PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Transient Source for the Highest Energy Galactic Cosmic Rays

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We show that the dipole anisotropy of CRs above 1 EeV measured by the Pierre Auger Observatory is well described as the sum of the contribution of an extragalactic population of CRs (ECRs) plus CRs from a Galactic source. Above 8 EeV the CRs are almost exclusively extragalactic and the ECR anisotropy is well constrained by data; the energy dependence of the dipole is weak and well-understood theoretically. Modeling the spectrum and composition of CRs above 1 EeV reveals two disjoint rigidity groups, attributable to ECR and GCR populations. This enables the relative contributions of GCRs and ECRs to the total flux in each energy bin to be determined. Thus the ECR dipole in the region containing both ECR and GCRs can be removed, allowing us to isolate the dipole anisotropy of the highest energy Galactic CRs.

The dipole of these highest energy GCRs is inconsistent at greater than 6σ with being toward or away from the Galactic center, disfavoring acceleration in the Galactic termination shock and preferring acceleration in a transient event whose longitude we constrain: $L \approx 70° \pm 20°$. The amplitude α of the high-energy GCR dipole is ≈ 0.05, which leads to an estimate for the distance/time since the event, using $\alpha \approx r/(2ct) \approx 0.05$. A candidate remnant of the transient is identified: SNR G65.3+5.7. This SN occurred about 800 pc away, about 20 kyr ago. This single transient event can be responsible for the entire local population of CRs with energies ranging over the bins 0.25-0.5 EeV to 4-8 EeV, with only a tiny fraction of the overall energy of the transient explosion being in VHE CRs. The pulsar PSR J1931+30 may also be a relic of the event; if so, it would confirm the core-collapse nature of the SN. Most massive young stars are in binary systems. We thus propose that the highest energy GCRs were accelerated when the shock created by a core-collapse supernova collided with the wind of its massive binary companion. From the rate of core collapse SNe and the fact that massive stars are generically in binaries with other massive stars, we estimate the probability of seeing an event close enough in space and time to give the observed flux and an anisotropy as large or larger than observed to be $O(0.1 - 1)$.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)488

Introduction

The puzzle of the nature and origin of Ultrahigh Energy Cosmic Rays (UHECRs, with energy $\geq 10^{18}$ eV = 1 EeV) has received extensive attention over several decades, but remains unresolved. Another important outstanding puzzle is the origin of the highest energy Galactic cosmic rays (GCRs) which are too high in energy to be accelerated in Supernova Remnants (SNRs), the mechanism responsible for the bulk of GCRs. These highest enegy CRs were dubbed "component B" by Hillas [1] hence we denote them herein as GCB, and use GCA to refer to the great bulk of Galactic CRs, accelerated by SNRs, whose maximum rigidity is $\approx 10^{15.5}$V.

There are two pieces of evidence for the existence of a distinct GCB population. First is the spectral feature called the "second knee" at about 10^{17} eV – just where one would expect GCA iron to cut-off, given the cut-off observed in protons at about $10^{15.5}$ eV which gives rise to the first-observed bend in the spectrum called the knee or now the first knee. (This "mirroring" of structures in energy follows because acceleration and confinement of Galactic cosmic rays depends mainly on rigidity = E/Z, with Fe at 10^{17} eV having the same rigidity as p at $10^{15.5}$ eV.) Thus the absence of a large gap in the spectrum between the end of the GCA spectrum at around 10^{17} eV and the onset of the extragalactic CRs around $10^{18} - 10^{18.5}$ eV, points to another population as emphasized by Hillas [1]. The second line of evidence for a distinct GCB population follows from the clear evidence from Auger of a transition between the light (low-mass) composition of UHECRs at the low-energy end of the UHECR spectrum $10^{18} - 10^{18.5}$ eV and a heavier composition at lower energies. There have also been hints for an analogous composition shift at the GCA-GCB transition around 10^{17} eV, although the evidence for these is murkier and different experiments report different conclusions [2–4]. The GCB population is consistent with production by a single acceleration mechanism, which only depends on rigidity and which peaks at $R \approx O(10^{17} - 10^{17.5}$ eV) – a value roughly two decades higher than thought to be possible in ordinary SNR.

