

Ultra-High Energy Cosmic Rays Detected by Auger and AGASA: Corrections for Galactic Magnetic Field Deflections, Source Populations, and Arguments for Multiple-Components

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ABSTRACT

Context. The origin and composition of Ultra-High Energy Cosmic Ray Events (UHECRs) are under debate. Possible sources include Active Galactic Nuclei - selected by various criteria - and extragalactic magnetars.

Aims. We aim to improve constraints on the source population(s) and compositions of UHECRs by accounting for UHECR deflections within existing Galactic magnetic field models (GMFs).

Methods. We used Monte Carlo simulations for UHECRs detected by the Pierre Auger Observatory and AGASA, to determine the UHECR trajectories within the galaxy and their outside-the-Galaxy arrival directions. The simulations, which used UHECR compositions from protons to Iron and seven models of the ordered GMF, accounted for uncertainties in the GMF and a turbulent magnetic field component. The trajectories and outside-the-Galaxy arrival directions were compared with Galactic and extragalactic sources.

Results. For a given proton or light UHECR, the multiple potential outside-the-Galaxy arrival directions within a given GMF model are not very different, allowing meaningful constraints on source populations. The correlation between a subset of UHECRs and nearby extended radiogalaxies (Nagar & Matulich 2008) remains valid, even strengthened, within several GMF models. Both the nearest radiogalaxy Cen A, and the nearest radio-extended BL Lac, CGCG 413-019, are potentially sources of multiple UHECRs. The correlation appears to be linked to the presence of the extended radio source rather than a tracer of an underlying matter distribution. Several UHECRs have trajectories which pass close to or through the Galactic plane, some passing close to Galactic magnetars and/or microquasars. For heavier UHECRs, the multiple potential outside-the-Galaxy arrival directions of any given UHECR are highly scattered but still allow meaningful constraints. It is possible, but unlikely, that all UHECRs originate in the nearby radiogalaxy Cen A.

Conclusions. Nearby radiogalaxies remain a strong potential source of a significant subset of UHECRs. For light UHECRs about a third of UHECRs can be “matched” to nearby galaxies with extended radio jets. The remaining UHECRs could also be explained as originating in extended radiogalaxies if one has at least one of: a large UHECR mean free path, a high cluster and/or intergalactic magnetic field, a heavy composition for two-thirds of the detected UHECRs. If extended radiogalaxies are, or trace, UHECR sources, the most consistent models for the ordered GMF are the BS-S and BS-A models; the GMF models of Sun et al. 2008 are acceptable if a dipole component is added.

Key words. interstellar-medium: Cosmic Rays – interstellar-medium: Magnetic Fields – Galaxies: Active – Galaxies: jets;

1. Introduction

Ultra-High Energy Cosmic Rays (UHECRs) are protons or fully ionized nuclei with energies greater than about 10^{19} eV (10 EeV). On entering the earth’s atmosphere they produce a shower of secondary particles and excite atmospheric molecules. The detection of both effects from the ground allows a precise measurement of both the initial energy and the arrival direction of the UHECR above the earth’s atmosphere e.g. AGASA (Takeda et al., 1999) and the Pierre Auger Observatory (Pierre Auger Collaboration et al., 2004). The resultant positional accuracy of the earth-arrival direction,

now better than a degree, allows correlations with astronomical sources in order to determine the source population(s) of UHECRs - a long held mystery. Exploiting the full potential of the earth-arrival directions nevertheless requires taking into account deflections suffered due to Galactic and extragalactic magnetic fields.

Suspected sources of ultra high energy cosmic rays include powerful active galaxies, magnetars, core collapse Supernovae (SN II), and gamma rays bursts (for reviews and lectures see Hillas (1999); Kachelriess (2008) and references therein). Specifically, an origin in nearby radiogalaxies and BL Lacs has long been predicted (Rachen & Biermann, 1993; Romero et al., 1996). More exotic explanations include dark matter annihi-

lation and evaporation of micro black holes. The main energy loss for a UHECR propagating over cosmological distances is expected to be pion-production triggered by interaction with a CMB photon, the so called Greisen Zatsepin Kuzmin (GZK) effect (Greisen, 1966; Zatsepin & Kuzmin, 1966). The predicted energy loss (around 30%) and mean free path of the UHECR (\sim 20–100 Mpc) depend on the composition and energy of the UHECR and details of the collision process, e.g. the photo-proton cross section (see e.g. Stanev (2004); Kachelriess (2008); PA08).

The Pierre Auger Observatory (PAO) has detected 81 events between 2004 January 1 and 2007 August 31 with reconstructed energies above 40 EeV and zenith angles smaller than 60° ; of these, 27 have energies above 56 EeV and have been reported in Pierre Auger Collaboration et al. (2007, 2008, hereafter PA07, PA08). The origins of the latter 27 UHECRs, together with 11 UHECRs detected by AGASA at energies above 56 EeV (Hayashida et al., 2000) are the focus of this paper. The PAO has since detected additional UHECRs (The Pierre Auger Collaboration et al., 2009a,b, hereafter PA09a, PA09b) but detailed positions and energies are not yet published. In this work we use “UHECR” to refer to UHECRs with energy above 56 EeV unless explicitly mentioned otherwise. The compositions of the detected UHECRs are still under debate (e.g. PA09a; PA09b; Matthews, 2007; Hooper & Taylor, 2009) with evidence for a mix of protons and heavy nuclei at the highest energies. There has been recent doubt about the measured energies of the UHECRs detected by PAO and AGASA. The PAO team have lowered their previous reported energies by a small percentage (PA09a, PA09b) and there have been suggestions that energies reported by AGASA should be lowered by up to 30%. To avoid confusion we report our results separately for PAO and AGASA UHECRs. Several other UHECR observatories, e.g. Haverah Park and Fly’s Eye, have detected a significant number of UHECRs: given that the GMF deflection calculations and source matching in this work require accurate energies ($\lesssim 10\%$) and arrival directions ($\lesssim 2^\circ$) we do not include their results in our analysis.

The arrival directions of the 27 UHECRs detected by PAO are not isotropic at a 99% significance level (PA07, PA08, PA09a, PA09b). Several correlations, or lack thereof, with extragalactic sources have been suggested: AGNs from the catalog of Véron-Cetty & Véron (PA07, PA08), hard X-ray selected AGNs (George et al., 2008), nearby extended radio galaxies (Nagar & Matulich, 2008), nearby spiral galaxies (Ghisellini et al., 2008), local volume galaxies (Cuesta & Prada, 2009) and large scale structure (Ryu et al., 2009).

Galactic and extragalactic magnetic fields deflect cosmic rays via the Lorentz force even at energies above 56 EeV. If the extragalactic field is unordered over large scales the expected deflections for these energies are only a few degrees (e.g. Harari et al., 2002; Dolag et al., 2004). An ordered Galactic Magnetic Field (GMF) can, however, produce significant deflections (e.g. Takami & Sato, 2008) especially on trajectories which pass close to the Galactic plane and/or for heavy composition UHECRs.

The line of sight integrated GMF of the Galaxy has been measured in various directions via e.g. the rotation measures

of pulsars and extragalactic radio sources, and polarization of starlight or radio synchrotron emission (e.g. Heiles, 1996; Brown et al., 2007; Noutsos et al., 2008; Sun et al., 2008; Han, 2009; Beck, 2009). Additionally, local magnetic fields can be measured accurately via Zeeman splitting of emission lines. For a given line of sight, the rotation measure traces the integrated parallel component of the GMF while a UHECR is deflected by the perpendicular component of the GMF. A global model of the ordered GMF is thus required to transfer information from rotation measures into information useful for UHECR deflections. Several models have been presented for ordered magnetic fields in the Galaxy. These typically consider one or more of the following: a toroidal type field in and near the galaxy disk, a toroidal field in the halo, and a poloidal field which reproduces the vertical component seen in the Solar neighbourhood and the Galactic center. Models for the ordered component of the magnetic field are discussed in the next section, and recent comprehensive reviews can be found in Han (2008) and Beck (2008). Studies of the global magnetic field of other galaxies has greatly facilitated the refinement of models of the Galactic GMF (see Beck, 2008, 2009, for a review), even though there is significant variation between galaxies in both the ordered and turbulent GMF, especially among those with high star formation rates.

In this article, we expand the work of Nagar & Matulich (2008) in two directions: first we use Monte Carlo simulations to derive UHECR trajectories within the Galaxy and corresponding outside-the-Galaxy arrival directions for all PAO and AGASA UHECRs. The simulations, run for six UHECR compositions - from protons to iron - and seven GMF models, include uncertainties in the GMF and a turbulent magnetic field component. We then compare the UHECR trajectories within the galaxy and their outside-the-Galaxy arrival directions with various Galactic and extragalactic sources, and discuss the implications of the results. The individual steps followed in this work have been addressed previously by various authors referenced here and in the next section. The new facet of this work is that we combine all of the above steps within the same Monte Carlo simulation, in order to model the trajectories of the PAO and AGASA UHECRs with energies greater than 56 EeV within a large number of ordered GMF models and UHECR compositions. Sec. 2 introduces the magnetic field models and describes the Monte Carlo simulations, Sec. 3 summarizes the sources of the data used, and Sec. 4 describes the principle results obtained. Finally, Sec. 5 contains a brief discussion and the conclusions of our study. Distances to galaxies are calculated using a Hubble constant of $72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, except for relatively nearby galaxies for which we use distances as referenced.

2. Magnetic Fields and Monte Carlo Simulations

We consider seven ordered magnetic field models for our Galaxy (for recent reviews of Galactic and extragalactic ordered magnetic fields see Beck, 2008; Han, 2008; Beck, 2009). Four of these models, the so called BS-S, BS-A, AS-S, and AS-A have been used previously by several authors. Here, the first two alphabets signify a (bi-)symmetric (BS) or asymmet-

ric (AS) configuration w.r.t. a transformation between θ and $\theta + \pi$, where θ is the cylindrical azimuthal angle in the Galactic plane. The last alphabet signifies whether the field reverses direction (A) or not (B) in passing from above the Galactic plane to below the Galactic plane. Given the evidence for a vertical (z) component of the GMF, both in the Galactic center and in the Solar vicinity, a dipole field model is usually added to the toroidal field above. Detailed descriptions and discussions of these GMFs can be found in Stanev (1997); Beck (2001); Han (2002); Tinyakov & Tkachev (2002); Prouza & Šmíd (2003); Brown et al. (2007); Kachelrieß et al. (2007); Men et al. (2008); Takami & Sato (2008); Han (2009). For these four models, we use the equations and their related normalizations strictly following Takami & Sato (2008), and always include the dipole field component as specified in Takami & Sato (2008).

Sun et al. (2008, hereafter S08) have recently presented three new variations of the above GMF models - AS-S+RING, AS-S+ARM and a modified BS-S - tailored to best fit observations of Galactic synchrotron emission and its polarization, and rotation measures of pulsars. For brevity we sometimes refer to these three models as ASS+R, ASS+A, and BSS(S) in the text and tables. Sun et al. (2008) find that the first two models provide the best fit to current radio observations. These two models use the basic configuration of the AS-S model, but introduce field reversals in a specified ring or arm, respectively. The modified BS-S model is based on the traditional BS-S model but with different parameters and normalizations. The three new models presented by S08 also include a toroidal halo field as initially presented in Prouza & Šmíd (2003), but do not include a dipole magnetic field component. We use these three models and their related halo field as described in S08 with only one difference: in the AS-S+ARM model we directly use the log spiral arm morphology described in Wainscoat et al. (1992) without correcting for their shape near the solar neighbourhood as in S08, who used the correction suggested in Taylor & Cordes (1993). We do not expect significant changes in the UHECR trajectories due to this small change in the morphology of the spiral arms. Sun et al. (2008) assumed that there is no ordered dipole field component in the Galaxy GMF, arguing that the vertical (z) component of the local magnetic field is a turbulent component. Since the parametric form and normalizations of the S08 models were derived via fits to radio observations, it is not strictly correct to add a dipole field to the models. Nevertheless, for illustrative purposes (and out of curiosity) we also performed simulations of the S08 GMF models including the dipole field component as specified in Takami & Sato (2008). We refer to these results as the Sun et al. (2008) GMFs plus dipole.

