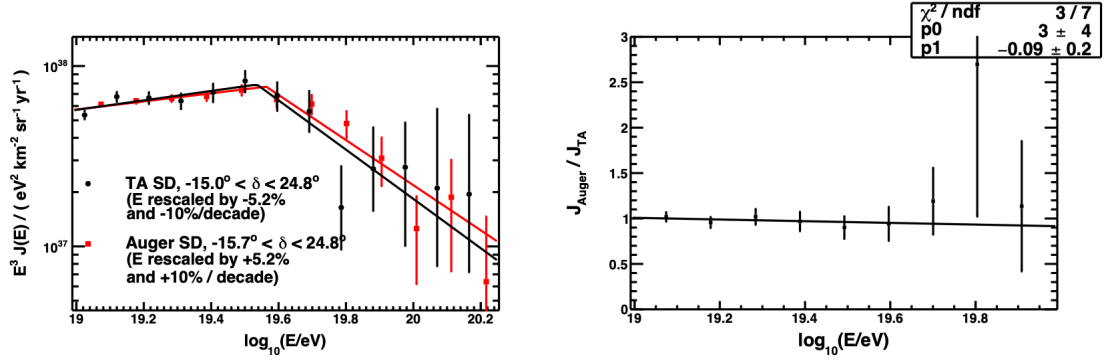


Figure 2.4.1: Left: UHECR energy spectra after re-scaling the energies by an -5.2% and -10% per decade for the TA data and by +5.2% and +10% per decade for the PAO data. Right: Comparison between the PAO and the TA spectra. After re-scaling the energies the spectra are in excellent agreement.

TA in the Northern Hemisphere found a higher energy cut-off over the limit of the common declination band. In other words, a flux excess that is not present in PAO. A possible conclusion is that the variation in the cutoff energy with declination is an astrophysical effect. However, the PAO collaboration reported that, in the southern hemisphere, the spectrum is independent of the declination. The nonlinearity when comparing both spectra over GZK energies could be due to variations in the source distances or source maximum energies between the northern and southern UHECR sky (Abbasi et al., 2018b).

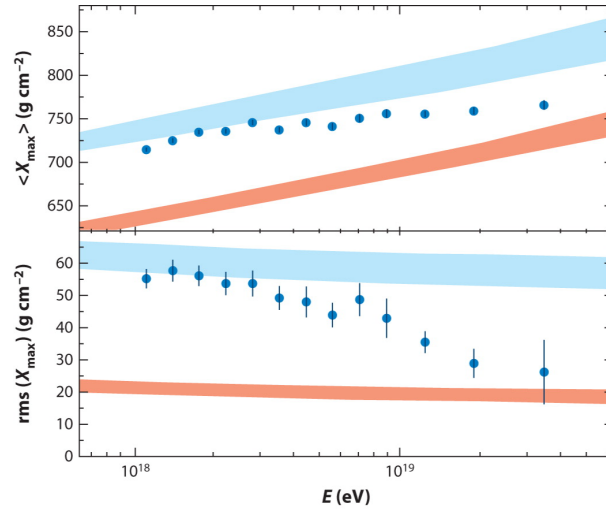
2.4.2 UHECR Composition

As noted, the measurement of the composition of the UHECRs is best performed by fluorescence detectors that observe the maximum depth X_{max} in the atmosphere of the electromagnetic component of the EAS induced by the cosmic ray.

PAO and HiRes X_{max} measurements of UHECRs at energies greater than 40-50 EeV were in tension. PAO shows an increase in mass at 40 EeV, and HiRes maintains a light composition around 50 EeV. The evolution of X_{max} in the Fly's Eye experiment and HiRes data shows a proton-dominated mixed composition. Meanwhile, PAO data show a flatter evolution of X_{max} above the ankle; therefore, more statistics are required from hadronic models to better understand the evolution of the X_{max} shape at the highest energies (Allard et al., 2008).

The decades-old view of UHECRs being a mix of only hydrogen and

iron (with relative composition varying with energy) now also expands to consider intermediate nuclear compositions. Furthermore, PAO and TA X_{max} measurements agree that around the ankle, a light composition dominates; at higher energies, PAO found an increase in mean mass $A \approx 14 - 20$ at ≈ 40 EeV. Over 50 EeV, there is a change in the dependence of X_{max} on E , pointing to a slow increase in mass at the highest energies. It is still necessary to reduce the statistical and systematic uncertainties in both PA and TA (Aab et al. (2017a); Abbasi et al. (2018a)). Figure 2.4.2 shows $\langle X_{max} \rangle$ and $\text{rms}(X_{max})$ data from PAO for events with energy greater than 1 EeV and simulated proton and iron with hadronic models.



A Kotera K, Olinto AV. 2011.
R Annu. Rev. Astron. Astrophys. 49:119–53

Figure 2.4.2: $\langle X_{max} \rangle$ and $\text{rms}(X_{max})$ measurements from PAO as a function of primary energy E . The expectations from hadronic interaction models in Abraham et al. 2010a for primary protons (blue shade) and primary iron nuclei (red shade) are shown. Figure from Kotera and Olinto (2011)

On the other hand, the UHECR spectrum has an implication in the mass composition, as, for example, in Allard et al. (2008) where the available GZK cutoff from the UHECR spectrum data was found to be compatible with photon interaction if a proton composition dominates and with photodisintegration processes if a heavy mass composition dominates. In the case of an intermediate mass the spectrum is compatible with the data, but the composition as observed at Earth cannot constrain a considerable amount of intermediate-mass UHECRs because of interactions with background photons.

2.4.3 Anisotropies in Sky Distribution

This thesis aims to find a distribution of astronomical sources, weighted by properties that can be considered as proportional to their UHECR flux, consistent with the anisotropies of the Out-of-Galaxy (i.e., corrected for Galactic magnetic field deflections) UHECR arrival directions.

Given this, it is relevant to first introduce previous studies of the anisotropies of UHECR distributions and the correlation of these with astronomical catalogs. Also relevant is the basis of the simulation of UHECR trajectories from Earth to the Galactic limit, i.e. back-tracking.

The anisotropies in the UHECR arrival directions can be approximated as dipoles or quadrupoles. They are interesting because they can be created by the large deflection of CRs in extragalactic and galactic magnetic fields that produce diffusion of CRs, or due to the anisotropic distribution of the nearby universe (Harari et al., 2015).

Deflection of cosmic rays can be associated with small to intermediate-scale anisotropies for the highest energies and large-scale anisotropies for the lowest energies; the last ones can be approximated as a dipole even for a mixed composition (Harari et al., 2015). As expected, the dipole and quadrupole amplitudes and directions are affected by GMF lenses (Eichmann and Winchen, 2020).

PAO reported anisotropy in the arrival directions of UHECRs with energies above 8 EeV. The anisotropy was approximated as a dipole, and it was consistent with an extragalactic origin. The reported anisotropy has a level of significance 5.2σ (Aab et al., 2017b). The amplitude of the dipole increases when energies above 4 EeV are considered. This result is expected due to the smaller deflections of CRs at higher rigidities, but also higher energy increases attenuation from distant sources, enhancing the contribution from nearby sources (Aab et al., 2018b).

Motivated by PAO results, the TA group searched for a large-scale anisotropy using the data from SDs of TA. The result is compatible with an isotropic distribution (but compatible with an extragalactic origin) and also with the dipole presented by PAO (Abbasi et al., 2020).

The TA added 80 SDs to be sensitive to energies below 8 EeV to find large-scale

anisotropy around 2 EeV. With the actual data, the amplitude of the dipole is consistent with an isotropic distribution. They concluded that more data from SDs is required to understand the origin of UHECRs (Kimura et al., 2023).

2.4.4 Previous studies of correlation without GMF deflection-correction

The Pierre Auger Collaboration reported a possible correlation between the UHECRs and nearby starburst galaxies (Aab et al. (2018a)). On a separate track, the Telescope Array Collaboration reported a UHECR hot spot spanning a $\sim 20^\circ$ region of the sky, and the starburst galaxy M82 was close to the best-fit source position (Kawata et al. (2016), He et al. (2016)).

The anisotropic distribution of different sky models constructed with astronomical catalog objects can be correlated with the UHECR Earth arrival directions distribution (Abreu et al. (2010); Aab et al. (2018a, 2015)).

2.4.5 Previous studies of correlation with GMF deflection-correction

To backtrack the path of the UHECR through the Galaxy, the trajectory of an antiparticle from Earth in the direction measured by the observatory to the end of the Galaxy (a distance at which the GMF is considered to be negligible) is simulated under a given magnetic field model. Once the UHECR leaves the Galaxy, its travel direction gives the 'out-of-galaxy' arrival direction. As an example, CRPropa is a public code that, among its features, allows the backtracking simulation of particles in different posited GMF models (Alves Batista et al., 2016).

The method of backtracking the trajectory of a UHECR from its source to Earth and then correlating their 'out-of-Galaxy' arrival directions with astrophysical sources, assuming that intergalactic magnetic fields do not produce systematic deflections, has been discussed and used, for example, in Nagar and Matulich (2010) and Sotomayor Webar et al. (2023).

Chapter 3

Theoretical background

The first part of this thesis involves simulating UHECR trajectories to obtain GMF-deflection-corrected arrival directions. This is done both for grids of arrival directions and for the sample of Earth-arrival directions and energies of UHECRs detected by the Pierre Auger observatory and The Telescope array. In this thesis, we explore two GMF models and focus primarily on an oxygen (i.e. 'intermediate') composition for UHECRs.

The second part of this thesis consists of calculating test statistics when comparing astronomical samples and UHECR arrival directions. The different astronomical catalogs are considered to create an anisotropic model, weighted by the relevant properties times an attenuation factor chosen for the oxygen composition. On the other hand, the 'isotropic model' consists of the exposure of the observatories of the UHECR sample but under GMF-corrected directions.