In the present work, we advance the discussion of the origin of GCBs by i) isolating the dipole anisotropy of GCB using Auger data, ii) interpreting the GCB anisotropy to discriminate between competing proposals for the GCB acceleration mechanism, iii) identifying a possible relic of the transient event which produced the GCBs and iv) examining the required energetics and demographics of GCB-capable transients to address the question whether seeing such a population should be expected, or is a lucky chance occurrence. The organization of the paper follows this structure.

Finding the Dipole Anisotropy of the highest-energy GCRs

Composition determination of UHECRs is still difficult, mainly impeded by the uncertainty of modeling UHE air showers and by the challenging observations required. Fortunately, we can expect rapid progress on both fronts due to the AugerPrime upgrade and the TAx4 and TALE augmentations to TA, and to likely improvements to air shower modeling thanks to detailed diagnoses of the model shortcomings such as [5, 6]. Nonetheless, multiple approaches to composition determination show two almost disjoint groupings in rigidity in the 1-10 EeV range, illustrated in Fig. 1. As can be seen, the general picture from different composition analyses is in agreement: one population (GCBs) peaked around lgR $\equiv \log_{10}E/Z \approx 17.2$ and another (ECRs) peaked above 18. As the energy bin shifts from high to low energy, the Galactic fraction increases from $\approx$ 10%, 30% and 50% in the 4-8, 2-4 and 1-2 EeV bins, respectively, following the analysis of [7] (MUF19, below).

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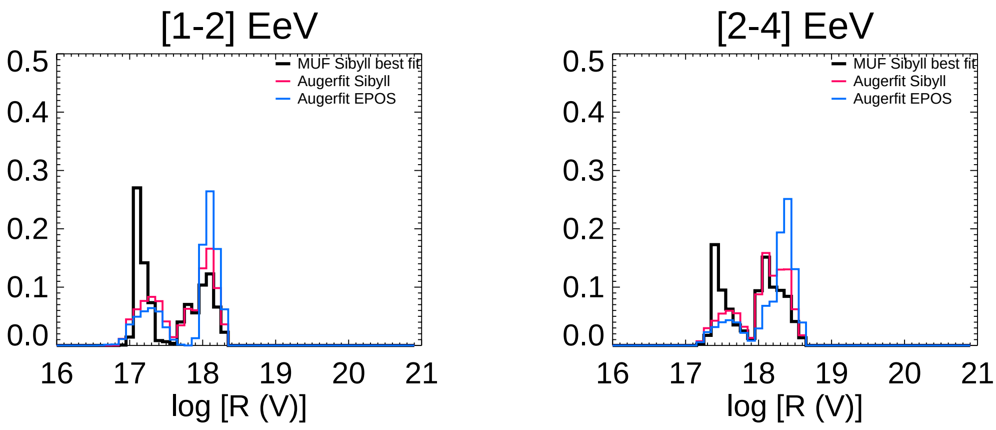

Figure 1: The rigidity breakdown as a function of energy from Auger using 2 different models, and from the modeling of MUF19 (dashed, thin lines and solid, respectively).

In separate work [8], denoted DGF21 below, we showed that the dipole anisotropy above 8 EeV and its evolution with energy can be explained with the simple ansatz that extragalactic UHECR production follows the distribution of matter, taking into account interactions and possible magnetic diffusion during extragalactic propagation en route to the Galaxy, and deflection and diffusion in the Galactic magnetic field. DGF21 used the Jansson-Farrar 2012 (JF12) GMF model whose random and coherent components were fit to all-sky rotation measure and synchrotron emission data [9]. The DGF21 model predicts that the energy dependence of the extragalactic dipole direction is weak. Given the plausibility of the DGF21 model and its good fit to the strength and direction of the dipole above 8 EeV, where composition measurements indicate that the Galactic contribution is negligible, we use DGF21 predictions at lower energy to subtract the extragalactic contribution to the total dipole, revealing the dipole of the highest energy GCRs.