We simulated UHECR trajectories for six different UHECR compositions: protons, He^{2+} , O^{8+} , Al^{13+} , Ca^{20+} , and Fe^{26+} . Once chosen, a composition was maintained fixed during the full trajectory within the galaxy: i.e. we do not consider photo-dissociation-produced composition changes to a UHECR during its Galactic trajectory. UHECR trajectories were simulated by firing an anti-particle with the corresponding UHECR mass, (anti)charge, and energy from the Earth in the earth-arrival direction of the UHECR and following its trajectory - including deflections in the magnetic field - in steps of 10 pc. The simu-

lations were carried out until the anti-particle left a sphere with diameter 40 kpc centered on the Galactic center. The Galactic coordinate pair (l, b) derived from the final position and velocity of the anti-particle in the simulation is equivalent to the arrival direction of the UHECR before it entered the Galaxy, and we refer to this direction as the ‘outside-the-Galaxy’ arrival direction, to distinguish it from the ‘earth-arrival’ direction measured by the observatory.

Each UHECR’s trajectory within each GMF model was simulated fifty times using a Monte Carlo approach: introducing uncertainties in the ordered magnetic field and a random turbulent magnetic field component. In more detail, in each 10 pc simulation step we (a) computed the 3-vector representing the Cartesian coordinates of the ordered magnetic field from the relevant model. For the AS-S, AS-A, BS-S, and BS-A models this was the sum of the cylindrical (disk) field and the dipole field. For the AS-S+ARM, AS-S+RING, and BS-S model of S08 this was the sum of the disk and halo fields (with or without the dipole field as described above); (b) added a Gaussian-distributed random error in each component of the ordered magnetic field, i.e. a change in both magnitude and direction of the ordered field. This was done by adding to the 3-vector of the previous step a 3-vector whose each component was a random number derived from a Gaussian distribution with mean = 0 and $\sigma = 0.5$ times the value of the corresponding Cartesian component of the GMF; (c) added a turbulent field component. The turbulent field component was computed following the recipe described in Prouza & Šmíd (2003), though with slightly different normalization parameters: the maximum turbulent magnetic field strength in each Cartesian component was taken to be $\pm 10\mu\text{G}$, and the probability of a turbulent field being present was taken to be 1% in the halo of the galaxy, 20% in the disk of the galaxy (Galactic radius less than 20 kpc and Galactic height less than 1.5 kpc) and 80% in the spiral arms of the Galaxy - where we used the spiral arm definition from Wainscoat et al. (1992), spiral arm thickness 0.75 kpc in the disk (i.e. coordinate r), and half-height 0.5 kpc (coordinate z). We therefore generated a random number to determine whether a turbulent field was required to be added following the probabilities above. If so, we generated a 3-vector in which each component was a random number uniformly distributed between $\pm 10\mu\text{G}$. This was added to the magnetic field 3-vector in the previous step in order to derive the total magnetic field used in the deflection calculation of this step. This turbulent field was then kept constant for the next 50 pc (i.e. an additional five simulation steps), the expected scale length of turbulent field in the Galaxy (Prouza & Šmíd, 2003; Beck, 2008). Note that the turbulent field used here is relatively large in comparison with current measurements of the turbulent field in the Galaxy (S08) and other galaxies (Beck, 2009).

In summary, within each GMF model we derived 50 outside-the-Galaxy arrival directions for each UHECR of a specific composition, or a total of 300 outside-the-Galaxy arrival directions for each UHECR over all six compositions modelled.

3. Data

Positions and energies of the 27 UHECRs detected by the PAO with energies ≥ 56 EeV were taken from PA08; we have not made the small energy corrections to these UHECRs as later reported by the PAO (PAO09b). Positions and energies of the UHECRs detected by AGASA with energies ≥ 56 EeV were taken from Hayashida et al. (2000) which is an updation of the data listed in Takeda et al. (1999). For AGASA UHECRs, we lowered the energies reported in Takeda et al. (1999) by 30%; this resulted in 11 UHECRs with energy above 56 EeV. In this work we use ‘AGASA UHECRs’ to refer to only these 11 UHECRs unless explicitly stated otherwise.

Our catalogs of astronomical sources were drawn from various publications and web-based source lists, and chosen to be representative of previously suspected or posited Galactic and extragalactic sources of UHECRs. In all cases, we attempted to select the most comprehensive catalog available. Source lists for galaxies, galaxy clusters, GRBs, Galactic supernova remnants, and extragalactic radio supernova are described in Nagar & Matulich (2008). As in Nagar & Matulich (2008), in the case of radiogalaxies and radio sources we used several surveys and catalogs, including NVSS (Condon et al., 1998), SUMMS (Bock et al., 1999), and NED. The list of extragalactic jets is based on that compiled by Liu & Zhang (2002); to this list we added data on the galaxies as given in NED, and re-measured the total flux and total extent of the radio emission from NVSS and SUMMS maps or from the list of DRAGNs compiled by P. Leahy ¹. The DRAGNs list is a subset of the 3CRR sources (Laing et al., 1983) which have one or all of radio-emitting jets, lobes, and hotspots. The total extent of the radio emission therefore includes both radio jets and any radio lobes. This extent is typically referred to as the Largest Angular Size (LAS) or Largest Linear Size (LLS). In the case of double sided jet or lobe sources, we added the LLS of the two jets and lobes as scalars instead of vectors in order to discount the effects of jet and lobe bending. Nagar & Matulich (2008) listed the 10 radiogalaxies in the field of view of PAO with $D \leq 75$ Mpc and $LLS \geq 180$ kpc. To this we added all other (northern) radiogalaxies satisfying the same criteria: NGC 315 ($D = 69.5$ Mpc; $LLS = 1111$ kpc), NGC 383 ($D = 71.7$ Mpc; $LLS = 907$ kpc), NGC 1275 ($D = 74.1$ Mpc; $LLS = 468$ kpc), NGC 5127 ($D = 68.3$ Mpc; $LLS = 230$ kpc), and CGCG 514-050 ($D = 72$ Mpc; $LLS = 506$ kpc). Together, these 15 galaxies, form our sample of all nearby ($D \leq 75$ Mpc) extended ($LLS \geq 180$ kpc) radiogalaxies. In the case of nearby galaxies, we also used the HIPASS catalog (Meyer et al., 2004; Wong et al., 2006) as used by Ghisellini et al. (2008) in their study of the correlation between UHECR arrival directions and nearby galaxies. Additionally, we used the revised Third Reference Catalog of Bright Galaxies (Corwin et al., 1994) to select a sample of nearby elliptical galaxies.

In this work we have considered several new source catalogs: Galactic Soft Gamma-Ray Repeaters (SGRs) and Galactic Anomalous X-ray Pulsars (AXPs) were taken from Woods & Thompson (2006) and updated with the online list

maintained by the McGill pulsar group². As of June 2009, this list includes six SGRs (two of which are candidates) and 10 AXPs (one of which is a candidate). These SGRs and AXPs are believed to be high magnetic field radio pulsars or “magnetars”. Of the total of 16 SGRs and AXPs, 14 are close to the plane of the Galaxy, and two are in the SMC and LMC.

Confirmed Galactic microquasars were taken from the list in Paredes (2005), and candidate micro-quasars from Combi et al. (2008). Various gamma-ray catalogs have been used: the BeppoSAX catalog of GRB and X-ray afterglows (de Pasquale et al., 2006), the BeppoSAX complete catalogue of GRBs (Vetere et al., 2007), Gamma-ray Blazars in northern sky (Sowards-Emmerd et al., 2003), Blazar counterparts for 3EG sources (Sowards-Emmerd et al., 2004), Gamma-ray Blazar candidates (Sowards-Emmerd et al., 2005), Sources detected by ISGRI (Bodaghee et al., 2007), and the Third EGRET catalog (Hartman et al., 1999). We also used the HESS (Hofmann, 2005) catalog of 54 Gamma-ray sources between 100 GeV and 100 TeV as obtained from the HESS online catalog in June 2009³.

4. Results

We performed several Monte Carlo test runs varying the magnitudes of the error of the ordered field and the maximum turbulent field strength. Here we present and discuss the results of simulations which used a Gaussian-distributed (mean = 0 and $\sigma = 50\%$ of the value of the Cartesian GMF component) error in each Cartesian component of the ordered GMF, and a turbulent magnetic field uniformly distributed between $\pm 10\mu\text{G}$ in each Cartesian component of the magnetic field, with details as described in Sec. 2. We note that for the simulated GMF error, using 25%–100% instead of 50% as described above does not significantly change the trajectories in the case of anti-protons. The relative deflections suffered by the UHECR from the ordered field and turbulent field components can thus be roughly judged by comparing the average and r.m.s. of the deflection angles corresponding to the fifty outside-the-Galaxy arrival directions for each UHECR within each GMF model.

We used the following distance limits between a single outside-the-Galaxy arrival direction and an extragalactic astronomical object in order to be considered a “match”: 2.5° for H, 3° for He, 6° for O, 9° for Al, 12° for Ca, and 15° for Fe. These semi-arbitrary values were chosen considering a constant additive error of 2° - to account for e.g. the error in determining the arrival direction of the UHECR - plus a composition-weighted error of 0.5 times the charge of the UHECR which roughly accounts for errors in the deflection calculations and deflections by intergalactic magnetic fields but avoids too large “match radii” for heavy nuclei. To match an astronomical source with a UHECR we require that at least 4 of the 50 outside-the-Galaxy arrival directions are ‘matched’ by the above criterion; this $\geq 8\%$ match probability was chosen as it implies roughly that a match cannot be ruled out at better than a 2σ level within the simulation parameters.

² <http://www.physics.mcgill.ca/pulsar/magnetar/main.html>

³ <http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/>

¹ <http://www.jb.man.ac.uk/atlas/dragns.html>

Graphical representations of our simulation results are shown in Figures 1 to 5. Coordinates of the arrival directions of the UHECRs detected by PAO (blue for UHECRs with energy ≥ 75 EeV and green for UHECRs with energy between 56 and 75 EeV) and AGASA (red) are shown as open circles of (arbitrary) radius 3.5° . The outside-the-Galaxy arrival directions of the UHECRs are plotted with small colored dots (50 per UHECR, each representing the result of one Monte Carlo simulation). Figures 1 and 3 appear in the printed version of this manuscript while Figures 2, 4, and 5 are available in the electronic version only. The outside-the-Galaxy arrival directions were plotted in the order red, green, blue, and yellow. When one of these colors is not seen for a UHECR, it lies below one of the following colors in the sequence above. For example, the pairs BS-S (red), BS-A (blue) and AS-S (green), AS-A (yellow) have the same deflection for positive values of Galactic latitude (b). To avoid overcrowding, results for the three models of S08 are shown separately from the other four models.