This chapter thus introduces the theory of backtracking and the maximum likelihood analysis.

3.1 GMF models

Creating 3D models of the Galactic magnetic field is complicated because of our location within the Galaxy. Rotation measures are observed in the interstellar medium in the direction of Galactic pulsars plus extragalactic sources to obtain the regular magnetic field component and thermal electron density model. In addition, the cosmic-ray electron density should be constrained by the total intensity and

polarization maps. The thermal electron density distribution model consists of different subparts, such as thin and thick disks, spiral arms, and complex thermal sources (Sun and Reich, 2010).

The most commonly used method is to divide the GMF model into disk and halo components, which can have different types and patterns. In some models, a dipole field component is added.

As in Sotomayor Webar et al. (2023), we use four classical GMF models from Takami and Sato (2010): AS-S, AS-A, BS-S, BS-A, three models proposed by Sun et al. (2008) (AS-S Ring, AS-S Arm, and BS-S), and a model proposed by Jansson and Farrar (2012) (hereafter JF12).

The complete model of Takami and Sato (2010) consists of a spiral disk, a spiral halo component, and a dipole field. The spiral component can be modeled as axisymmetric (AS) or bisymmetric (BS). The main difference is that the AS model does not present reversals, unlike the BS model. The halo component model adopted has two different parities, symmetric (S) or asymmetric (A)-type parity, which produce four different spiral models.

Sun et al. (2008) models have a halo field component, spatial variations of the field strength, reversals, or asymmetries on the disc component. Also considered is observational high-latitude rotation measure data, which constrain the model above and below the Galactic plane with a toroidal magnetic field model. The Galactic plane is considered an axisymmetric magnetic field with reversals to fit observations and create a realistic model of the Galactic magnetic field. The models proposed are AS-S models with reversals in rings (AS-S+RING), AS-S models with reversals following the arms (AS-S+ARM), and a modified BS-S type model (hereafter BS-S Sun).

The JF12 GMF model also considered rotation measurement data for a more realistic model. It has an extended halo field, a disk field, and an out-of-plane component with an 'X-shape' motivated by radio observations of external galaxies. The JF12 field has random striated and small-scale random turbulent fields (Jansson and Farrar, 2012).

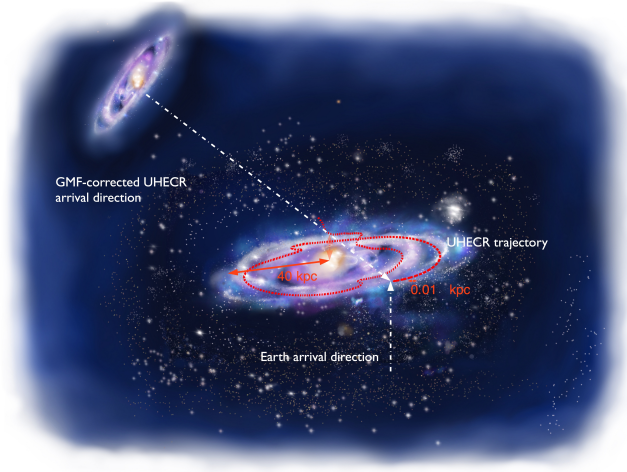


Figure 3.1.1: Illustration of the simulations - detailed in Nagar and Matulich (2010) - that backtrack the Earth-arrival directions of UHECRs through the deflections suffered by the GMF model in steps of 0.01 kpc, until they reach a distance of 40 kpc from the Galactic center, at which point their velocity vector is used to determine their 'out-of-Galaxy' arrival direction.

3.1.1 Back-tracking simulations

The code we use to calculate the UHECR trajectories in GMF was first introduced in Nagar and Matulich (2010) and improved in Sotomayor Webar et al. (2023). First, the magnetic field components are calculated from a given position in kpc centered on the Galaxy, depending on the magnetic field model and for different components of the GMF model, such as the disk, halo, and dipole fields.

The simulation solves the equation of motion of the UHECR in steps of 0.01 kpc. At each step, the position and velocity vector of the UHECRs and the sum of the absolute deflections are stored. The process is iterated until the UHECR is further than 40 kpc from the Galactic center. At this point, it is assumed that further GMF deflections are negligible, and thus the velocity vector points to the out-of-Galaxy arrival direction (see Figure 3.1.1).

3.1.2 Monte Carlo simulations

The backtracking simulations were repeated 50 times for each UHECR adding an error at each 0.01 kpc in the ordered GMF (uniformly distributed between 0 and 50% of the value of the GMF at that location) plus adding a turbulent component; also in each simulation, an error is added in the energy of the UHECR uniformly

distributed between 0 and 5% of the energy. The final simulations give a set of 50 out-of-galaxy arrival directions per UHECR to trace the error in the distribution of directions.

3.2 GMF models comparison

Sotomayor Webar et al. (2023) presented Monte Carlo simulations of deflections of oxygen composition UHECRs in all GMF models used in this thesis. Here we repeat this exercise but with the latest UHECR energy updates (see Section 5.2.1). The resulting density maps of the MC points for oxygen composition under some GMFs used in Sotomayor Webar et al. (2023) are shown in 3.2.1; the results are slightly different from those shown in Sotomayor Webar et al. (2023).

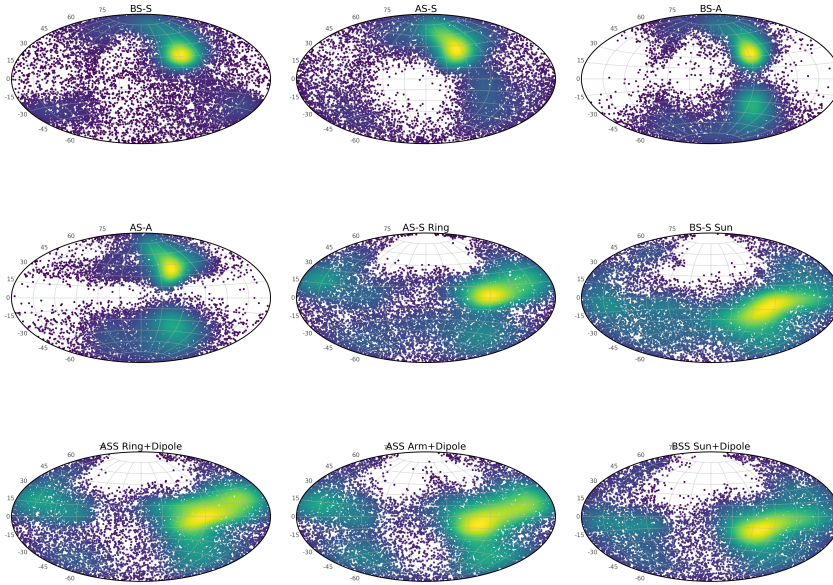


Figure 3.2.1: Results of the Monte Carlo simulations of oxygen UHECRs for a selection of the GMF models shown in Sotomayor Webar et al. (2023) in an Aitoff projection of Galactic coordinates, but now with updated UHECR energies. The colors trace the density of the MC out-of-galaxy directions, with yellow being the highest value.

3.3 Comparison of CNO deflections

We simulated the out-of-Galaxy arrival directions of oxygen, carbon, and nitrogen for the BSS and JF12 GMFs. Figure 3.3.1 shows a histogram of the angular distance between the deflection-corrected arrival directions of oxygen versus nitrogen or

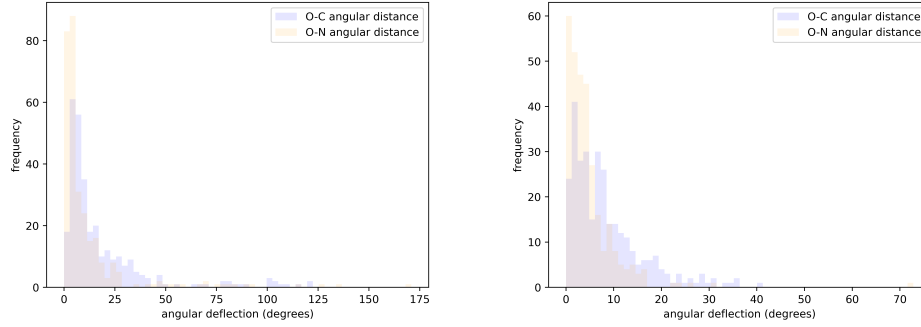


Figure 3.3.1: Histogram of the angular distance in degrees between the out-of-Galaxy arrival direction for an oxygen mass composition and the out-of-Galaxy arrival direction for a carbon (nitrogen) composition in blue (orange). The left (right) panel is for the BSS (JF12) GMF model.

carbon in each model. The out-of-Galaxy arrival directions for oxygen, carbon, and nitrogen UHECR compositions are relatively similar over most of the sky; the few very large differences are for UHECRs with Earth-arrival directions close to the direction of the Galactic center. Given this, and the high ISM abundance of oxygen as compared to carbon and nitrogen, in this thesis we use only oxygen as the representative 'intermediate-mass' composition.