Using the JF12 model and tracking simulations [10] enables one to estimate the local isotropic diffusion coefficient, $D(R)$. The main uncertainties are the coherence length, which is estimated to be 5-30 pc near the Galactic plane, and the rms B field strength which we allow to range from 1-3 μG. The extremes of the resultant values for rigidity lgR $\approx$ 17.2, relevant for GCB are $0.06 < D_{17.2} < 3\,\mathrm{kpc}^2/\mathrm{kyr}$. The actual value of the diffusion coefficient is relatively unimportant for the first part of our analysis, as we shall see below. Rather, the important question is whether the propagation can be taken to be diffusive on the time scales of interest (> 20 kyr); this is indeed the case for the rigidities relevant for local GCB's (lgR$\lesssim$ 17.4).

Including all three components of the CRs, the total dipole anisotropy in any energy bin is

$$\boldsymbol{\alpha}(E) = \sum_i f_i(E) \sum_j f_j(R_j, E)\, \boldsymbol{\alpha}_i(R_j) \tag{1}$$

where $i = 1, 2, 3$ labels ECR, GCB and GCA, and $f_i(E)$ are their respective fractional contributions to the total flux at energy E. Within a given component, the direction and magnitude of its anisotropy at energy E is a weighted sum over the anisotropies $\boldsymbol{\alpha}_i(R_j)$ of the contributing composition components j, with $R_j = E/Z_j$. The symbols $\boldsymbol{\alpha}(E)$ and $\boldsymbol{\alpha}_i(R_j)$ represent, symbolically, the arrival distribution in spherical coordinates for a specified dipole magnitude, $\alpha(E)$ or $\alpha_i(R_j)$, pointing in direction $\hat{\alpha}(E)$ or $\hat{\alpha}_i(R_j)$. Thus the amplitude of the dipole anisotropy of a given component could be very large, but if that component makes only a small contribution to the total flux in the given energy bin, the total dipole amplitude can be small. Also, the total anisotropy can be small if the directions of the anisotropy of different components are distinctly different, as proves to be the case for the Galaxy.

A valuable tool in our treatment and interpretation of the GCB anisotropy is the result derived in [11], for the magnitude of the dipole anisotropy of the flux produced by a transient source in a homogeneous diffusive medium:

$$\alpha = r/(2ct). \tag{2}$$

It is noteworthy that α only depends on the ratio of distance and time since the event, and is independent of the diffusion coefficient. This means that if GCB is due to a transient, its dipole anisotropy should be independent of rigidity, to the accuracy of Eq. (2). Furthermore, Eq. (2) implies that once we determine $\alpha_{\rm GCB}$ we can constrain the ratio of distance and time since the transient occurred. To the extent that coherent magnetic deflections can be ignored, the direction of the dipole points to the location of the event. We will see later that the distance to the probable transient source is small, so the coherent shift of the GCB anisotropy direction due to GMF deflection is $\lesssim 10°$ and can be ignored in first approximation.

To start, we restrict our analysis to high enough energy that we can take $f_{\rm GCA}(E) = 0$. If we assume we know the extragalactic anisotropy from DGF21 and could confidently determine the fractional contributions of GCB to the total flux in the energy range of our analysis, and take the GCB anisotropy to be rigidity-independent, there would be only 3 free parameters to determine: the magnitude and direction of the GCB dipole anisotropy. To allow for a possible rigidity dependence of the GCB anisotropy magnitude if GCB's are not from a transient source, and also because there is some uncertainty in the GCB composition fractions, we allow the GCB dipole magnitude to vary monotonically from one energy bin to the next by a factor $f_{[2-4]}$, $f_{[4-8]}$ relative to the 1-2 EeV bin. After determining the direction of the transient source dipole and its magnitude above 1 EeV, we extend the analysis to lower energy bins where the only new element is the dilution of the GCB and ECR contributions by the nearly-isotropic regular GCRs from supernova remnants.