Figures 1 to 5 include the positions of all galaxies with radio jets from the catalog of Liu & Zhang (2002) within 500 kpc and the 16 confirmed and candidate SGRs and AXPs in the Galaxy (Woods & Thompson, 2006). As in Nagar & Matulich (2008) - but with different cutoffs - we have divided the galaxies with radio jets into three redshift bins: “nearby” ($D \leq 75$ Mpc; red circular symbols), “intermediate” ($75 \text{ Mpc} < D \leq 200$ Mpc; blue circular symbols), and “distant” ($200 \text{ Mpc} < D \leq 500$ Mpc; black circular symbols). In all redshift bins, we distinguish between galaxies with radio structures more extended than 180 kpc (“extended”; solid symbols) and those with radio structures less extended than 180 kpc (“compact”; open symbols). Filled triangles are used for Galactic magnetars: red for SGRs and blue for AXPs. Of the 16 magnetars, two are in the LMC and SMC and the others are close to the plane of the Galaxy.

4.1. UHECR Trajectory Simulations: Protons

Columns 5 to 7 of Tables 1 and 2, present the results of the deflection simulations for proton UHECRs within the BS-A GMF model. Tabular results for other models are not shown for space reasons and can be requested from the authors. The first four columns of the tables identify the UHECR by an index number, its arrival direction in Galactic coordinates, and its energy. Then, for each UHECR composition simulated, we list the average and r.m.s. of the deflection angles corresponding to the 50 outside-the-Galaxy arrival directions of each UHECR, followed by the nearby extended radiogalaxy which best matches the fifty outside-the-Galaxy arrival directions (see the previous section for a definition of a match). A nearby extended radiogalaxy is only listed if more than four of the 50 outside-the-Galaxy arrival directions are matched. For proton UHECRs, the average deflection and its r.m.s. for each UHECR are both typically 1° – 5° though values greater than 30° are seen for a few UHECRs whose trajectories pass close to the Galactic plane and/or Galactic center.

We emphasize four important results of the proton-UHECR trajectory simulations: (a) even after considering errors in the

model GMF and adding a relatively strong turbulent magnetic field component, the outside-the-Galaxy arrival directions of the majority of proton-UHECRs are typically sufficiently concentrated to allow meaningful comparisons with Galactic and extragalactic sources; (b) for a given proton-UHECR, the outside-the-Galaxy arrival directions are typically significantly different for different GMF models. An assumption of the source population therefore allows constraints on competing models of the ordered GMF; (c) almost all UHECRs with Galactic latitude $-25^\circ < b < 0^\circ$ have trajectories which pass close to or cross the Galactic plane within certain GMF models, especially those which include an ordered dipole field; (d) as discussed in detail in Sec. 4.5, the match between proton-UHECRs and nearby extended radiogalaxies (Nagar & Matulich, 2008) is maintained in most GMF models, and significantly strengthened in some GMF models.

4.2. UHECR Trajectory Simulations: Heavy Nuclei

With increasingly heavy UHECR compositions, the increased deflections suffered by the UHECRs tend to scatter their out-of-Galaxy arrival directions over larger regions of the sky. Figure 3, which compares the deflections suffered by UHECRs in four models for different UHECR compositions, emphasizes the importance of UHECR composition for source identification. The simulation in this figure does not include a Monte Carlo approach: i.e. we did not consider GMF uncertainties or turbulent magnetic fields. We remark on several interesting features in Figure 3, especially for compositions near Oxygen: (a) the three PAO UHECRs near $l = 200^\circ$, $b = -45^\circ$ move close to the radiogalaxy 3C120 for a UHECR composition of Oxygen; (b) the twin mystery PAO UHECRs near $l = 335^\circ$, $b = -18^\circ$ move toward the Galactic plane in the case of light compositions, and then toward the Cen A concentration of radiogalaxies for an Oxygen composition. (c) several UHECRs move toward the extended radiogalaxies NGC 315 and NGC 383 (near position $l = 130^\circ$, $b = -30^\circ$) for compositions near Oxygen.

A summary of the results of our Monte Carlo simulations for heavy-nuclei UHECRs within the BS-A GMF model can be found in Tables 1 and 2. Graphical representations for Oxygen and Iron UHECRs within the BS-S, BS-A, AS-S, and AS-A models are presented in Figures 4 and 5. As expected, both the average and the r.m.s. of the deflection angles corresponding to the 50 outside-the-Galaxy arrival directions for each UHECR increase with increasing UHECR mass (Tables 1 and 2). For compositions up to around Oxygen, the 50 outside-the-Galaxy arrival directions corresponding to each UHECR are typically still identifiably together on the sky - allowing potential source searches (Figure 4). For compositions close to and higher than Ca, the fifty outside-the-Galaxy arrival directions corresponding to each UHECR are typically scattered over most of the sky. However, even in the case of Iron UHECRs (Figure 5) a concentration can still be seen in the region of the SuperGalactic plane near to and north of Cen A.

4.3. Source Populations: Centaurus A

The concentration of UHECRs in the Cen A region has drawn a lot of attention since its first report by the PAO team. Our Monte Carlo simulations can be used to test whether Cen A is the dominant, or only, source of UHECRs. The results of these tests are shown in Table 3 for UHECRs detected by PAO and Table 4 for UHECRs detected by AGASA. In these tables, the first column for each composition reports the fraction of the total (1350 for PAO and 550 for AGASA) outside-the-Galaxy arrival directions which fall within three 20° circles centered on the Cen A nucleus and its northern and southern radio lobes. The second column for each composition shows the number of UHECRs (of the total of 27 for PAO and 11 for AGASA), for which at least one of the fifty outside-the-Galaxy arrival directions falls in the 20° circles described above.

Within our simulation parameters, it is possible but unlikely that Cen A is the source of all PAO-detected UHECRs: for proton UHECRs one third or less of the total outside-the-Galaxy arrival directions are within the 20° circles around Cen A in any GMF model, and almost two thirds of PAO UHECRs do not have even one outside-the-Galaxy arrival direction within the above area. For heavier compositions a smaller fraction of total outside-the-Galaxy arrival directions are within the 20° circles around Cen A but a larger fraction of PAO UHECRs, almost 100% for Ca and Fe, have at least one outside-the-Galaxy arrival direction which falls within the Cen A circles. The latter result is due to the large scatter of the outside-the-Galaxy arrival directions of any given heavy composition UHECR. In the case of AGASA UHECRs, the fraction of outside-the-Galaxy arrival directions which fall within the Cen A circles is very small for all compositions, though for heavy UHECR compositions, a large fraction of all UHECRs have at least one outside-the-Galaxy arrival direction falling within the Cen A circles.

If we consider all 300 outside-the-Galaxy arrival directions corresponding to each UHECR (6 compositions, 50 outside-the-Galaxy arrival directions per composition) then within the models AS-S, AS-A, BS-S and BS-A, all PAO-detected UHECRs have at least one outside-the-Galaxy arrival direction which falls within the 20° circles around Cen A. In the Sun et al. 2008 models a few (two to six) PAO UHECRs do not satisfy the above criterion. For the AGASA-detected UHECRs, for the AS-S and AS-A models all UHECRs have at least one outside-the-Galaxy arrival direction which falls within the 20° circles around Cen A for some one composition, while in the other models between two and eight UHECRs do not satisfy this criterion.

4.4. Source Populations: The Radio Galaxy Concentration around Cen A

As Nagar & Matulich (2008) have pointed out, the area around Cen A hosts the highest density of nearby extended radiogalaxies. We repeated the analysis of the previous section, but using a box around all nearby extended radiogalaxies in this area. For simplicity we used the following limits for the box: Galactic longitude between 240° and 360° and Galactic latitude between -10° and 70° (the “RG box”). The results are listed in

sub-columns 3 and 4 for each composition in Table 3 for PAO UHECRs and Table 4 for UHECRs detected by AGASA.

As expected the match statistics are better than in the case of only the 20° circles around Cen A and its radio lobes. The “RG box” contains between a quarter and a half of all outside-the-Galaxy arrival directions for any one given composition. For light UHECRs at least half of all PAO-detected UHECRs have at least one outside-the-Galaxy arrival direction which falls in the RG box. For Ca and Fe compositions all UHECRs satisfy this criteria. In the case of AGASA UHECRs heavy compositions are required to provide a good match between the UHECRs and the RG box.

If we consider all 300 outside-the-Galaxy arrival directions corresponding to each UHECR then within the models AS-S, AS-A, BS-S and BS-A, all PAO and AGASA UHECRs have at least one outside-the-Galaxy arrival direction which falls within the RG box. In the Sun et al. models a few (two to four) AGASA-detected UHECRs do not satisfy the above criterion.

4.5. Source Populations: Nearby Extended Radio Galaxies

Nagar & Matulich (2008) have previously argued that the arrival directions of a subset of PAO-detected UHECRs are correlated with the directions of nearby extended radiogalaxies. A distance of less than 3.5° was found between the radio structures of six extended radiogalaxies (of the 10 “visible” to the PAO) and 8 UHECRs detected by PAO. Considering the full sky, we have a total of 15 nearby ($D < 75$ Mpc) galaxies with extended (> 180 kpc) radio structures, with the new galaxies listed in Sec. 3, to be compared to 38 UHECRs. Adding the AGASA-detected events, adds two new matches to earth-arrival directions of UHECRs: an AGASA event with original reported energy $E = 120$ EeV matched to NGC 7626 (which is also matched to a PAO-detected UHECR) and a match between an AGASA event with original reported energy $E = 68$ EeV with CGCG 514-050 (this event does not appear in the figures as its 30% reduced energy is below our UHECR cutoff of 56 EeV). The correlation between nearby extended radio-galaxies and UHECRs detected by PAO and AGASA therefore remains highly statistically significant even before considering deflections by the GMF. We remark that the Supergalactic plane in the Cen A region passes close to the Galactic longitudes where the deflection produced by an ordered GMF with azimuthal symmetry is minimal (e.g. Takami & Sato, 2008). It may be this fortuitous coincidence which allowed us to find several UHECR events “matched” to nearby extended radio galaxies in Nagar & Matulich (2008).

Including deflections of UHECRs by the GMF maintains, and in some models increases, the correlation between UHECRs and nearby extended radiogalaxies. Table 5, in its first four columns, lists the statistics of matches between UHECRs and our sample of 15 nearby extended radiogalaxies for all compositions and models simulated. The BS-S and BS-A models clearly result in the best match between nearby extended radiogalaxies and UHECRs. For proton UHECRs the matches are few: in part due to using a rather strict match

criterion of 2.5° . At heavy compositions a large fraction of UHECRs are matched to nearby extended radiogalaxies.

For proton-UHECRs, of the seven models tested the BS-S and BS-A models maintain the high correlation between UHECRs and radiogalaxies in the Cen A region (Figs. 1 to 5). Accounting for deflections within the BS-S and BS-A models lead to a higher concentration of UHECRs around Cen A (the UHECR detected toward Cen B is now also deflected up to Cen A) and the radiogalaxy WKK 4432. Applying deflections from the models of S08 do not result in good matches between UHECRs and radiogalaxies in this region, though adding a dipole field to these models significantly improves the matches. In the case of the three matched events near NGC 7626, CGCG 413-019 and CGCG 514-050 (see Nagar & Matulich, 2008), all of BS-S, BS-A, and AS-S are acceptable for UHECR-radiogalaxy matches; however, the S08 models - with or without a dipole component - do not provide consistently good matches.