3.4 Maximum likelihood analysis

Sky models consist of an isotropic and an anisotropic component. The anisotropic model was created using a Fisher function centered on the coordinates of the sources in each catalog, as in [Abreu et al. \(2010\)](#) and [Aab et al. \(2018a\)](#). The final probability function of detecting a UHECR in a direction $\hat{n}$ is given by equations (1) and (2) of [Abreu et al. \(2010\)](#):

$$F(\hat{n}) = \frac{\epsilon(\hat{n})}{I} \times \left[\frac{f_{iso}}{\Omega} + f_{aniso} \frac{\phi(\hat{n})}{\langle \phi \rangle} \right] \quad (3.4.1)$$

where f_{iso} is the isotropic fraction, f_{aniso} is the anisotropic fraction, Ω is the solid angle covered by the sky model, and $\epsilon(\hat{n})$ is the 'extragalactic exposure map' of both telescopes. $\phi(\hat{n})$ is the flux in the $\hat{n}$ direction defined as:

$$\phi(\hat{n}) = \sum_i w(\hat{s}_i) \times \frac{d(\hat{s}_i, \hat{n})^2}{2\sigma^2} \quad (3.4.2)$$

with $w(\hat{s}_i)$ the weight assigned to the source in the direction $\hat{s}_i$ multiplied by the attenuation factor, $d(\hat{s}_i, \hat{n})$ the angular distance in degrees between the pixel in the direction $\hat{n}$ and the i -th source in the direction $\hat{s}_i$, and σ the search radius in degrees.

The log-likelihood is defined as:

$$L = \sum_{\hat{n}} \ln F(\hat{n}) \quad (3.4.3)$$

where $\hat{n}$ is the direction of the n -th UHECR.

The test statistic (TS) ratio test consists of the ratio between two hypotheses: the null hypothesis, which is the isotropic model, and the anisotropic model, defined as

$$TS = -2 \times \frac{L_{isotropy}}{L_{anisotropy}} \quad (3.4.4)$$

In other words, the test statistic gives the difference between two likelihoods, defined as the sum of the probabilities in the UHECR directions, in the case that $f_{anisotropy} = 0$, and when all the components of Equation 3.4.1 are considered, which includes the contribution from the astrophysical sources. The maximum likelihood test is based on finding the biggest test statistic value leaving two free parameters: σ and $f_{anisotropy}$.

3.4.1 Replication of maximum likelihood test with PAO data

In Abreu et al. (2010) the UHECR data from the PAO collected between 1 Jan 2004 - 31 Dec 2009 (periods I+II in the paper) were used to perform statistical tests on smoothed density maps created with the X-ray catalog from Swift-BAT and near-IR catalog from 2MASS Redshift Survey (2MRS).

Following the approach of Abreu et al. (2010), we replicated the TS calculations of their PAO sample using the same mask in latitude for the Swift-BAT and 2MRS samples to find similar behaviors. The TS profile and the probability map constructed with Equation 3.4.1 using the Swift catalog are shown in 3.4.1. The

TS profile is comparable with the top panel of their Figure 6. The same for the 2MRS sample is shown in 3.4.2.

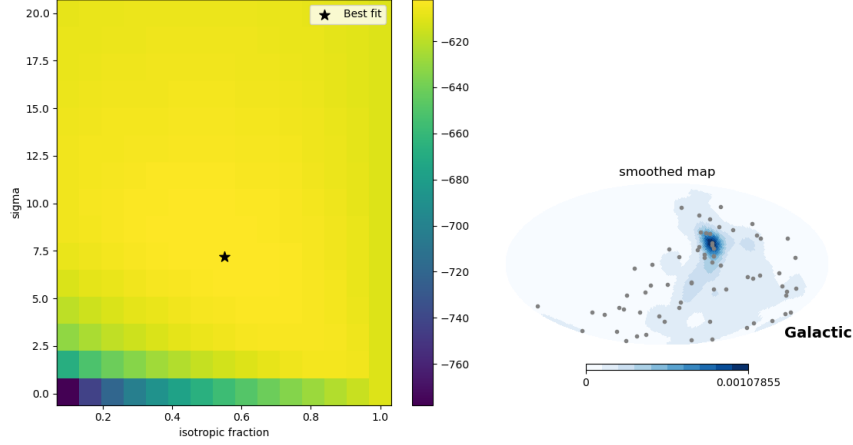


Figure 3.4.1: Left: Test statistic profile as a function of sigma and the isotropic fraction. The parameters that maximize the TS are plotted with a black star ($\sigma = 7.2^\circ$ and $f_{iso} = 0.55$). The anisotropic model was constructed with the SWIFT-BAT catalog. The likelihood calculation considers the Earth-arrival direction of the UHECRs from the data of PAO in the periods from 1 Jan 2004 - 31 Dec 2009 used in [Abreu et al. \(2010\)](#). Right: The smoothed density map of the catalog tested with the best parameters found is shown in color following the color bar beneath the panel. The Earth-arrival directions of UHECR are over-plotted as grey dot. The map is in Galactic coordinates.

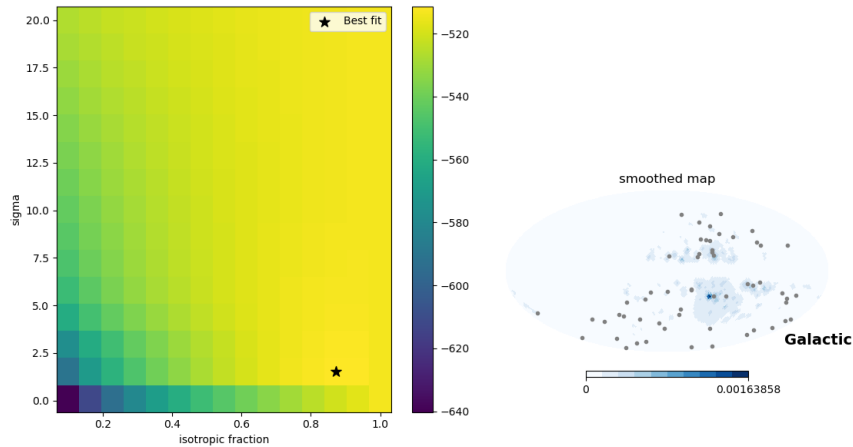


Figure 3.4.2: Same as Figure 3.4.1 but for 2MRS flux, the parameters that maximize the TS are $\sigma = 1.25^\circ$ and $f_{iso} = 0.88$.

Chapter 4

Extragalactic exposure maps

Under some conditions, UHECRs follow the Liouville theorem, which ensures that if there is an isotropic distribution of UHECRs outside the galaxy, then an isotropic flux will be received at Earth. Still, in reality, the Earth-arrival directions are anisotropic (Section 2), which implies that the flux outside the Galaxy should be anisotropic due to magnified and suppressed regions produced by the GMF deflections (Eichmann and Winchen, 2020).

This section presents our results on the distribution of the GMF-corrected UHECR directions produced from simulated grids of UHECRs whose Earth arrival directions are uniformly distributed and consider the exposure map of the observed UHECR samples of the combined PAO and TA observatories.

The smoothed density maps of the sky models consider an exposure map as is shown in Equation 3.4.3. To create them, the exposure of both telescopes outside the Galaxy must be utilized, that is, the exposure on Earth must be associated with a new direction, which is determined by the deflection due to the GMF under the assumed UHECR mass composition. This generates zones of magnification and suppression of the UHECR flow outside the Galaxy.

There are two elements required to create the extragalactic exposure maps. We first constructed the combined Earth-exposure maps of PAO and TA combined. To do this, for each of PAO and TA, we fit a polynomial function to the individual exposure weights per declination in order to create an exposure map of each observatory. These were normalized and then multiplied by the total operational time of each observatory. The two exposure maps were then summed.

Second, the trajectories of the hydrogen, oxygen, and iron UHECR compositions were simulated to obtain out-of-Galaxy arrival directions. This allowed us to map each Earth-arrival direction to an out-of-Galaxy arrival direction. The extragalactic exposure maps were created using HEALPix¹ with an NSIDE of 32, which results in an approximate pixel size of 1.8 degrees.

In the cases of hydrogen and iron composition, these focal-point maps give a preliminary idea of consistency with the sky models for future work, and allow a contrast with the results of oxygen.

4.1 Galactic Magnetic Field Focal-points

Three hundred and three grids of UHECRs with Earth-arrival directions spaced in steps of 2 deg in latitude and longitude at the equator were used as a starting point Earth-arrival direction grid. Each grid was assigned the energy of one of the UHECRs of the sample, thus fully sampling the TA and PAO energy spectra.

For each grid point, the equivalent out-of-Galaxy arrival directions were computed using backtracking. A HEALPix map was used to associate a 'deflected pixel' or out-of-galaxy direction with the exposure weight assigned to the 'Earth arrival direction pixel' in the Earth exposure map.

The extragalactic exposure map for each given GMF model for the hydrogen, oxygen and iron compositions was smoothed by 0.08 radians (4.6 degrees) The results are shown in Figure 4.1.1.

It should be noted that although the original Earth-arrival grids have uniformly distributed directions, they do not represent an isotropic distribution. This is because they are only used to associate a starting pixel with a terrestrial exposure value (which varies given the nonuniform exposure map of PAO and TA) to a deflected corrected pixel. Therefore, the first statement of this chapter is valid.