Thus our treatment of the GCB dipole introduces 5 parameters: the direction of the dipole, and the weighted dipole magnitude in the 1-2, 2-4 and 4-8 EeV bins. There are 7 observables to be fit: for the 4-8 EeV bin we have the full 3D dipole magnitude and direction while in the 1-2 and 2-4 bins we have the RA of the dipole and its magnitude projected on the equatorial plane (the "equatorial dipole", $d_\perp$). The direction of the GCB dipole anisotropy which gives the best fit to the data is $\ell = 68.9°$, $b = -9.6°$, and its magnitude in the 1-2 EeV bin is 5.1%. Because we lack the dz constraint in the lower energy bins, a band of possible positions for the GCB source give almost equally good fits, as shown in Fig. 2. When d_z is eventually determined observationally in these bins, the direction of the transient source dipole can be better constrained.

With the parameters of the GCB dipole fixed by fitting the anisotropy in the 1-8 EeV bins, we can predict the anisotropy in the 0.25-0.5 and 0.5-1 EeV bins where phase information and limits have been reported by Auger [13]. This energy range contains events from sources of all three types: extragalactic, Galactic transient, and conventional SNRs. The extragalactic contribution to these bins is completely predicted by the DGF21 model; it is small but not negligible. Regular SNR GCRs of high-Z make some contribution, mainly in the lower energy bin; in first approximation we take these CRs to be isotropic. Their anisotropy – due to the sources being more centrally concentrated in the Galaxy and additionally modified by the coherent magnetic field (for an indicative estimate see

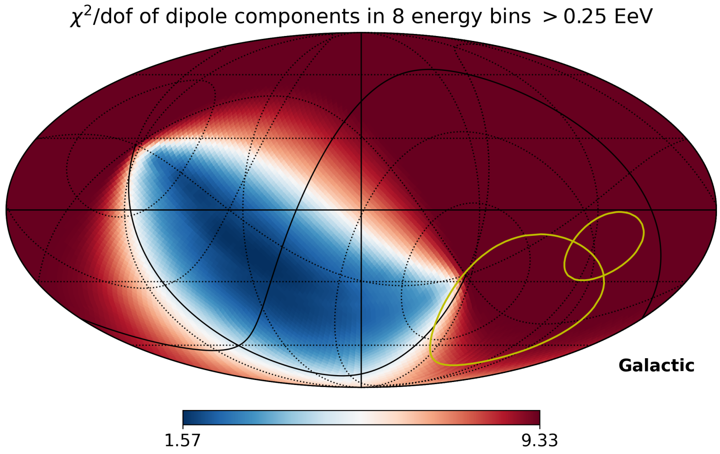

Figure 2: $\chi^2/n_{\rm dof}$ for the dipole direction of highest energy Galactic CRs; an Equatorial Coordinate grid is overlaid. The dipole pointing toward or away from the Galactic center is excluded by more than 6σ. The 1-σ domains of the direction of the total dipole in the 4-8 EeV and >8 EeV bins measured by Auger [12] are the large and small yellow ovals.

Fig. 5 of [12]) – will be modeled in a future more comprehensive analysis. Accurate composition determination in this regime would quantify the transition in the proportions of predominantly heavy regular GCRs (GCA) to predominantly light transient-produced GCRs (GCB), and provide a stronger prior on the relative weight between the approximately isotropic GCA contribution and that of the transient.

Implications for the GCB acceleration mechanism

Given that the rigidity of the GCB component is nearly two orders of magnitude higher than produced by conventional SNR acceleration, some other acceleration mechanism is required. The two major competitors are acceleration in the Galactic wind termination shock or in some as-yet unidentified transient event. (See [4] for an overview.) The $\chi^2/n_{\rm dof}$ of our fit to the Auger anisotropy data is shown as a function of direction of the GCB dipole in Fig. 2. A dipole direction toward the Galactic center is excluded at more than 6 σ. This strongly disfavors acceleration in the termination shock, which by azimuthal symmetry and N-S symmetry must produce a dipole anisotropy toward or away from the Galactic center.