For many other UHECRs in Figures 1 to 5 we do not see obvious matches between the earth-arrival direction of UHECRs and nearby or intermediate (red and blue symbols) galaxies with radio jets. However, accounting for deflections by the GMF suggests several new potential matches between proton-UHECRs and extended radio jets. Some interesting potential matches between galaxies with distance < 200 Mpc and jet structures larger than 180 kpc are worth specifically noting: (a) we see possible matches between NGC 1275 and two AGASA-detected UHECRs; (b) CGCG 403-019, apart from a direct match to a PAO-detected UHECR, is potentially the source of three additional AGASA-detected UHECRs; (c) the extragalactic Gamma-ray source with the highest maximum flux at HESS, Mrk 421, matches to an AGASA UHECR; (d) the BL Lacs H 2356-309 and 1ES 0347-121, both detected by HESS, can also be matched to AGASA events. Note that some of the AGASA events mentioned above do not appear in the figures as their 30% reduced energies are below 56 EeV.

To explain the majority of UHECRs as originating in galaxies with extended radio jets requires one of the following: (a) a stronger, or more ordered, intra-cluster and intergalactic magnetic field resulting in extragalactic deflections greater than the current estimate (e.g. Harari et al., 2002; Dolag et al., 2004) of a few degrees for UHECRs; (b) a larger mean free path or lower energy loss than current estimates of the GZK effect, such that more distant radiogalaxies can contribute to the detected UHECR events; (c) a large fraction of heavy composition UHECRs. The higher deflections of heavy UHECRs in Galactic and extragalactic magnetic fields result in differences of several tens of degrees between the out-of-Galaxy and earth arrival directions. Recent results on UHECR composition from the Auger collaboration make this scenario likely (PA09a; PA09b).

Given the small sample size of known UHECRs it is difficult to evaluate how including UHECR deflections in the GMF effects the correlation between UHECRs and nearby massive spiral galaxies (Ghisellini et al., 2008); this is best left for later analysis with a larger number of UHECRs. Our comparisons of UHECR outside-the-Galaxy arrival directions with the DRAGN sample, and with the several catalogs of

Gamma-Ray sources also revealed individually interesting coincidences. However, their statistical significance is difficult to evaluate and we do not discuss them here.

4.6. Source Populations: Nearby Extended Radio Galaxies vs. Nearby Elliptical Galaxies

Given the match between a subset of UHECRs and nearby extended radio galaxies, it is relevant to test whether the potential association comes directly from the presence of extended radio emission or from some underlying material associated with massive elliptical galaxies, for e.g. luminous or dark matter concentrations. As a preliminary test, we have used the RC3 catalog (Corwin et al., 1994) to extract all nearby ($D \leq 75$ Mpc) elliptical galaxies. From this subset we identified all nearby RC3 ellipticals with extended radio jets and lobes, obtaining a list of 11 galaxies which includes all of our 15 nearby extended radio galaxies except NGC1275, Cen B, WKK 4552, and CGCG 514-050. The limits in RC3 parameters for this subset of ellipticals are: distance $D \leq 75$ Mpc, morphological type $-5 \leq T \leq -2$, apparent B-band magnitude $7.69 \leq m_B \leq 13.38$, absolute B-band magnitude $-22.6 \leq m_B \leq -19.9$, and size $1.2 \leq D_{25} \leq 2.42$, $0.02 \leq R_{25} \leq 0.2$, $1.21 \leq D_0 \leq 2.45$. We then selected a control sample of all RC3 ellipticals without extended radio jets and lobes which satisfied the above limits in RC3 measured parameters. This resulted in a control sample of 183 “radio-compact” ellipticals. Histograms comparing the distribution of distance, absolute magnitude, size, and angular separation from Cen A, of the two samples are shown in Fig. 6. The two samples are reasonably well matched with a small tendency for the radio-extended ellipticals to have slightly higher absolute magnitudes and to be slightly closer to Cen A on average.

A comparison of the statistics of matches of the two elliptical samples to the outside-the-Galaxy arrival directions of PAO UHECRs is shown in Table 5. When normalized for the number of galaxies in each sample, the matches between UHECRs and extended radiogalaxies is significantly higher than in the case of radio-compact ellipticals. This difference is most extreme in the BS-S and BS-A models.

4.7. Source Populations: Potential Galactic Plane Sources

Very few UHECRs have been detected by PAO and AGASA in the region within 10° of the Galactic plane. Accounting for deflections in the GMF, however, results in several “Galactic plane crossing UHECRs” in most GMF models. In particular, the BS-S and AS-S models, and the models of S08 with or without a dipole component, serve to move the arrival directions of several UHECRs at $-30 < b < 0$ towards the Galactic plane.

We searched for potential matches between the UHECR trajectories within the Galaxy and objects from the catalogs of Galactic microquasars and Galactic magnetars. For the GMF models used, two or three UHECRs have trajectories which pass close (within 1 kpc) to a SGR or AXP: in the case of SGR 1900+14, a good match is obtained in all models ex-

cept the S08 models without a dipole component. In the case of SGR 1627-41, AS-S and AS-A model deflections lead to a connection to the mysterious close pair of events detected by PAO. Several UHECR trajectories also pass close to confirmed or candidate Galactic microquasars, and HESS-detected Galactic sources (e.g. Vela X and Vela Junior). Of course, fine tuning of the normalizations of the model permit closer matches; given the many free parameters (not least the uncertain distances to these Galactic sources, and the mass of the UHECR). We thus do not attempt a detailed study of the coincidences, but merely note that some UHECRs potentially cross the Galactic plane near candidate UHECR sources.

5. Discussion & Concluding Remarks

The UHECR deflection simulations presented here, and the derived outside-the-Galaxy arrival directions of UHECRs, highlight several interesting points. For light (proton or Helium) UHECRs, the relatively small dispersions in the outside-the-Galaxy arrival directions for a specific UHECR and GMF model confirm that tantalizing insights into the source population of UHECRs can be gained with a small sample of UHECRs. While heavy composition UHECRs suffer deflections of several tens of degrees the concentration of outside-the-Galaxy arrival directions in the quadrant containing the SuperGalactic plane near Cen A also allows source population constraints. Conversely, picking one or a few UHECR source populations permits an evaluation of competing models of the ordered GMF.

For light compositions, the trajectories of several UHECRs pass close to or through the Galactic plane within several GMF models. Interestingly, several pass relatively close to SGRs, AXPs, and/or microquasars in the Galaxy. Ghisellini et al. (2008) have argued that magnetars in nearby galaxies could be responsible for the PAO detected UHECRs. The integrated flux of HI emission from our galaxy is greater than the summed integrated HI fluxes of all massive spirals in the HIPASS survey considered by Ghisellini et al. (2008). If UHECRs originate in magnetars in steady state - rather than in formation - then it would not be surprising to detect some magnetar-related UHECR events in the Galaxy.

In Nagar & Matulich (2008) we claimed a correlation between nearby galaxies with extended radio jets and the earth-arrival direction of a subset of UHECRs. By fortuitous chance these matched pairs lie along the lines of Galactic longitude which suffer the minimum deflection by axisymmetric ordered Galactic magnetic fields. The correlation is strengthened with the results presented here. Accounting for deflections by BS-S and BS-A GMFs do not significantly change the previously claimed matches in the case of proton UHECRs. Rather, using the BS-S model actually concentrates proton UHECRs closer to the nucleus of Cen A, and also results in several new UHECR-radiogalaxy matches. The models of S08, with a dipole GMF component added, also maintain the previous matched pairs. Both the nearest radiogalaxy and the nearest radio-extended BL Lac are potentially sources of multiple UHECRs. It is possible but unlikely that all UHECRs originate in Cen A. In the best case, i.e. choosing the most conve-

nient global GMF model for any given match, about 30% of UHECRs outside the range $-25^\circ < b < 0^\circ$ could be matched to a galaxy with extended radio jets or an extragalactic Gamma-ray source in the case of proton only UHECRs. For heavy composition or varied composition UHECRs we cannot rule out the possibility that all UHECRs originate in nearby galaxies with extended radio jets. We particularly noted several interesting and new matches between UHECRs and radiogalaxies for compositions near Oxygen.

A remaining question is whether the correlation between radiogalaxies and UHECRs depends directly on the presence of extended radio jets and lobes or whether both trace an underlying source population. We have briefly addressed this issue in a comparative test of nearby ellipticals with and without extended radio structure: there is a strong indication that, within the BS-S and BS-A models of the GMF, the correlation with nearby extended radiogalaxies is directly related to the radio jets rather than to an underlying source population traced by massive elliptical galaxies.

If radiogalaxies, or sources traced by radiogalaxies, are responsible for a subset of UHECRs, a BS-S or BS-A model for the GMF is supported towards the Cen A region, i.e. the northern hemisphere of the fourth quadrant. The BS-S model (but not the BS-A) also allows a match between some UHECRs and Galactic plane sources. The models of S08 are consistent with both of the above only after we added a dipole field component (see Sect.2 for why this is dipole addition is not necessarily a self-consistent step).

Finally, we remark that this work identifies the subset of UHECRs which can be matched to extended radiogalaxies using a light composition (H or He) for UHECRs, and those which require a medium to heavy composition (e.g. Table 1). The relative ratio of proton to heavy composition UHECRs then roughly agree with the composition mix suggested by PA09a and PA09b. It would be interesting to verify if the X_{\max} distributions of these two UHECR sub-samples confirm this composition difference.

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References

- Abraham, J. et al. for the Pierre Auger Collaboration, 2004, *Nucl. Instr. and Meth. A* 523, 50
- Abraham, J. et al. for the Pierre Auger Collaboration, 2007, *Sci.* 318, 938 (PA07)
- The Pierre AUGER Collaboration, et al. 2008, *Astroparticle Physics*, 29, 188 (PA08)
- The Pierre Auger Collaboration: J. Abraham, et al. 2009, arXiv:0906.2319 (PA09a)
- The Pierre Auger Collaboration: J. Abraham, et al. 2009, arXiv:0906.2347 (PA09b)
- Beck, R. 2001, *Space Science Reviews*, 99, 243

Beck, R. 2008, American Institute of Physics Conference Series, 1085, 83

Beck, R. 2009, *Ap&SS*, 320, 77

Bock, D., Large, M. I., & Sadler, E. M. 1999, *AJ*, 117, 1578

Bodaghee, A., et al. 2007, *VizieR Online Data Catalog*, 346, 70585

Brown, J. C., Haverkorn, M., Gaensler, B. M., Taylor, A. R., Bizunok, N. S., McClure-Griffiths, N. M., Dickey, J. M., & Green, A. J. 2007, *ApJ*, 663, 258

Combi, J. A., Albacete-Colombo, J. F., & Martí, J. 2008, *A&A*, 477, 125

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, *AJ*, 115, 1693

Corwin, H. G., Jr., Buta, R. J., & de Vaucouleurs, G. 1994, *AJ*, 108, 2128

Cuesta, A. J., & Prada, F. 2009, arXiv:0910.2702

de Pasquale, M., et al. 2006, *VizieR Online Data Catalog*, 345, 50813

Dolag, K., Grasso, D., Springel, V., & Tkachev, I. 2004, *Nuclear Physics B Proceedings Supplements*, 136, 234

George, M. R., Fabian, A. C., Baumgartner, W. H., Mushotzky, R. F., & Tueller, J. 2008, *MNRAS*, 388, L59

Ghisellini, G., Ghirlanda, G., Tavecchio, F., Fraternali, F., & Pareschi, G. 2008, *MNRAS*, 390, L88