Finally, this extragalactic exposure map includes information on the magnification and bias due to the GMF together with the observed exposure of both telescopes from which the data have been obtained. Therefore, the probability function created when mixing this extragalactic map with a sky model will reflect areas

¹<http://healpix.sourceforge.net>

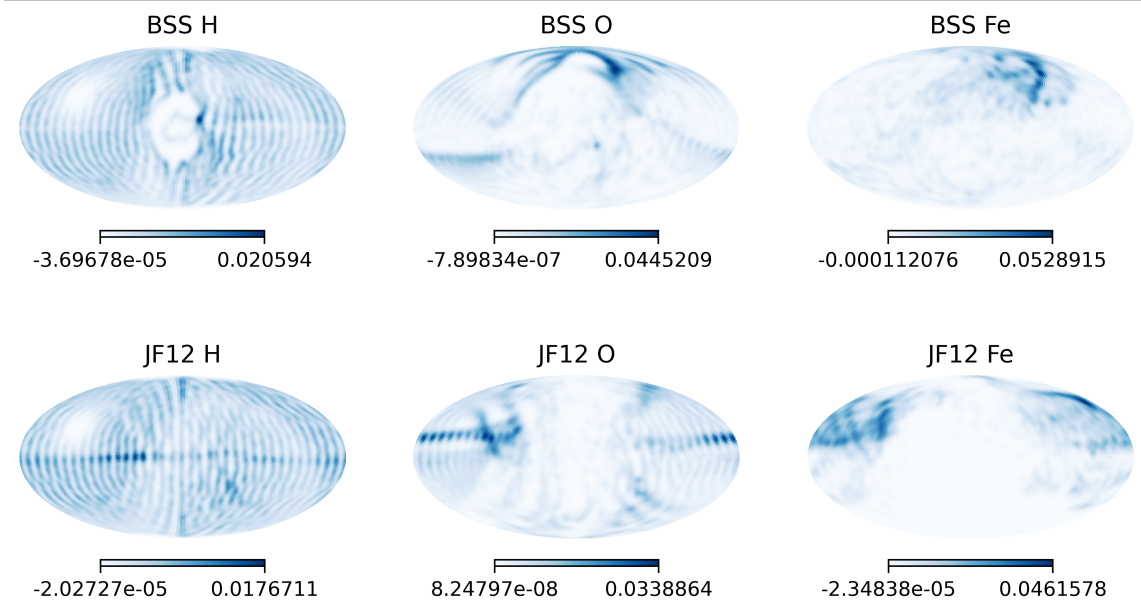


Figure 4.1.1: Normalized density maps of the GMF-corrected directions of the 303 grids of UHECRs, all added together in each panel, with uniformly distributed Earth-arrival directions; each grid had energy equal to the energy of one of the UHECRs of the sample.

with little exposure and others that are completely missed by the GMF and from which UHECRs should never reach Earth if this GMF model is assumed.

Chapter 5

Anisotropic maps and correlations

After considering the effects of the magnification and bias of some regions in the UHECR sky outside the galaxy due to the GMF, the smoothed density map of each anisotropic model was created to compare it with the distribution of the UHECR out-of-Galaxy directions.

5.1 Catalogs and weighting

As mentioned in subsection 3.4 the UHECR distribution (either Earth-arrival or out-of-Galaxy directions) is compared to a sky distribution model composed of an isotropic and an anisotropic fraction. The fraction of the anisotropic model and the smoothing (σ) applied to it are varied to find the maximum value and hence the best test statistic.

The anisotropic fraction is multiplied with the anisotropic smoothed (with σ) density model, in which each direction or pixel has assigned a probability of detecting a UHECR. To create the anisotropic sky model four catalogs were considered: the catalog of radio galaxies with radio fluxes and radio luminosities (van Velzen et al., 2012) (hereafter Vanv), the SWIFT-BAT catalog of hard X-ray sources (only Seyfert, LINERs, and other AGNs were selected from this catalog) (Oh et al., 2018), the Super Massive Black Holes (SMBH) catalog of Hernández-Yévenes et al. 2024 (submitted) which contains SMBH masses and stellar masses (SM) of the associated galaxy, and the Nearby Galaxy Catalog (Karachentsev et al., 2013) which contains positions and distances of galaxies with distance less

than 25 Mpc.

The mass estimates of SMBH used in this work come from the WISE2MBH catalog of Hernández-Yévenes et al. 2024 (submitted), which used a scaling-based algorithm to estimate the mass of SMBH using the WISE photometric bands W1, W2, and W3. These estimates were obtained using WISE magnitudes to estimate the total stellar mass of a galaxy, a bulge-to-total ratio from morphology or WISE color, and combining this to obtain the bulge mass. Finally, the bulge-mass-black hole-mass (MBulge-MBH) scaling relation is used to estimate the MBH. These estimates showed good accuracy compared to a control sample of the measured MBH, making it a good sample for our purposes.

5.1.1 SFR and SM estimations

We used equations from Cluver et al. (2014) to compute the SFR and SM of all galaxies in the Nearby Galaxy Catalog of Karachentsev et al. (2013) and add SFR values to the SMBH catalog. For this, WISE-photometry data has been used to obtain WISE-derived SFR and SM following equations of Cluver et al. (2014) using the best fit of their entire sample:

$$\log_{10} M_{\text{stellar}}/L_{W1} = -2.54(W_{3.4\mu\text{m}} - W_{44.6\mu\text{m}}) - 0.17 \quad (5.1.1)$$

with $L_{W1}(L_{\odot}) = 10^{0.4M_{\text{sun}}}$, where M is the magnitude in the W1 band and $M_{\text{sun}} = 3.4$.

The star formation rates were derived from Cluver et al. (2017), as in the case of Jarrett et al. (2019):

$$\log_{10} \text{SFR}_{\text{TIR}}(M_{\odot}/\text{yr}) = 0.873 \times \log_{10} \nu_{12\mu\text{m}}(L_{\odot}) - 7.62 \quad (5.1.2)$$

Here $\nu_{12\mu\text{m}}$ is the spectral luminosity, normalized by the solar luminosity $L_{\odot}$, and the stellar continuum is removed using the W1 luminosity as a representative of the stellar continuum (15.8% in the W3 band). The integrated flux of the extended galaxies was obtained from the WISE extended source catalog (WXSC) (Jarrett et al., 2019).

5.2 Correlations and Statistics

5.2.1 UHECR sample

The sample of UHECR consists of a total of 303 UHECR (same as in [Sotomayor Webar et al. \(2023\)](#)): 231 detected by PAO between January 2004 and March 2014 ([Aab et al., 2015](#)), and 72 UHECR detected by TA between May 2008 and May 2013 ([Abbasi et al., 2014](#)) with energies between 50.32 EeV and 148.76 EeV.

In addition to the +5.2% for PA and −5.2% for TA energy scale corrections, we corrected the published energies of the TA and PAO UHECRs by +10% / decade for PA and −10% / decade for TA beginning at 10 EeV following the recommendations of the PAO-TA energy spectrum working group ([AbuZayyad et al., 2019](#)).

5.2.2 Weight attenuation

The factor $w(\hat{s}_i)$ in Equation 3.4.2 is the weight chosen for each catalog, multiplied by an attenuation factor that was considered as the fraction of UHECR produced above a given energy threshold that can reach Earth from a source at a distance D with energy still above that same threshold.

We used Figure 2.2.3 (which reflects the results obtained by [Allard et al. \(2008\)](#)) to obtain the attenuation factor as a function of distance for an oxygen composition. A digitized version of their curve was used to assign the attenuation factor, as a function of distance, to each of our sources.

5.2.3 Test statistic profile

The TS was calculated with the search radius σ and the anisotropic fraction f_{aniso} as free parameters. The TS profile was constructed for $0.1 \leq \sigma \leq 20$ degrees and $0 \leq f_{aniso} \leq 1$ for each astronomical sample (repeated using different source weighting schemes and out-of-galaxy directions for each GMF model).

The confidence level intervals for each TS profile were calculated at 60, 95, and 99 percentiles. First, a parameter is fixed to the value that maximizes the TS, and the other is iterated on a fine grid until the TS maximizes. Later, the TS is calculated with $\pm$ twice the parameter error obtained in the iteration. With

the 3 points obtained in the last steps (a maximum TS and the two obtained by adding the error in the parameter), the curve is optimized. Assuming a chi-squared distribution for the TS, the minimum and maximum values of each confidence level interval are computed.

The exact process is repeated for the other parameter. With the pre-intervals obtained, a square matrix of TS values is calculated, with steps in f_{aniso} and σ values equally divided. Then, the confidence contours at 90, 95, and 99 percentile are computed for the TS matrices.

Chapter 6

Analysis

In this section, we present an analysis of the out-of-galaxy arrival direction distributions and the results of the correlations.

6.1 Out-of-Galaxy focal points

As expected, from Figure 4.1.1, the GMF acts as a lens whose properties change with rigidity, showing mirror images and magnification regions. For a hydrogen composition, the out-of-Galaxy directions do not present strong magnification regions; if the BSS model is considered, the Galactic center is suppressed. However, with oxygen composition, the Galactic center is strongly suppressed in both GMF models. With the BSS model, a magnification region in the northern region of the sky is seen, and with the JF12 model two opposite magnification regions are formed closer to the Galactic equator. For an iron composition, which has the lowest rigidity considered, the out-of-Galaxy directions are strongly deflected and anisotropic, producing a single 'hot spot' in the north (BSS) or anti-Galactic center (JF12).

6.2 Update of maximum likelihood test with TA and PAO

In subsection 3.4.1 we showed the TS profile obtained by (Abreu et al., 2010) for Earth-arrival UHECR in an early release of PAO, and the 2MRS and SWIFT-BAT

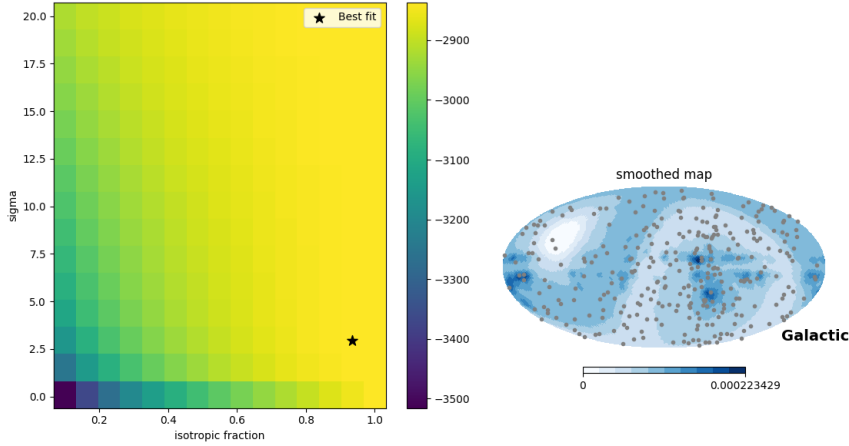


Figure 6.2.1: Left: Test statistic profile as a function of sigma and isotropic fraction for the 2MRS catalog. The values that maximize the TS are plotted with a black star ($\sigma = 2.9^\circ$ and $f_{iso} = 0.9$). The likelihood calculation uses the Earth-arrival directions of the full UHECR sample used in this work. Right: Smoothed density map considering the K-band flux from 2MRS catalog as the anisotropic component. The map is constructed using the best parameters found in the left panel.

samples. Here we use the updated PAO and TA UHECR list and the updated SWIFT-BAT catalog to update the TS profiles and results.