If GCBs are not accelerated in the termination shock, their source must be transient. This is because if the source were continuous it would likely be very striking at other wavelengths and would produce a corresponding or even stronger dipole in gammas than presently observed. Bykov et al (2018) [14] proposed a colliding shock flow (CSF) mechanism, in which a SN explosion in a cluster of massive young stars creates a sort of “super-shock" when colliding with the winds of those stars, as an explanation for some astrophysical neutrinos. However there is no star cluster in the relevant region of the Galaxy to explain the GCB anisotropy, so their proposed realization of the CSF acceleration mechanism does not work for GCBs. Nonetheless, as we argue below, the fundamental CSF mechanism can be correct, but realized due to the SN occurring in a binary pair.

A crucial remark is that CR acceleration and the deflections of the CRs during propagation from the transient source (including time delay) depend only on the rigidity of the CR and not on its energy *per se*[1]. The peak observed rigidity of the highest energy GCRs is about 0.2 EV, as seen in Fig. 1, so the low-Z CRs from the same transient arriving today should be protons and He with peak energies in the 2-4 10^{17} eV range. The anisotropy of these events is, as stressed, *identical* to that of their heavier cousins seen in the higher energy bins and analyzed above. Of course, the contribution of the transient source events to the overall dipole is diluted differently in different energy bins, depending on the abundance of different charges accelerated in the event and the contribution of other sources (Galactic SNR and Extragalactic) in the given bin.

Transient source of the high energy GCRs observed today

Given the χ^2 map in Fig. 2, we seek a relic of the event in the Galactic longitude range $30° - 100°$. Massive young stars, whose core collapse SN could produce the colliding shock flow conditions for GCB acceleration, are formed and explode close to the Galactic plane. This would give a secondary constraint, on Galactic latitude, but it is not needed: that is already reflected in the latitude range of SNRs. From the observed $\alpha_{\rm GCB} \approx 0.05$, we expect the time since the explosion should approximately satisfy

$$t_{\rm kyr} \approx 30\, r_{\rm kpc} \left(\frac{\alpha_{\rm GCB}}{0.05}\right) \quad , \tag{3}$$

so we reject extremely old relics.

"A Catalogue of Galactic Supernova Remnants", 2019, by D. A. Green (available at http://www.mrao.cam.ac.uk/surveys/snrs/) is a comprehensive listing of the 294 known SNR. Searching it yields a unique candidate in the required longitude range, SNR G65.3+5.7, at a distance of 0.8 kpc. Its estimated time-delay is $\approx$ 20 kyr based on the size of the SNR shell. Allowing for the additional light transit time from 0.8 kpc, leads to a propagation time of $\approx$ 22.4 kyr for CRs observed today. Using Eq. (2), the predicted anisotropy if the SN producing G65.3+5.7 were responsible for Galactic component B would be $\alpha_{\rm G65.3+5.7} \approx 0.053$, in excellent agreement with our determination from anisotropy data. The pulsar PSRJ1931+30 is aligned with the center of G65.3+5.7; if it is a relic of the same event, that would provide corroboration that G65.3+5.7 is the relic of a core-collapse SN and not of a SN1a. The alignment may be a chance coincidence since the distance to PSRJ1931+30 estimated via its dispersion measure (DM) is too great for it to be associated with G65.3+5.7. But DM distance estimates are found to often be unreliable [15] (not surprising, given their reliance on simplistic, homogeneous models of the thermal electron density), so whether PSRJ1931+30 is a relic of the same event is an open question for now. Much can be learned from more detailed observation of the spin-down of PSRJ1931+30, including its magnetic field and age – the latter being another handle on whether it is associated with G65.3+5.7. Moreover if PSRJ1931+30 is a relic of the event, its magnetic field would be very informative to modeling acceleration in the explosion.