Greisen, K. 1966, *Phy. Rev. Lett.*, 16, 748

Han, J. 2002, *Astrophysical Polarized Backgrounds*, 609, 96

Han, J. L. 2008, *Nuclear Physics B Proceedings Supplements*, 175, 62

Han, J. L. 2007, *IAU Symposium*, 242, 55

Han, J. 2009, *IAU Symposium*, 259, 455

Harari, D., Mollerach, S., & Roulet, E. 2002, *Journal of High Energy Physics*, 7, 6

Hartman, R. C., et al. 1999, *ApJS*, 123, 79

Hayashida, N., et al. 2000, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0008102

Heiles, C. 1996, *ApJ*, 462, 316

Hillas, A. M. 1999, *Nuclear Physics B Proceedings Supplements*, 75, 109

Hofmann, W. 2005, *International Cosmic Ray Conference*, 10, 97

Hooper, D., & Taylor, A. M. 2009, arXiv:0910.1842

Kachelreiss, M. 2008, lecture notes on high energy cosmic rays (astro-ph/0801.4376)

Kachelrieß, M., Serpico, P. D., & Teshima, M. 2007, *Astroparticle Physics*, 26, 378

Liu F.K., & Zhang Y.H. 2002, *A&A*, 381, 757

Laing, R. A., Riley, J. M., & Longair, M. S. 1983, *MNRAS*, 204, 151

Matthews, J. N. 2007, *Collicers to Cosmic Rays*, 928, 47

Men, H., Ferrière, K., & Han, J. L. 2008, *A&A*, 486, 819

Meyer, M. J., et al. 2004, *MNRAS*, 350, 1195

Nagar, N. M., & Matulich, J. 2008, *A&A*, 488, 879

Noutsos, A., Johnston, S., Kramer, M., & Karastergiou, A. 2008, *MNRAS*, 386, 1881

Paredes, J. M. 2005, *Chinese Journal of Astronomy and Astrophysics Supplement*, 5, 121

Prouza, M., & Šmídá, R. 2003, *A&A*, 410, 1

Rachen, J. P., & Biermann, P. L. 1993, *A&A*, 272, 161

Romero, G. E., Combi, J. A., Perez Bergliaffa, S. E., & Anchordoqui, L. A. 1996, *Astroparticle Physics*, 5, 279

Ryu, D., Kang, H., & Das, S. 2009, arXiv:0906.4850

Sowards-Emmerd, D., Romani, R. W., & Michelson, P. F. 2003, *ApJ*, 590, 109

Sowards-Emmerd, D., Romani, R. W., Michelson, P. F., Healey, S. E., & Nolan, P. L. 2005, *ApJ*, 626, 95

Sowards-Emmerd, D., Romani, R. W., Michelson, P. F., & Ulvestad, J. S. 2004, *ApJ*, 609, 564

Stanev, T. 1997, *ApJ*, 479, 290

Stanev, T. 2004, *C. R. Physique* 5, 453

Sun, X. H., Reich, W., Waelkens, A., & Enßlin, T. A. 2008, *A&A*, 477, 573 (S08)

Takami, H., & Sato, K. 2008, *ApJ*, 681, 1279

Taylor, J. H., & Cordes, J. M. 1993, *ApJ*, 411, 674

Tinyakov, P. G., & Tkachev, I. I. 2002, *Astroparticle Physics*, 18, 165

Takeda, M., et al. 1999, *ApJ*, 522, 225

Vetere, L., Soffitta, P., Massaro, E., Giommi, P., & Costa, E. 2007, *VizieR Online Data Catalog*, 347, 30347

Wainscoat, R. J., Cohen, M., Volk, K., Walker, H. J., & Schwartz, D. E. 1992, *ApJS*, 83, 111

Wong, O. I., et al. 2006, *MNRAS*, 371, 1855

Woods, P. M., & Thompson, C. 2006, *Compact stellar X-ray sources*, 547

Zatsepin, G. T., & Kuzmin, V. A., *Soviet Phys. JETP*, 4, 78

TABLE 1
RESULTS OF THE MONTE CARLO SIMULATIONS FOR PAO UHECRS AND THE BS-A GMF MODEL

Event	1		b		Energy		H		He		O		Al		Ca		Fe			
	dist	rms	dist	rms	dist	rms	dist	rms	dist	rms	dist	rms	dist	rms	dist	rms	dist	rms		
0	15.4	8.4	70.0	28.0	4.9	—	118.1	73.3	—	94.4	16.2	—	123.9	55.8	—	119.5	62.6	N 4760(7) 121.2 57.0 N 3557(4)		
1	-50.8	27.6	81.0	2.7	1.4	—	5.2	2.7	—	18.1	7.4	—	19.1	15.9	N 3557(7)	26.4	32.0	I 4296(6) 49.7 69.1 N 5128(12)		
2	-49.6	1.7	66.0	6.7	4.3	—	9.0	8.5	N 5128(5)	15.4	60.5	63.1	N 3557(4)	73.0	88.9	I 4296(5)	86.3	86.3 N 5128(9)		
3	-27.7	-17.0	83.0	9.6	3.5	—	16.7	9.3	—	39.2	46.3	—	87.1	46.2	—	90.7	69.2	N 1316(5) 97.4 81.7 N 5128(7)		
4	-34.4	13.0	63.0	8.2	3.0	—	9.9	11.4	—	63.0	44.9	N 3557(8)	62.9	37.5	N 3557(4)	60.2	69.4	N 4760(11) 102.2 104.8 N 5128(7)		
5	-75.6	-78.6	84.0	3.1	5.0	—	4.1	8.8	—	28.6	36.6	—	34.9	41.9	N 1316(6)	46.5	54.4	—	61.0	66.0 N 1316(6)
6	58.8	-42.4	71.0	3.9	2.9	—	6.3	6.2	—	36.1	46.2	—	58.5	52.4	—	93.7	84.5	—	101.8	89.9 N 4452(7)
7	-52.8	14.1	58.0	1.1	2.0	N 5128(12)	2.0	4.1	N 5128(17)	17.7	13.4	I 4296(7)	32.4	41.9	N 4760(4)	54.3	93.2	N 5128(6) 82.7 107.6 W 4452(7)		
8	4.2	-54.9	57.0	41.0	34.6	—	40.5	28.0	—	71.6	44.4	—	89.7	60.2	—	103.8	68.3	—	144.1	91.1 N 1316(4)
9	48.8	-28.7	59.0	6.3	5.0	—	12.6	8.3	—	69.9	44.5	—	113.4	70.8	—	122.4	76.0	—	144.1	94.8 N 5128(7)
10	-103.7	-10.3	84.0	4.4	2.3	—	8.7	5.7	—	43.1	25.2	—	35.1	48.7	—	76.2	130.3	—	86.3	125.6 N 5128(7)
11	-163.9	-46.9	83.0	4.7	2.0	—	10.1	3.8	—	38.2	28.1	N 1316(4)	52.5	42.0	—	37.3	74.8	—	46.6	91.4 N 5128(7)
12	-27.6	-16.5	59.0	11.2	4.8	—	24.2	29.5	—	75.0	49.6	—	86.2	55.0	—	91.1	82.7	N 5128(4) 104.7 102.6 N 5128(7)		
13	-52.3	7.3	79.0	3.3	2.0	—	5.3	4.4	N 5128(14)	13.4	18.9	N 5128(14)	49.8	59.6	I 4296(9)	28.8	59.5	I 4296(6) 38.4 80.6 N 5128(7)		
14	88.8	-47.1	83.0	4.5	2.8	N 7626(11)	8.4	7.2	—	16.7	42.5	—	65.3	74.8	N 7626(5)	84.6	71.3	—	95.6	67.9 N 5128(7)
15	-170.6	-45.7	69.0	6.0	2.0	—	12.5	5.4	—	48.8	33.7	—	65.4	46.0	—	37.6	86.0	—	34.8	86.8 N 5128(7)
16	-51.2	17.2	69.0	0.6	1.9	N 5128(35)	2.3	3.5	N 5128(24)	15.8	12.6	N 5128(8)	38.0	37.3	I 4296(6)	67.1	86.4	I 4296(4) 47.6 113.8 N 5090(8)		
17	-57.2	41.8	148.0	1.7	0.6	—	3.5	1.3	—	10.6	4.4	—	15.0	6.7	N 3557(6)	14.9	11.2	N 3557(16) 14.7 15.0 N 3557(22)		
18	63.5	-40.2	58.0	4.2	3.4	—	9.5	7.8	—	70.8	54.6	—	93.1	61.2	—	107.5	80.3	N 1316(4) 109.4 78.3 N 5128(7)		
19	-51.4	19.2	70.0	1.2	1.9	N 5090(35)	2.2	3.4	N 5090(22)	11.8	14.0	N 5128(7)	30.8	40.5	50.5	70.3	62.0	—	88.7	I 4296(7) N 5128(6)
20	-109.4	23.8	64.0	6.1	2.2	—	12.6	4.9	—	53.5	12.3	I 4296(8)	23.5	67.7	I 4296(4)	51.3	123.7	N 5090(4) 83.4 124.1 N 5128(6)		
21	-163.8	-54.4	78.0	5.3	2.2	—	11.1	4.5	—	41.2	29.3	—	57.9	42.7	—	42.9	68.7	—	36.5	98.4 N 5128(7)
22	-41.7	5.9	64.0	5.7	2.8	W 4452(8)	8.0	6.9	W 4452(4)	34.9	32.4	N 3557(1)	56.1	57.9	—	46.5	68.8	N 5128(9) 118.8 N 5128(7)		
23	12.1	-49.0	90.0	4.9	5.3	—	60.8	57.3	—	69.7	37.6	—	81.0	51.6	—	88.2	59.3	—	102.6	63.3 N 1316(5)
24	-21.8	54.1	71.0	2.7	1.4	—	6.4	3.3	—	47.3	11.3	—	50.0	16.9	—	42.7	20.6	N 4760(12) 35.3 26.9 N 4760(13)		
25	-65.1	34.5	80.0	1.3	1.3	—	2.7	2.0	—	5.1	8.4	—	5.2	16.2	N 3557(8)	7.4	35.8	1.4296(11) 18.6 53.3 N 5128(16)		
26	-125.2	-7.7	69.0	5.7	3.0	—	11.6	5.1	—	58.1	25.5	—	38.4	66.4	—	60.9	116.3	—	48.3	108.1 N 5128(7)

Note. — This table summarizes the results of our Monte Carlo simulations for each PAO-detected UHECR within the BS-A model of the Galactic Magnetic Field. The first four columns specify a UHECR index number, the arrival direction at the observatory in Galactic coordinates, and the energy in EeV used for the UHECR. The remaining columns summarize the results for the six compositions for UHECRs simulated. For each composition we list the average (first column for each composition and rms, second column for the 50 deflection angle) of the 50 deflection angles, corresponding to the fifty Monte Carlo simulations. The deflection angle is the angular distance between the earth-arrival direction and the outside-the-Galaxy arrival direction. In the third column for each composition we list the nearly extended radiogalaxy which best matches the 50 outside-the-Galaxy arrival directions of the UHECR and, in parenthesis, the number of outside-the-Galaxy arrival directions matched to this nearly extended radiogalaxy (maximum 50).