A new smoothed density map and TS test were computed for the full sample of 303 UHECRs comparing Earth-arrival UHECR directions with the anisotropic component following the 2MRS model (Fig. 6.2.1) and the SWIFT model (Fig. 6.2.2). In both cases we used the same source weighting used by (Abreu et al., 2010): the K-band flux for 2MRS and the hard X-ray flux for SWIFT.

In the case of the 2MRS model, the additional PAO UHECR and the TA UHECR changes the correlation: a slightly larger isotropic fraction now maximizes the TS. On the other hand, in the case of the SWIFT-BAT model, the isotropic fraction remains almost the same as the previous result, but the sigma increases by about 10 degrees.

Overall, neither the 2MRS (large isotropic fractions are favored) nor the SWIFT (large smoothing is required to correlate the directions of the UHECR and sky sources) can provide a satisfactory explanation as the origin of UHECR.

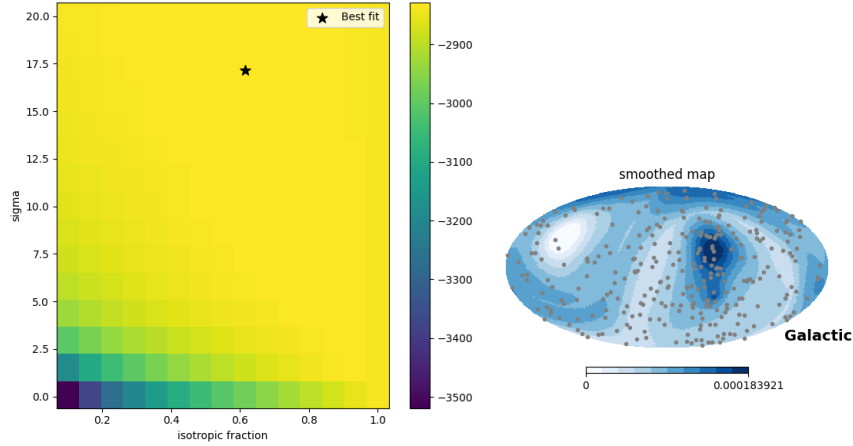


Figure 6.2.2: Same as Figure 6.2.1, but for the SWIFT-BAT catalog. The values that maximize the TS are $\sigma = 17.4^\circ$ and $f_{iso} = 0.6$.

6.3 Smoothed density maps

An example of the generation of the smoothed density map or probability map for the sky distribution is shown in Figure 6.3.1. In this specific case, we use the SMBH catalog supplemented by the Nearby Galaxy catalog. These maps are created using Equation 3.4.1, where each $\hat{n}$ direction or pixel had assigned a pixel of the exposure map (already normalized by the minimum exposure of the UHECR sample), and later the probability $F(\hat{n})$ is computed in each direction. The underlying color map in the left panel shows the exposure map (BSS GMF and oxygen composition), and the catalog sources are plotted as stars with sizes proportional to their weight (in this case SFR) attenuated by a factor for oxygen composition which traces the energy losses suffered by the UHECR during intergalactic propagation.

The equivalent (i.e. as in the right panel of Fig. 6.3.1) probability maps created with an anisotropic fraction of 1 and a search radius (sigma) of 5 degrees, for all the other anisotropic models used by us, are presented in Figure 6.3.2. Here as in Fig. 6.3.1 the extragalactic exposure map is used in the generation of the smoothed density map. The smoothed maps of the different sky models are all significantly different, though the presence of Cen A and the supergalactic plane can be noticed in several of the models. The stellar mass model obviously most clearly traces the supergalactic plane, and Cen A is dominant as the dominant hot-spot in hard X-ray and radio smoothed maps.

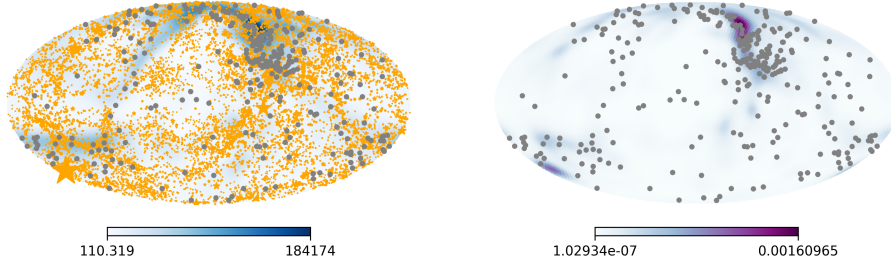


Figure 6.3.1: Left: Illustration showing the generation of smoothed density maps. The extragalactic exposure density map (for the BSS GMF model and oxygen composition) is shown in color following the color bar beneath the panel. Astronomical sources from the SMBH and Nearby Galaxy sample are over-plotted as yellow stars with area proportional to the SFR attenuated with a factor depending on the source distance and for an oxygen UHECR composition. Right: The smoothed density map (using the exposure map and sources of the left panel) is shown in color following the color bar beneath the panel. Source flux is smoothed with a sigma of 5 degrees and an anisotropic fraction of 1 is considered. In both panels, the out-of-galaxy arrival directions of UHECR (for the BSS GMF model and oxygen composition) are over-plotted as grey dots.

If the extragalactic exposure map is not used (i.e. if each pixel has the same exposure weight), then the smoothed density maps can change significantly: these are shown Figure 6.3.3. The SMBH model changes the most when the exposure map is considered or not, though all models show subtle changes with or without exposure maps taken into account.

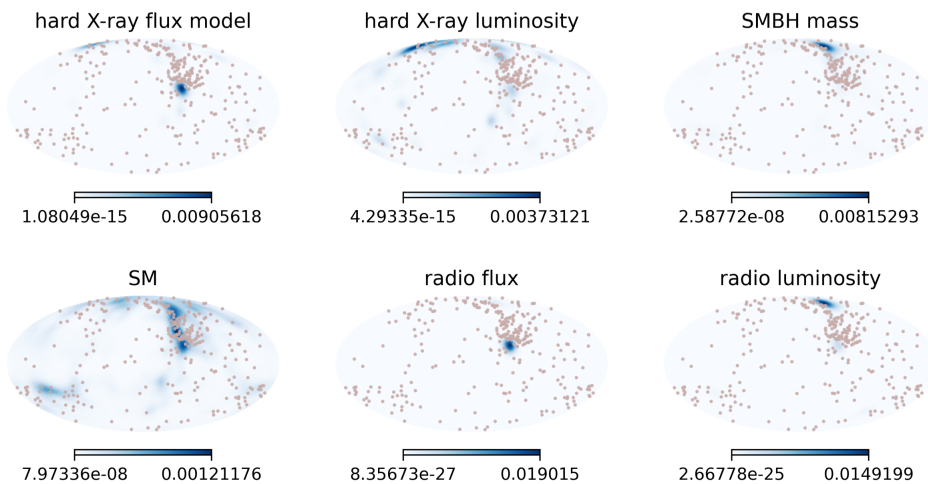


Figure 6.3.2: Smoothed density map (same as the right panel of Figure 6.3.1) but for the other anisotropic models used by us.

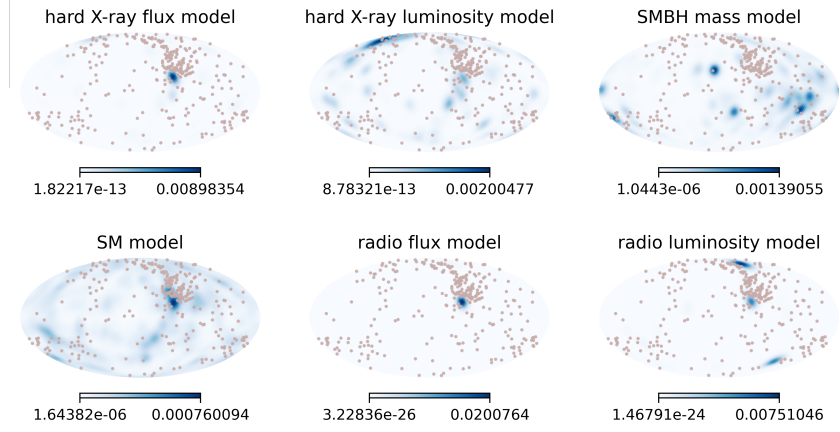


Figure 6.3.3: Same as Figure 6.3.2 but here the extragalactic exposure map is not used, i.e. each pixel has the same exposure weight.

6.3.1 Final test statistic profiles

After obtaining the smoothed density maps, a likelihood can be calculated using the probability that these maps provide in the direction of the UHECRs, one associated with the anisotropic model, and another for the isotropic model. Finally, the test statistical compares these two likelihoods. The value of the test statistic was calculated as described in Subsection 5.2.3, producing TS profiles that vary with the sigma and anisotropic fraction.

The TS profile with contours of the 68, 95, and 99 confidence levels are plotted, and smoothed maps with the parameters that maximize TS are shown, in Figures 6.3.4, 6.3.6, 6.3.5 and 6.3.7 as examples of different anisotropic models.