Treating GCB diffusion in the GMF in homogeneous-isotopic approximation, the solution of the diffusion equation gives the density of CRs at a distance r after a time t, in any rigidity bin:

$$n(R,r,t) = \frac{N_0(R)\, e^{-r^2/(4D(R)\,t)}}{(8\pi D(R)\,t)^{3/2}} \quad , \tag{4}$$

where $N_0(R)$ is the total number of CRs emitted in rigidity bin R and $D(R)$ is the diffusion coefficient for CRs of rigidity R; Eq. (2) is derived from Eq. (4). Since the local number density is related to

[1]Corrections due to interactions with ambient gas and photons are negligible, given the short propagation distances.

the measured flux, $n = 4\pi j/c$, knowledge of r, t and $D(R)$ enables us to determine $N_0(R)$, the total number of CRs emitted in rigidity bin R, and the total energy emitted in CRs in energy bin lg$E$:

$$E_{\rm tot} = \sum_{\rm lgR} \epsilon_{\rm lgR}\, (8\pi D(R)\, t)^{3/2}\, e^{r^2/(4D(R)\, t)} \;\;, \tag{5}$$

where $\epsilon_{\rm lgR}$ is the local energy density of CRs in each contributing rigidity bin, lg$R$:

$$\epsilon_{\rm lgR} = \sum_Z \frac{4\pi}{c}\, (Z\, 10^{{\rm lg}R})\, j({\rm lg}E = {\rm lg}R + {\rm lg}Z) \;\; . \tag{6}$$

Summing the energy in GCB above 0.25 EeV, for the representative choices of coherence length and rms field strength discussed above, the energy in CRs produced by the transient event is of order $10^{44} - 10^{45}$ erg – a very tiny fraction of the total available energy of the SN, $\approx 10^{54}$ erg.

A final question is whether observing a GCB-like component of CRs with energies beyond the cutoff of normal SNR acceleration, and a flux and anisotropy magnitude in the observed ranges is exceptional or expected. We can address that question as follows. Using the equations above, one can determine the maximum distance to observe as great or greater anisotropy as observed, while keeping the power requirement within a factor-10 of our example and the flux within a factor-10 of the observed flux, the distance should be $\lesssim 2$ kpc. The rate of core collapse SNe in the Galaxy is about 1 per 100 yr, so there are 300 in 30 kyr. About 4% of all SNe are within 2 kpc of us, so about 12 ccSN occurred sufficiently close and recently to produce a GCB comparable to our observed one. Since one event is currently contributing, we conclude that 10-100% of ccSNe produce high energy CRs with $E/Z \gtrsim 100$ PeV according to this scenario. This is consistent with the fact that most massive young stars are in binaries such that their SN ejecta will produce a colliding shock flow sufficient for acceleration to these rigidities, sometime during their expansion into the wind of their companion.

Summary

We have used Auger measurements of UHECR anisotropies above 1 EeV to determine the magnitude and direction of the dipole anisotropy of the highest energy Galactic CRs, whose energies extend from about 0.1 EeV into the 4-8 EeV bin. The rigidity of these GCRs peaks around 0.2 EV, making the same source also likely responsible for the light (H, He) component of Galactic cosmic rays reported in the $10^{17-17.5}$ eV range [2, 3]. The direction of our derived dipole anisotropy strongly disfavors acceleration in the Galactic wind termination shock and favors a transient event roughly in the Galactic plane and at Galactic longitude $\approx 70^\circ \pm 20^\circ$. We argue that the acceleration is plausibly due to the colliding shock flow mechanism, created by the ejecta of a core-collapse SN colliding with the wind of its massive binary companion. The rate of close-enough events of this type is shown to be high enough that the observed GCB flux and anisotropy are not surprising. In this scenario, the level of the flux and strength of the anisotropy should vary on the tens-of-thousands of years timescale, and the direction of the anisotropy will change after another event occurs near enough to our location to compete with the currently-dominant source. A unique supernova remnant is identified which is consistent in direction, distance and time-delay, to be responsible for the entire population of highest energy Galactic cosmic rays presently observed at Earth.

Acknowledgments

We thank O. Deligny, D. Ellison, N. Globus, J. Lockman, S. Mollerach and M. Muzio for help and information; the research of GRF has been supported by NSF-PHY-2013199.

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