TABLE 2
RESULTS OF THE MONTE CARLO SIMULATIONS FOR AGASA UHECRS AND THE BS-A GMF MODEL

Event	1	b	Energy	H			He			O			Al			Ca			Fe		
				dist	rms	match	dist	rms	match	dist	rms	match	dist	rms	match	dist	rms	match	dist	rms	match
0	63.5	19.4	68.5	3.8	2.9	—	8.3	3.9	—	41.5	13.7	—	96.6	39.7	—	79.2	40.9	N 5127(8)	108.0	46.4	N 4261(7)
1	108.8	25.6	63.7	4.3	2.4	—	101	4.3	—	42.7	39.7	—	81.5	33.8	N 5127(5)	74.0	40.3	N 5127(4)	86.2	41.5	N 4261(7)
2	180.5	13.9	64.7	4.6	2.1	—	9.9	4.6	—	63.0	22.8	—	108.7	18.6	N 5128(8)	70.5	66.7	N 5128(6)	31.9	86.1	N 3557(5)
3	206.7	26.4	70.7	4.7	2.1	—	10.4	4.6	—	60.9	13.3	N 4760(5)	91.8	17.5	N 5128(16)	84.6	34.7	N 5128(15)	28.1	76.3	N 5090(11)
4	130.5	-41.4	149.1	2.3	1.2	—	5.1	2.6	—	22.9	12.4	—	21.2	34.7	—	29.2	59.1	—	56.1	88.2	N 7626(5)
5	77.6	20.9	93.8	2.5	1.8	—	5.5	2.9	—	32.0	13.2	—	68.2	48.6	N 5127(4)	90.5	49.5	N 5127(8)	67.2	54.7	N 5127(23)
6	38.9	45.8	100.8	4.8	0.9	—	9.2	1.7	—	27.5	6.2	—	35.5	11.3	N 5127(27)	38.0	22.3	N 5127(12)	58.4	15.8	N 4261(26)
7	56.8	-4.8	73.5	4.1	3.6	—	8.8	7.0	—	33.3	57.6	—	140.6	93.7	—	125.6	82.6	N 5127(5)	144.6	65.5	—
8	33.1	-1.1	105.0	9.6	2.3	—	17.3	4.9	—	45.3	18.1	N 7626(6)	78.3	41.9	N 7626(5)	120.9	79.3	N 120(4)	161.7	81.7	N 4261(6)
9	89.5	-44.3	84.0	4.4	3.0	N 7626(17)	102	6.1	N 7626(6)	27.3	43.9	—	55.5	58.5	—	78.5	74.5	—	72.4	78.8	—
10	98.5	-23.8	72.8	3.7	2.7	—	8.7	7.4	—	36.7	52.1	—	63.3	82.8	—	79.2	105.4	—	114.0	84.0	—

Note. — Columns are as in Table 1 but for the AGASA-detected UHECRs

TABLE 3
PAO-UHECR MATCHES TO CEN A AND THE RADIOGALAXY CONCENTRATION NEAR CEN A

Model	H				O				Al				Ca				Fe				
	CenA		RG Box		CenA		RG Box		CenA		RG Box		CenA		RG Box		CenA		RG Box		
	Frac	Match	Frac	Match	Frac																
BS-S	0.33	10	0.55	15	0.29	18	0.56	19	0.17	20	0.55	25	0.16	26	0.58	27	0.16	26	0.53	27	
AS-S	0.32	9	0.52	16	0.16	16	0.40	18	0.07	21	0.39	27	0.08	27	0.42	27	0.08	26	0.37	27	
BS-A	0.33	10	0.49	15	0.23	13	0.43	17	0.12	21	0.42	27	0.12	23	0.40	27	0.12	24	0.40	27	
AS-A	0.28	9	0.45	14	0.08	13	0.22	21	0.06	22	0.24	25	0.06	26	0.22	27	0.06	25	0.21	27	
ASS+R	0.28	9	0.48	13	0.09	12	0.42	18	0.08	15	0.36	23	0.05	19	0.30	27	0.05	23	0.27	27	
ASS+A	0.26	10	0.46	13	0.08	11	0.38	16	0.05	13	0.31	20	0.05	17	0.28	25	0.04	20	0.24	27	
BS-S(S)	0.25	10	0.46	13	0.05	11	0.31	18	0.03	13	0.23	20	0.03	17	0.17	24	0.03	16	0.16	26	

Note. — This table summarizes the statistics of the matches between UHECRs detected by the Pierre Auger Observatory and selected areas around Cen A and around the concentration of extended radio galaxies. Columns are: (1) GMF model; (2) fraction of the total (1350) outside-the-galaxy arrival directions which fall within a distance of 20° of Cen A and its extended radio lobes in the case of proton UHECRs; (3) number of UHECRs (of the total of 27) which have at least one of their fifty outside-the-galaxy arrival directions within 20° of Cen A and its extended radio lobes in the case of proton UHECRs; (4) fraction of the total (1350) outside-the-galaxy arrival directions which fall within the ‘Radiogalaxy box’ with limits in Galactic coordinates $240^\circ \geq l \leq 360^\circ$ and $-10^\circ \geq b \leq 70^\circ$; (5) number of UHECRs (of the total of 27) which have at least one of their fifty outside-the-galaxy arrival directions within the ‘Radiogalaxy box’ described above; (6 to 21) as in columns 2 to 5 but for heavier compositions as labelled.

TABLE 4
AGASA-UHECR MATCHES TO CEN A AND THE RADIOGALAXY CONCENTRATION NEAR CEN A

Model	H			O			Al			Ca			Fe							
	CenA	RG Box	Frac	Match																
BS-S	0.00	0	0.00	0	0.00	1	0.14	6	0.12	2	0.38	8	0.07	5	0.28	10	0.03	6	0.31	11
AS-S	0.00	0	0.00	0	0.01	2	0.25	6	0.15	5	0.54	10	0.10	10	0.57	11	0.09	11	0.54	11
BS-A	0.00	0	0.00	0	0.01	2	0.14	4	0.11	4	0.34	9	0.07	5	0.28	10	0.05	5	0.29	11
AS-A	0.00	0	0.00	0	0.01	2	0.23	6	0.16	5	0.48	10	0.06	8	0.45	11	0.06	10	0.44	11
ASS-R	0.00	0	0.00	0	0.00	0	0.01	1	0.00	0	0.03	2	0.01	3	0.06	6	0.00	1	0.09	9
ASS+A	0.00	0	0.00	0	0.00	0	0.01	1	0.00	0	0.03	2	0.01	3	0.05	5	0.00	1	0.08	7
BSS(S)	0.00	0	0.00	0	0.00	0	0.00	1	0.00	0	0.02	3	0.00	1	0.03	4	0.01	2	0.06	8

Note. — Columns are as in Table 3, but for UHECRs detected by AGASA. In this table we report 11 UHECR events corresponding to 550 outside-the-Galaxy arrival directions over all six compositions.

TABLE 5

MATCHES BETWEEN PAO-UHECRS & NEARBY ELLIPTICAL SAMPLES

C	Model	RG Extended		RC3 Extended		RC3 Non-extended	
		Match	Frac.	Match	Frac.	Match	Frac.
H	BSS	4	7.4	3	9.4	9	1.2
	ASS	0	0.3	0	0.1	12	1.3
	BSA	5	7.1	4	8.8	8	1.2
	ASA	1	0.1	1	0.1	13	1.4
	ASS+R	1	1.2	0	0.1	10	1.3
	ASS+A	2	1.3	0	0.1	9	1.2
	BSS(S)	2	1.7	0	0.0	9	1.3
He	BSS	5	5.6	5	7.3	13	1.8
	ASS	2	1.5	1	1.0	9	1.2
	BSA	5	7.5	5	9.5	11	1.6
	ASA	1	0.5	1	0.7	11	1.5
	ASS+R	5	4.7	2	3.5	6	1.1
	ASS+A	3	2.3	0	0.2	5	0.8
	BSS(S)	1	1.1	0	0.3	7	0.9
O	BSS	10	10.7	10	13.1	18	3.6
	ASS	1	5.1	1	6.1	6	2.4
	BSA	7	8.5	7	11.0	15	3.6
	ASA	1	2.4	1	3.2	5	2.3
	ASS+R	2	5.9	2	5.5	10	2.6
	ASS+A	3	6.3	3	6.5	9	2.5
	BSS(S)	2	3.9	2	3.5	10	2.1
Al	BSS	11	13.3	11	17.0	25	4.8
	ASS	2	8.8	1	10.2	9	3.9
	BSA	8	10.7	8	13.3	19	4.9
	ASA	1	5.1	1	5.2	10	3.9
	ASS+R	4	8.7	4	9.2	20	3.7
	ASS+A	1	6.3	0	5.6	11	3.7
	BSS(S)	0	5.1	0	3.5	10	3.0
Ca	BSS	15	24.5	14	29.8	19	5.7
	ASS	4	16.2	4	19.6	16	4.8
	BSA	12	18.2	12	22.4	20	5.4
	ASA	2	8.7	1	8.9	10	4.6
	ASS+R	4	9.7	4	11.3	19	4.6
	ASS+A	3	10.0	3	9.7	16	4.6
	BSS(S)	0	8.1	0	6.0	13	4.3
Fe	BSS	18	31.2	17	37.8	22	5.9
	ASS	7	20.6	7	23.5	19	5.6
	BSA	14	24.9	14	29.2	23	5.9
	ASA	5	15.9	4	16.1	14	5.5
	ASS+R	6	13.8	6	14.6	23	5.7
	ASS+A	2	12.3	1	11.2	17	5.3
	BSS(S)	5	13.1	2	10.1	19	5.3

Note. — This table summarizes the match statistics between UHECRs detected by the Pierre Auger Observatory and three samples of ellipticals at $D \leq 75$ Mpc: all 15 nearby extended ($LLS \geq 180$ kpc) radiogalaxies (columns 3 and 4), all ellipticals from the RC3 catalog with extended ($LLS \geq 180$ kpc) radio structure (columns 5 and 6) and a matched sample of ellipticals from the RC3 catalog without extended radio structure (columns 7 and 8; see text). Columns 1 and 2 list the UHECR composition and GMF model. The two columns for each sample of ellipticals list the number of UHECRs (of the total of 27) which can be matched (see text) to some member of the sample, and the fraction of the total (1350) Monte Carlo points which fall within the match distance-limit of the sample's galaxies.