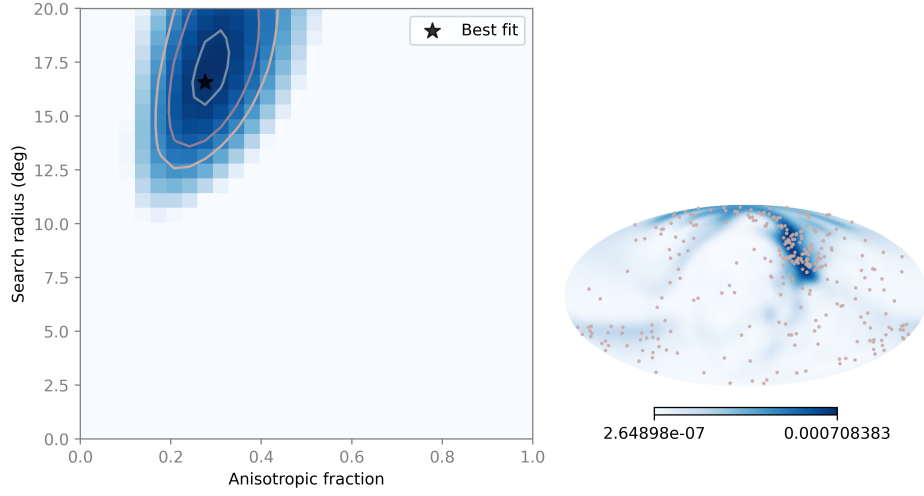


Figure 6.3.4: TS profile and smoothed density map for the hard x-ray flux, BSS GMF, and oxygen composition. Left: TS profile for each combination of sigma and anisotropic fraction values. The values which maximize the TS are shown with the black star, and the 68, 95, and 99 confidence intervals are plotted. Right: Smoothed density map generated with the parameters that maximize the TS and the hard X-ray model. The out-of-galaxy arrival directions of the 303 UHECR are over-plotted as gray dots.

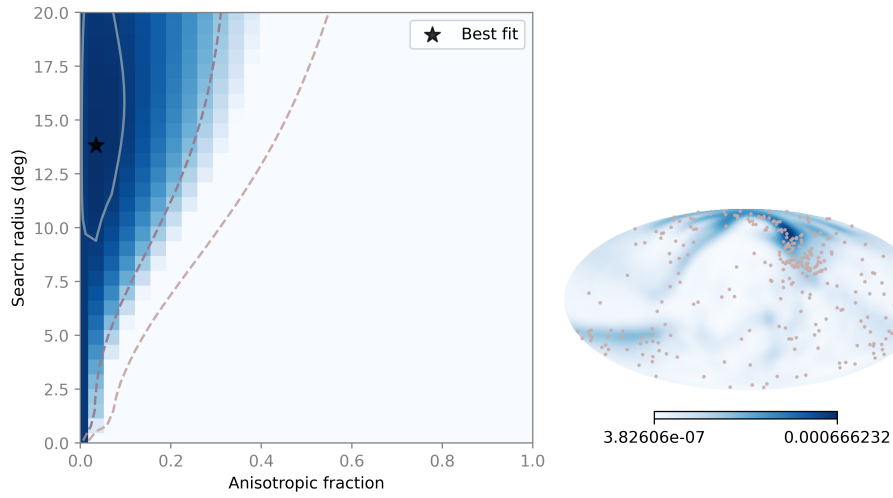


Figure 6.3.5: Same as 6.3.4 but for hard X-ray luminosity.

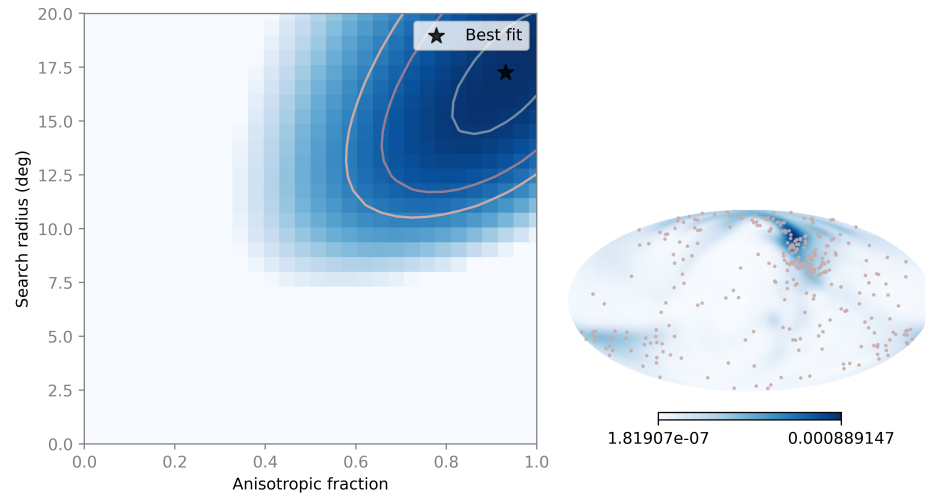


Figure 6.3.6: Same as 6.3.4 but for SFR.

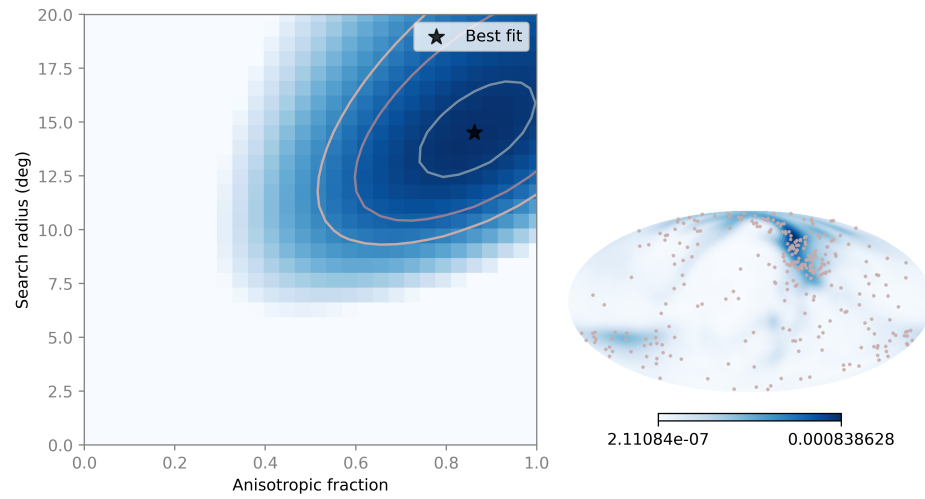


Figure 6.3.7: Same as 6.3.4 but for SM.

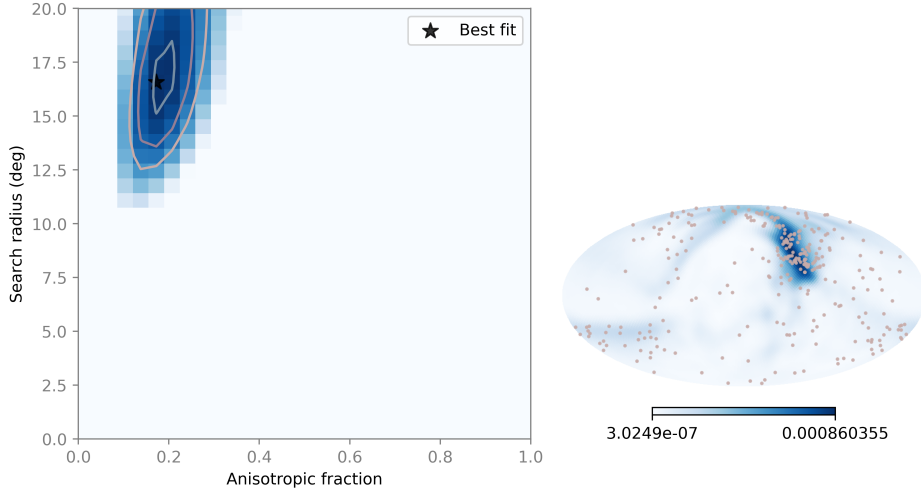


Figure 6.3.8: Same as 6.3.4 but for radio flux.

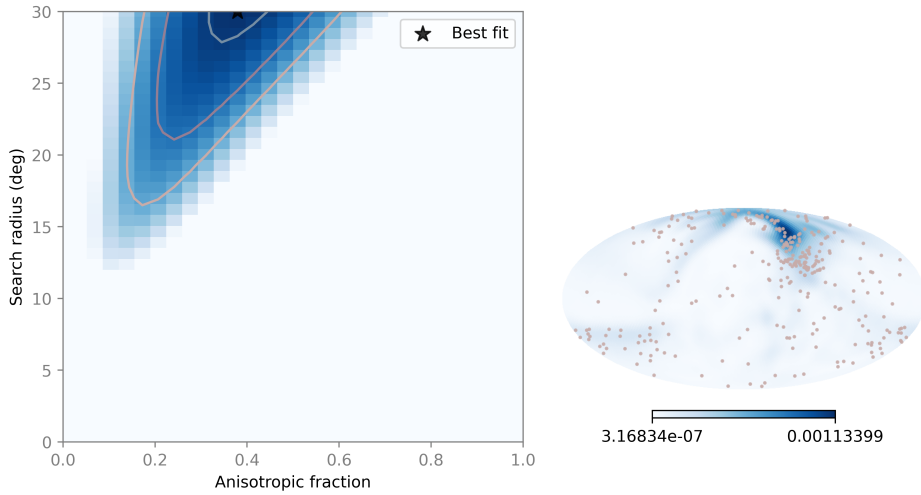


Figure 6.3.9: Same as 6.3.4 but for radio spectral luminosity.