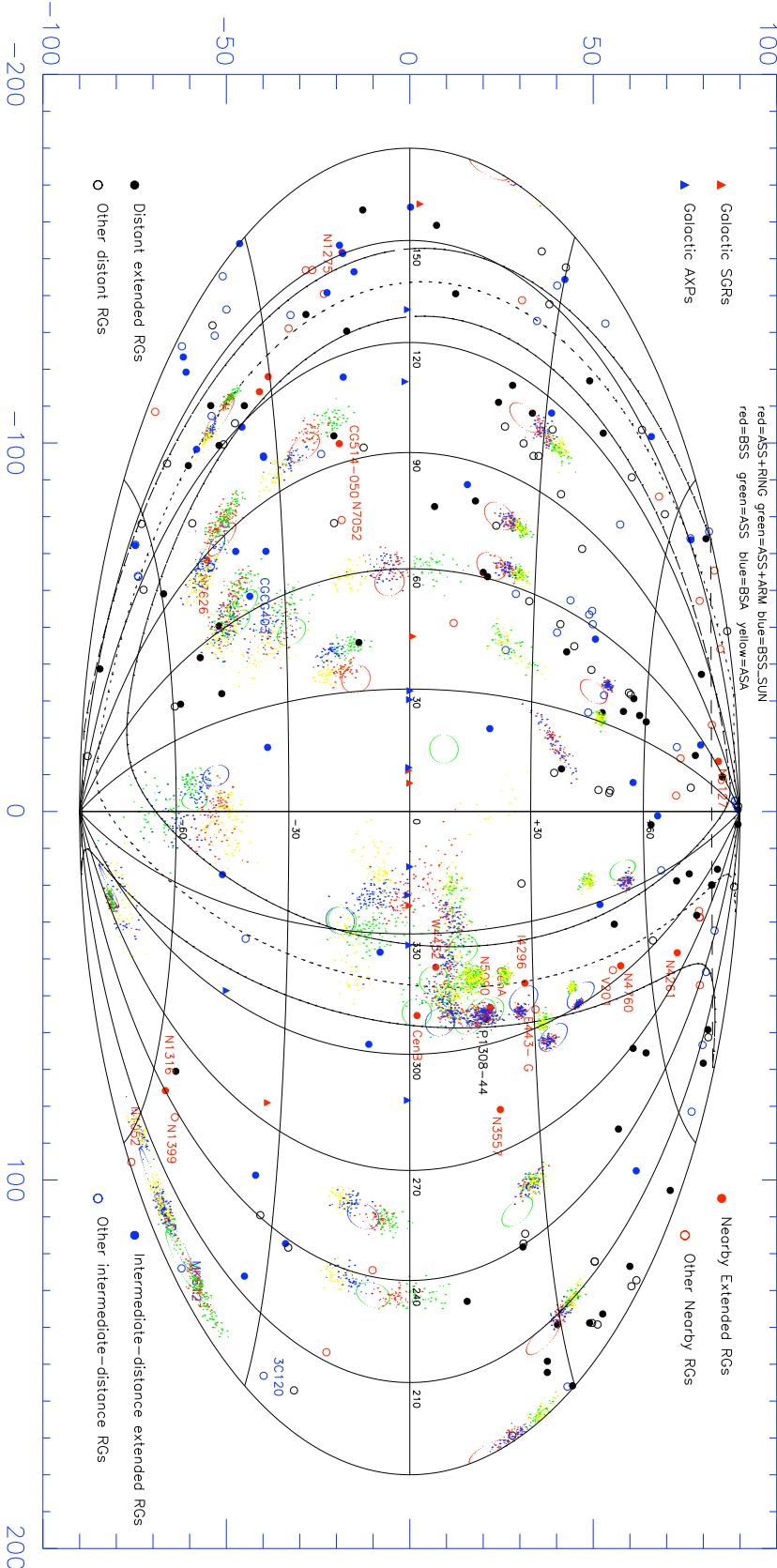


Fig. 1. A comparison of the earth-arrival directions of all UHECRs with energies above 56 EeV detected by PAO (blue for UHECRs with energy ≥ 75 EeV and green for UHECRs with energy between 56 and 75 EeV) and AGASA (red open circles of radius 3.5°) with the estimated outside-the-Galaxy arrival directions of the same UHECRs (small colored dots) for our Monte Carlo simulations of the BS-S (red), AS-S (green), BS-A (blue), and AS-A (yellow) GMFs using a proton composition for the UHECRs. The colored circular symbols mark the positions of galaxies with radio jets at $D \leq 75$ Mpc (red), $75 \text{ Mpc} < D \leq 200$ Mpc (blue), and $200 \text{ Mpc} < D \leq 500$ Mpc (black). In all redshift bins, filled circular symbols are used for galaxies with radio structures more extended than 180 kpc, and open circular symbols for galaxies with radio structures less extended than 180 kpc. Galactic SGs (red triangles) and AXPs (blue triangles) are also plotted. The Supergalactic plane is marked by the dashed line. In this and following figures we use an Aitoff-Hammer (equi-area) projection in Galactic coordinates.

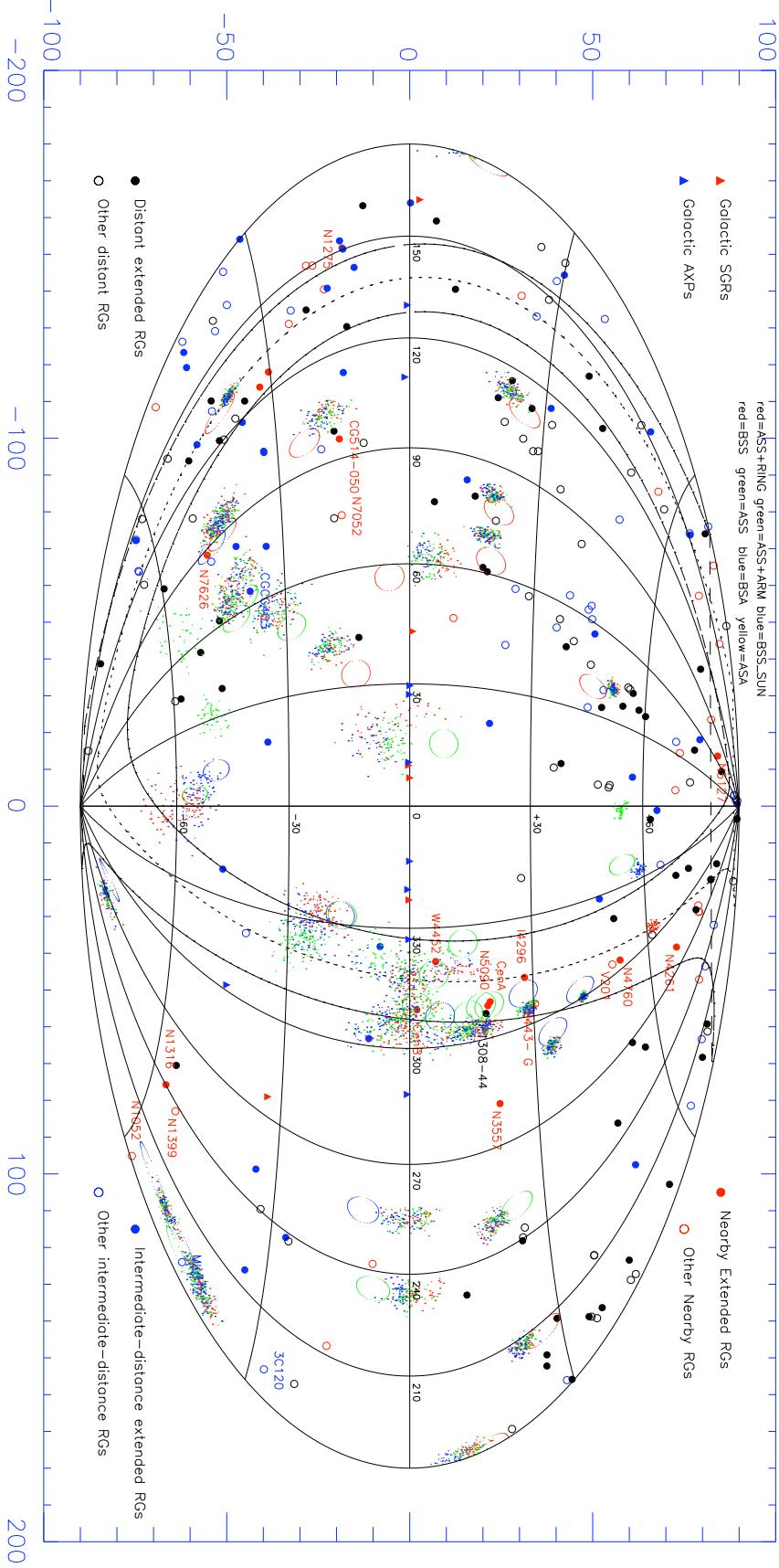


Fig. 2. Same as Fig. 1 for the three new models proposed by S08: AS-S+RING (small red dots), AS-S+ARM (small green dots), and BS-S (small blue dots). Here, as in S08, no ordered dipole field component was used.

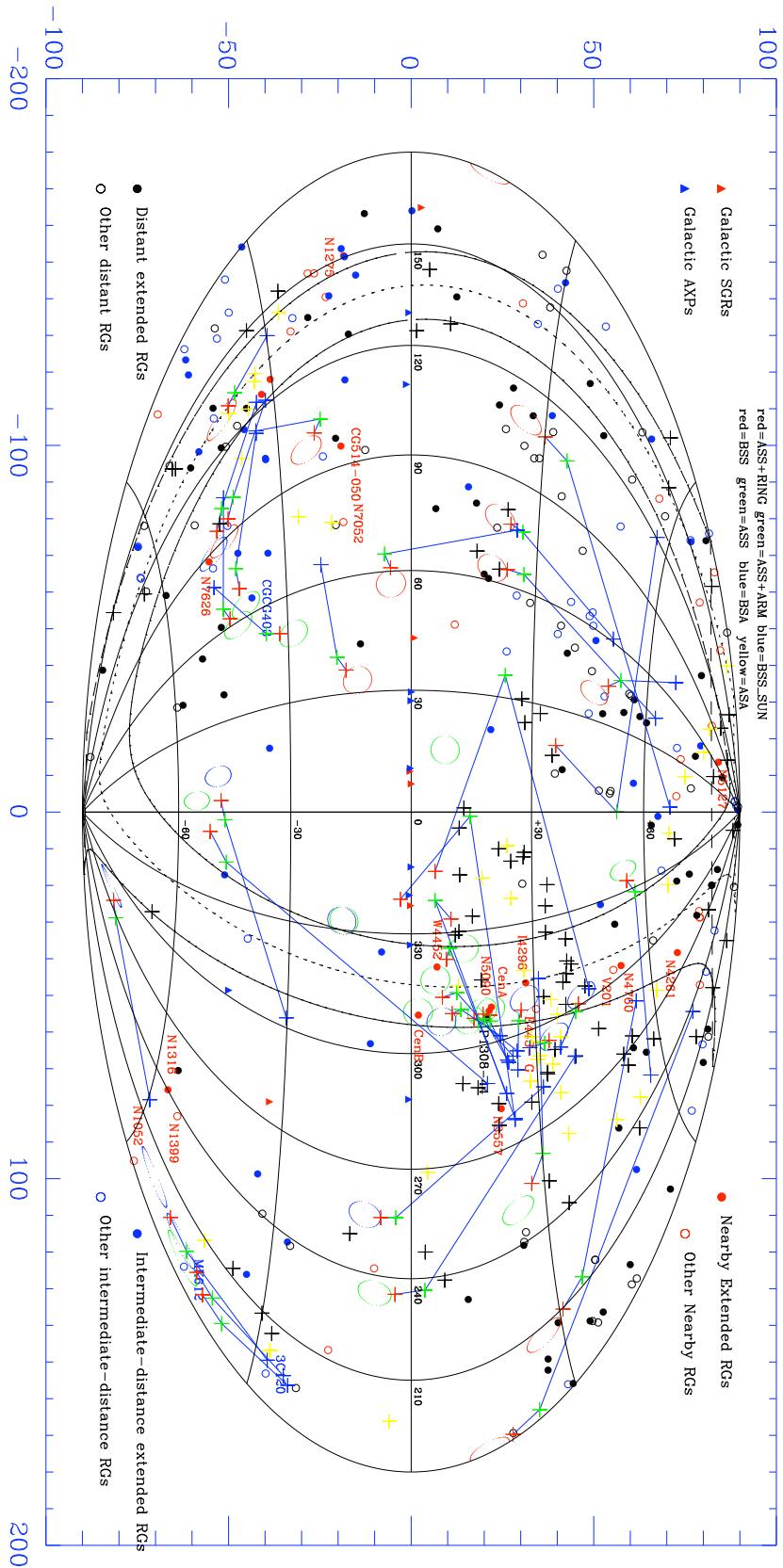


Fig. 3. A comparison of the measured earth-arrival directions of all UHECRs with energies above 56 EeV detected by PAO and AGASA (blue, green, and red open circles with radius 3.5° as in Fig.1) with the estimated outside-the-Galaxy arrival directions of the same UHECR (crosses) within the BS-S model for UHECR compositions of protons (red), He (green), Oxygen (blue), Aluminum (yellow), and Calcium and Iron (black). The first three compositions of the same UHECR are connected with blue lines while the heavier compositions are not connected to avoid overcrowding. Other symbols and names in the figure are the same as in Fig. 1.