6.3.2 Summary of TS Results

A summary of the results of the maximum likelihood analysis for an oxygen composition, the BSS model, and all sky models used, is presented in Table 6.3.1.

Table 6.3.1: Results for oxygen composition and BSS GMF model.

Test	TS	f_{aniso}	Search
Hypothesis			radius
hard X-ray flux	70.73	0.27	17.25
hard X-ray luminosity	0.76	0.034	13.82
SFR	54.53	0.93	17.25
SM	56.44	0.82	14.51
radio flux	87.94	0.17	16.56
radio luminosity *	33.36/39.43	0.2/0.37	20/30
SMBH *	16.78 /21.97	0.27/0.44	20/30

* The TS is maximized at the boundary of the sigma range. We thus quote the results separately for two different maximum search radii (20 and 30 degrees).

The first results to highlight here are those for the SFR and SM models. Here the TS is reasonably low (~ 55), the anisotropic fractions high (~ 0.85) and the smoothing required is not too high (~ 16 deg; reasonably within the errors of deflection calculations). Thus out-of-galaxy arrival directions could be well explained by originating in nearby (due to attenuation) galaxies weighted by stellar mass or star formation rate. The hard X-ray flux and radio flux models provide higher TS values and significantly lower isotropic fractions (0.17 and 0.27), at similar smoothing. These are thus not favored as an originating population in the current scenario of oxygen composition and the BSS model. For the hard X-ray luminosity model we get a very low TS; here however the test favors an isotropic model. In the case of the SMBH and the radio luminosity models, the maximal likelihood is achieved at the highest values of sigma explored, and the anisotropic fraction increases with increasing sigma. This happens when exploring out to a maximum of sigma = 30.

A summary of the equivalent results for an oxygen composition and the JF12 GMF model is shown in Table 6.3.2. Here we also find consistency between the UHECR distribution and the SFR and SM sky models, but for a larger radius and lower values of TS as compared to the BSS model.

Table 6.3.2: Results for oxygen composition and JF12 GMF model.

Test	TS*	f_{aniso}	Search
Hypothesis			radius
hard X-ray flux *	3.13/8.17	0.06/0.2	20/30
hard X-ray luminosity	0.1	0	0
SFR	17.16	0.55	18.46
SM *	11.68/12.88	0.55/0.82	20/30
radio flux *	4.12/10.3	0.06/0.12	20/30
radio luminosity *	8.27/16.72	0.15/0.27	20/30
SMBH mass *	11.18	0.34	26.16

* The TS is maximized at the boundary of the sigma range. We thus quote the results separately for two different maximum search radii (20 and 30 degrees).

6.3.3 Significance of the TS results

To determine the significance of the results in the previous sub-section, we require Monte Carlo simulations. Here the analysis in the previous subsection is repeated 100,000 times, each time with 303 MC-generated UHECR directions, and for both an 'isotropic' distribution and for the best fit sky model distribution. The difference is that we keep the log likelihood value instead of the TS. For each of these MC simulations we calculate the mean (per UHECR) log likelihood (eqn. 3.4.3). Histograms of the resulting mean log likelihoods for the isotropic models and the sky models (Fig. 6.3.10) can be compared with the likelihood obtained in the previous section.

For the 'isotropic distribution', the 303 UHECR positions are chosen randomly from the isotropic model (which considers the observatory Earth-exposure map). For the best fit sky model, 303 positions are randomly picked based on the density of the best fit sky model (which includes the exposure map, the isotropic and anisotropic best fractional maps).

When the best fit sky model is relatively uniform in probabilities each MC iteration produces relatively different positions for the 303 generated UHECR positions. However, as can be seen in Fig. 6.3.2 the best fit sky models are often highly non-uniform with a few hot-spots which dominate. This distribution with a few extremely high probability pixels compared to the majority of the values pixels, means that multiple MC iterations tend to produce very similar UHECR positions,

and produce an overestimation of the mean log-likelihood of the distributions (compared with the data). To address this, the number of UHECR directions generated in each MC iteration was increased until the mean of the isotropic model histogram matches the isotropic mean log-likelihood of the data. But when doing this, the difference between the isotropic and anisotropic distributions become substantial in the majority of the cases. Both distributions (when using 303 UHECRs and 1150 UHECRs) are shown in Figures 6.3.10, 6.3.11, 6.3.12, 6.3.13, 6.3.14 and 6.3.15 for different sky models. Better methods to choose the 303 MC UHECR directions in a way that is more similar to the observed 303 UHECR direction data are being evaluated.

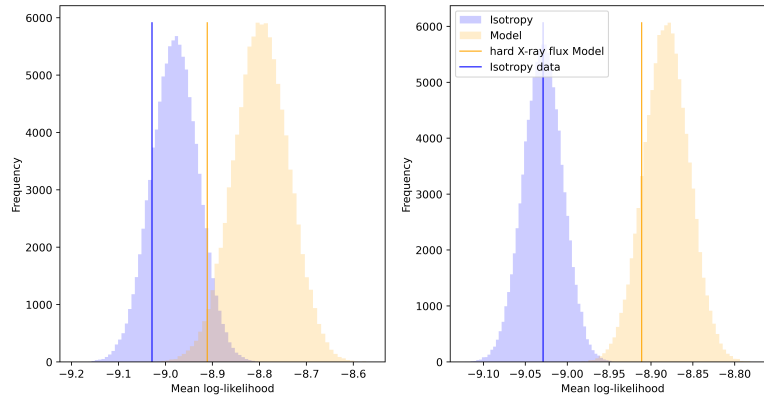


Figure 6.3.10: Left: Histograms of the mean (per UHECR) log likelihood in the best-fit sky (yellow) and isotropic (blue) models choosing the same number of UHECRs as the data. One hundred thousand Monte Carlo iterations were used. The mean log-likelihood found for the data (previous section) is over-plotted with solid lines in the corresponding color. The anisotropic component of the best fit sky model here is the hard X-ray flux model. Right: The same as in the left panel but using 1150 UHECR in each MC iteration in order to match the mean log-likelihood of the isotropic model with the mean log-likelihood for isotropy of the data.

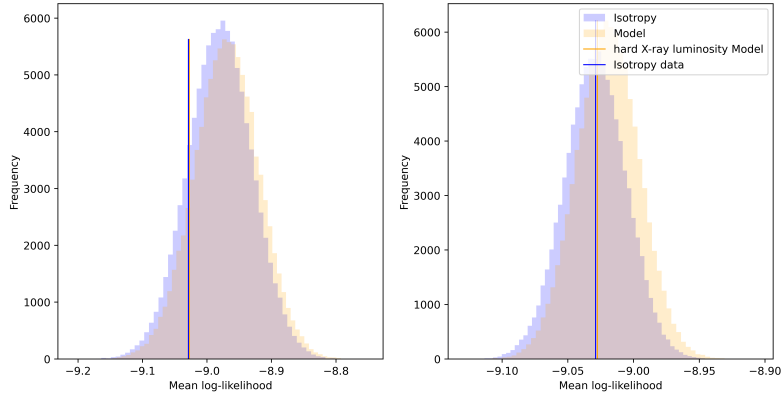


Figure 6.3.11: As in 6.3.10 but for the hard X-ray luminosity model.

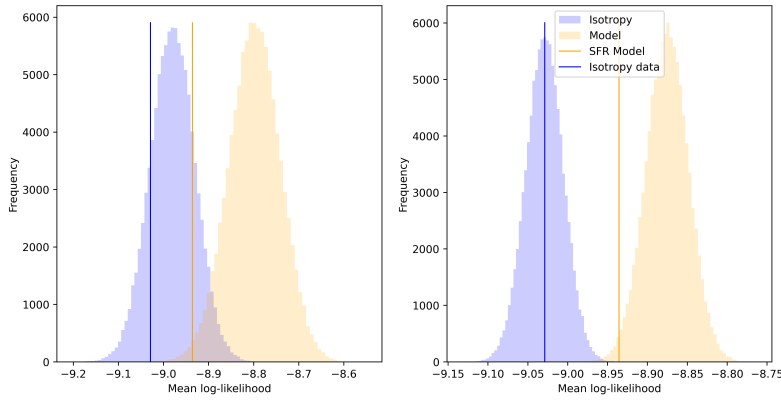


Figure 6.3.12: As in 6.3.10 but for the SFR model.

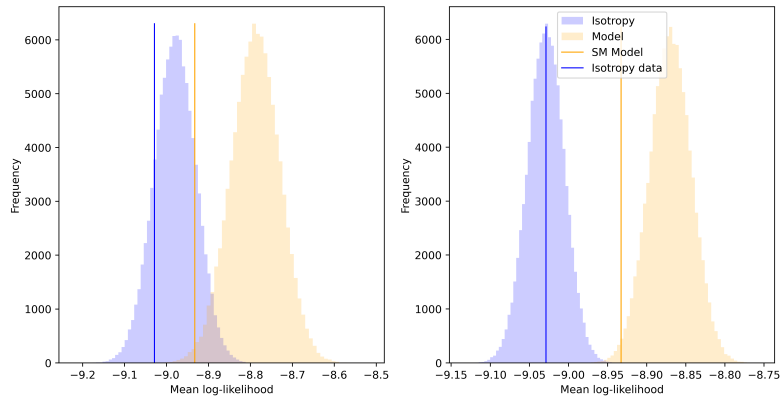


Figure 6.3.13: As in 6.3.10 but for the SM model.