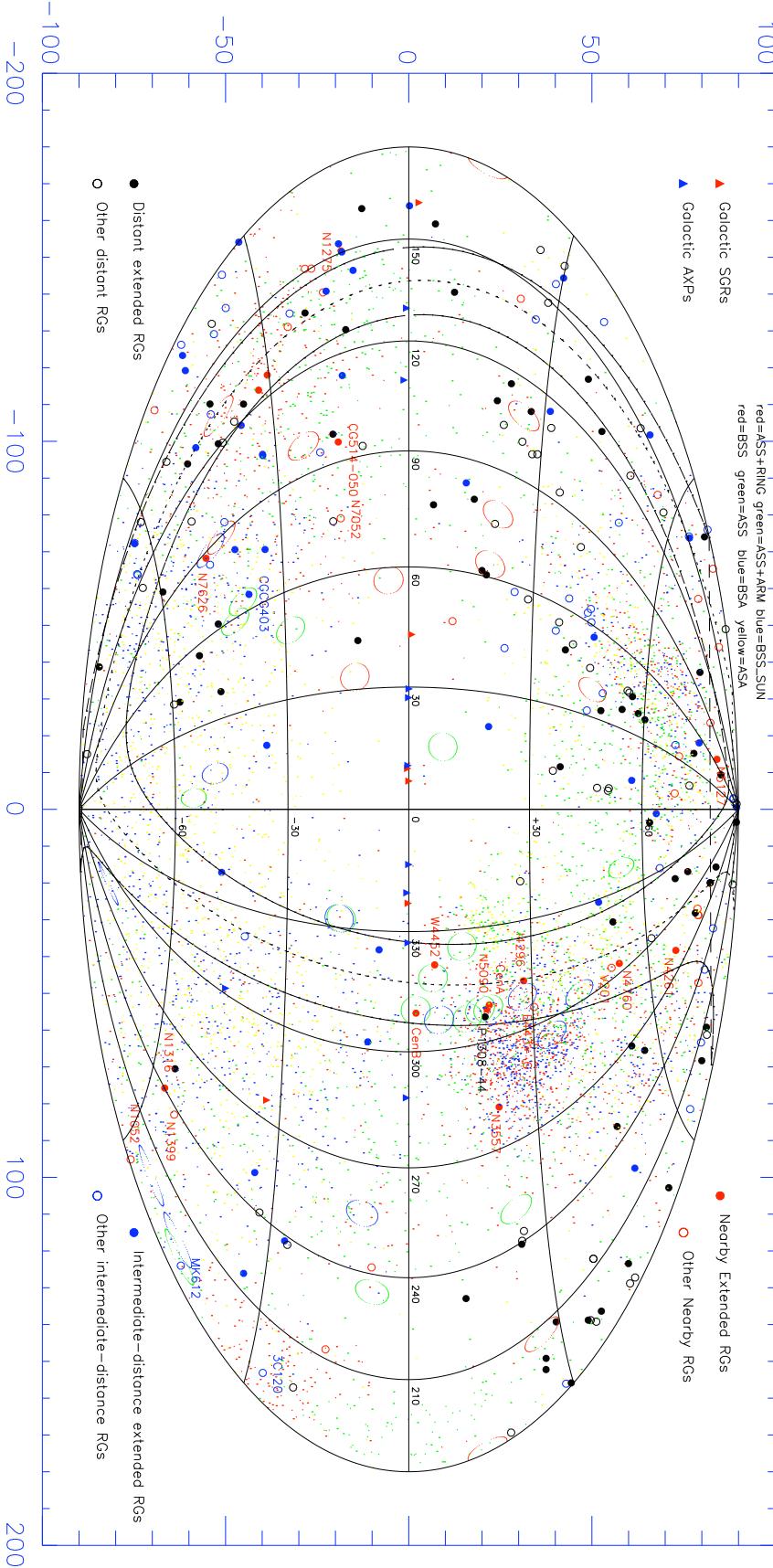


Fig. 4. Same as Fig. 1 but for a UHECR composition of Oxygen.

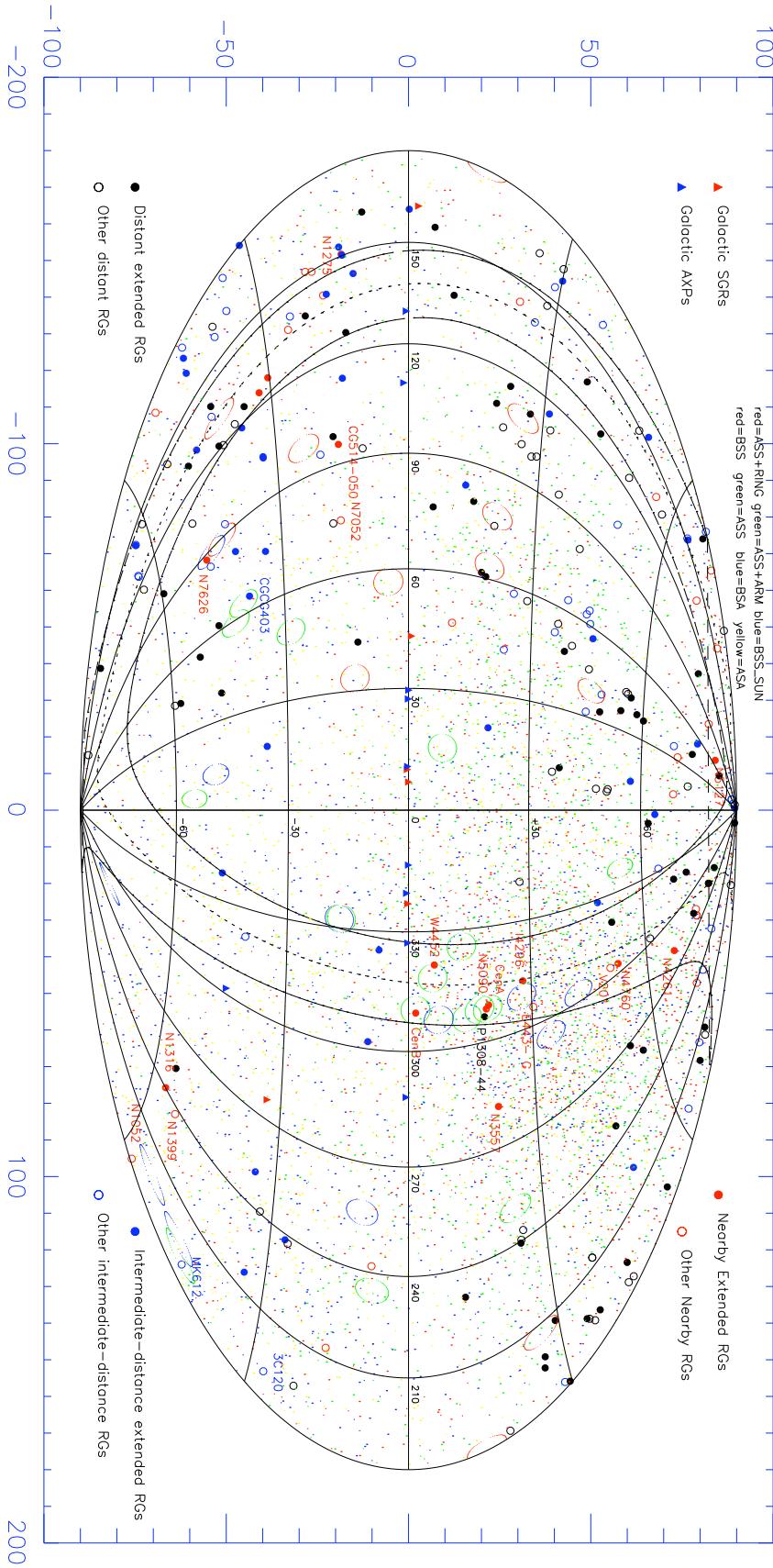


Fig. 5. Same as Fig. 1 but for a UHECR composition of Iron.

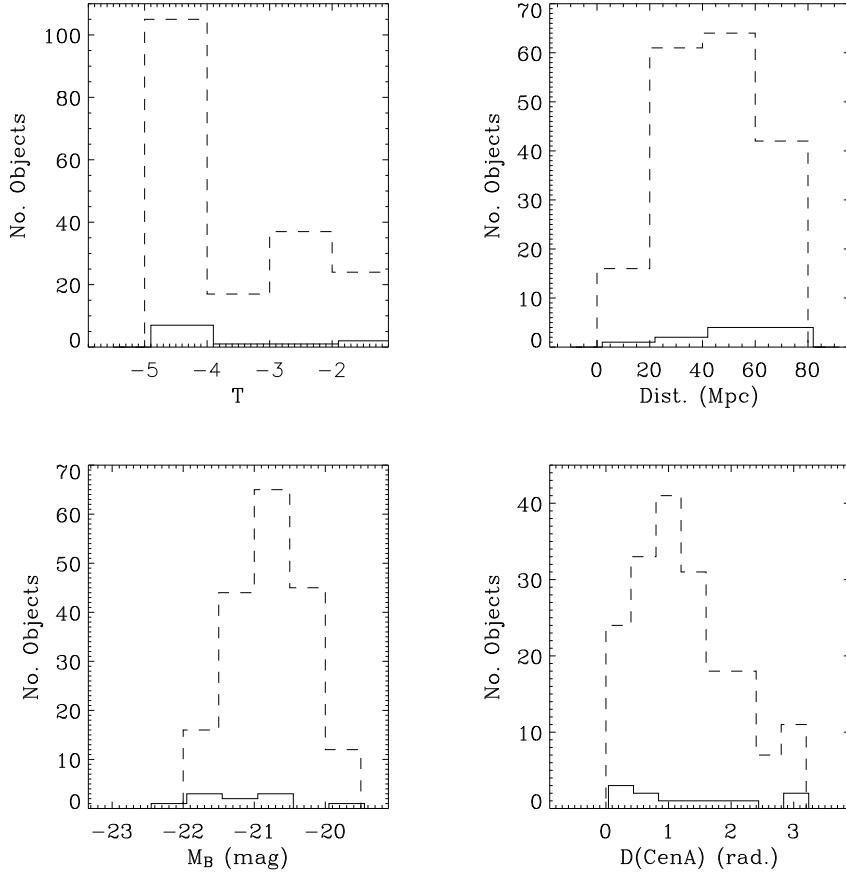


Fig. 6. Histograms of Morphological Type, Distance, Absolute B magnitude and distance from Cen A for the two samples of $D \leq 75$ Mpc elliptical galaxies drawn from the RC3 catalog (see text): the 11 nearby RC3 ellipticals with extended radio structures (solid line histograms) and the matched control sample of 183 nearby RC3 ellipticals without extended radio structures.