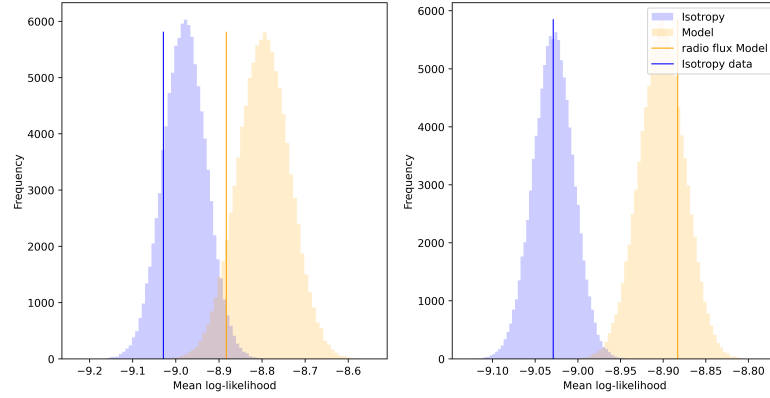


Figure 6.3.14: As in 6.3.10 but for the radio flux model.

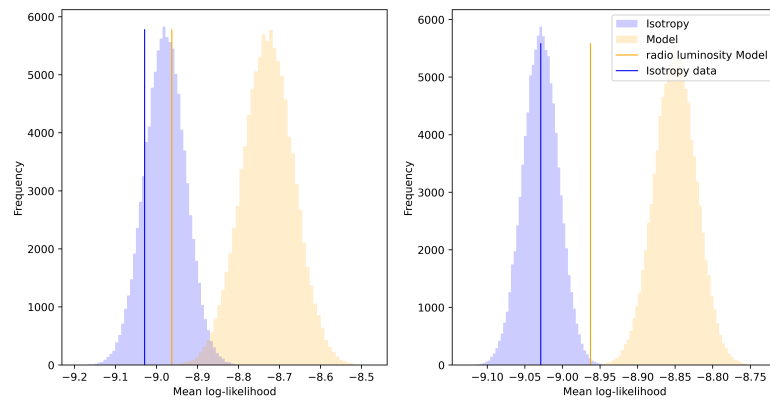


Figure 6.3.15: As in 6.3.10 but for the radio luminosity model.

Chapter 7

Discussion and Summary

This thesis aims to find a distribution of astronomical sources, weighted by properties that are considered proportional to their UHECR flux, which is most consistent with the arrival directions of UHECR observed by PAO and TA (with or without correction for Galactic magnetic field deflections; though with a focus on the latter).

We specifically focus on an oxygen composition motivated by three factors: (a) the results of [Sotomayor Webar et al. \(2023\)](#) who found that for an oxygen composition and the BSS model, a large fraction of the out-of-galaxy UHECR arrival directions aligned closely with the supergalactic plane; (b) the composition results of PAO and TA that suggest an increase in mean mass $A \approx 14 - 20$ with energy, at energies greater than 40 EeV ([Aab et al. \(2017a\)](#); [Abbasi et al. \(2018b\)](#)). This would imply a changing proportion of H and Fe or the presence of intermediate mass nuclei; (c) the fact that correlations of intermediate-mass UHECR with astronomical samples have not been extensively explored in the literature.

Since intermediate mass UHECR suffer relatively large ($\gg 10$ degrees) systematic deflections in most posited GMF models, directly comparing earth-arrival UHECR directions to astronomical samples with tests like TS and maximum likelihood is difficult. These are forced to use increasingly larger smoothing parameter (sigma) values to compensate for (deflection-created) offsets between UHECR and sky objects. But since the deflections are systematic and different for different regions of the sky, a symmetrical smoothing with sigma would be unable to compensate for the deflections. In this thesis, we thus focus on comparing deflection-corrected

(i.e. out-of-galaxy) arrival directions of UHECR with astronomical samples. Here, of course, a correct GMF model is critical. In the absence of this, one requires to explore all current GMF models.

Monte Carlo back-tracking was performed with all the GMF models used in [Sotomayor Webar et al. \(2023\)](#) and hydrogen, oxygen, and iron UHECR compositions. The Monte Carlo method takes into account the errors in each UHECR energy, and errors in GMFs. As expected, the deflections for a hydrogen composition are a few degrees; for oxygen and iron, the increased charge, thus decreased rigidity, generates larger deflections. The deflection calculations on uniform grids of earth-arrival direction UHECRs were used to convert the earth-exposure map of PAO and TA to out-of-Galaxy exposure maps for each GMF and composition. Here, highly anisotropic extragalactic exposure maps are found. Deflection calculations were also performed for the Earth-arrival directions of the 303 detected UHECR in the combined PAO and TA sample.

The BSS and JF12 models for the oxygen composition were tested for correlation with different astronomical models using a test statistic approach that compares an isotropic model with the anisotropic model (the astronomical sample). The TS method of comparing two models can be a great tool for identifying whether any anisotropic distribution is consistent with the UHECR distribution. In this case, the UHECR distribution outside the galaxy is anisotropic depending on the assumed composition and the GMF model. The deflections due to the GMF produce magnification and suppression regions that bias some regions.

Under the assumption that the UHECR composition is oxygen and the GMF follows the BSS model, an anisotropic distribution of nearby galaxies weighted by either their SFR or SM is consistent with the out-of-galaxy arrival directions of the UHECR sample. Other sky models, such as the hard X-ray flux, hard X-ray luminosity, radio galaxy luminosity and flux, and SMBH mass, show similarity with the extragalactic exposure map, but overall are not as correlated with the UHECR arrival distributions - in these cases the TS implies lower fractions of UHECRs can be explained with the sky model, and larger fractions with an isotropic distribution. The radio luminosity and SMBH mass sky models require large values of sigma to reach a considerable level of anisotropy.

For the oxygen UHECR composition and the JF12 GMF model, nearby galaxies,

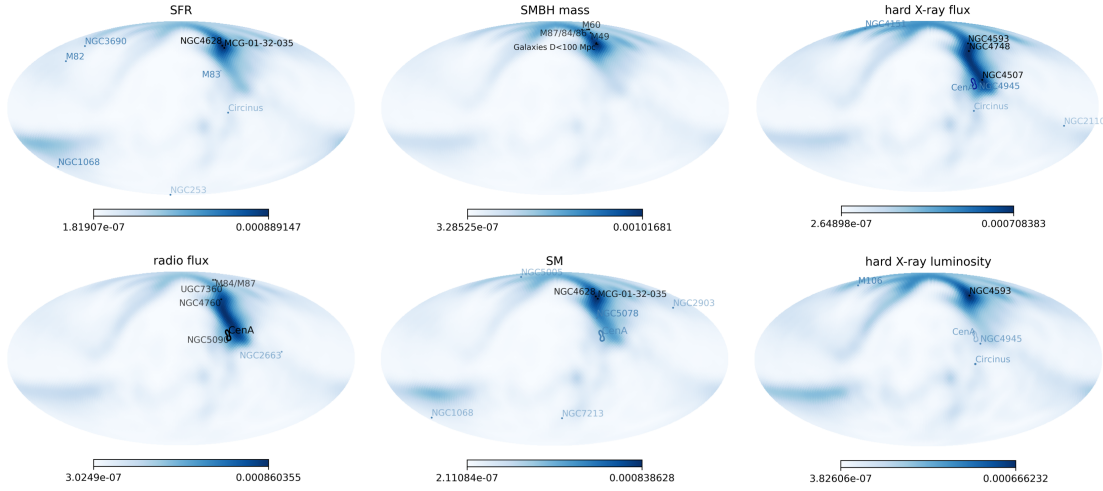


Figure 7.0.1: The smoothed density maps generated with the parameters that maximize the TS in the different models are shown in color following the color bar beneath the panels, using oxygen UHECR and the BS-S GMF model. The names of the main contributors are overplotted, with black letters if the source contribution is high after applying the exposure map, and with lighter blue letters if a source was a main contributor before applying the exposure map and later the GMF model suppresses the sources.

weighted by SFR or SM are once more most consistent with the UHECR arrival directions, but the fraction of anisotropy required is lower than in the case of the BSS GMF. For the other sky models, the TS supports large isotropic fractions. As for the BSS GMF, the radio luminosity and SMBH mass sky models require large values of sigma to reach a considerable level of anisotropy; for JF12 the hard X-ray flux joins this category. Further, the TS test between the hard X-ray luminosity sky model and UHECR directions does not give a meaningful result.

The main contributors in the different sky models are Circinus galaxy, M83, NGC 253, NGC 1068 (M77), NGC 3690 and M82, NGC 7213, Cen A, NGC 5078, NGC 2903, NGC 5005, M74, M87, M81, and NGC 5090. See Figure 7.0.1.

7.1 Further analysis

The likelihood ratio test is sensitive to whether the UHECR direction lies in a high-density region of the sky model. Other methods can be used to test the general proportionality between the sky distribution and the models, [Pierre Auger Collaboration and Aublin \(2009\)](#) have created a method based on smoothed density maps that simultaneously tests the correlation and intrinsic clustering of

the data compared to the models. Another promising examination is to analyze the directions with the greatest contribution and obtain the cumulative number of events as a function of the angular distance from the direction of a special source as in [Sotomayor Webar et al. \(2023\)](#) and [Abreu et al. \(2010\)](#).

Even if the likelihood ratio test does not provide quantitative proof of anisotropy, it does identify which models of the distribution of matter in the nearby universe are consistent with the anisotropic distribution of UHECRs or, in the isotropic case, can be explained by the GMF deflection itself.

The attenuation factor used assumes that UHECRs arrive at Earth with energies above 60 EeV. Still, in reality, UHECRs arrive with different energies, therefore the weight in the smoothed density maps of the models needs to be adjusted. Thus, a more correct and probabilistic method is required to be chosen to add an attenuation factor in the direction of the sources.

The estimates shown in this work require further analysis and refinement. While they do not definitively prove the presence of anisotropy, they indicate consistency between the UHECRs distribution and matter distribution in the nearby universe.

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