Extragalactic Sources for Ultra High Energy Cosmic Ray Nuclei

Luis Anchordoqui, Haim Goldberg, Stephen Reucroft, and John Swain
Department of Physics, Northeastern University, Boston, MA 02115, USA

In this article we examine the hypothesis that the highest energy cosmic rays are complex nuclei from extragalactic sources. Under reasonable physical assumptions, we show that the nearby metally rich starburst galaxies (M82 and NGC 253) can produce all the events observed above the ankle. This requires diffusion of particles below $10^{20}$ eV in extragalactic magnetic fields $B \approx 15$ nG. Above $10^{19}$ eV, the model predicts the presence of significant fluxes of medium mass and heavy nuclei with small rate of change of composition. Notwithstanding, the most salient feature of the starburst-hypothesis is a slight anisotropy induced by iron debris just before the spectrum-cutoff.

I. INTRODUCTION

The cosmic ray (CR) spectrum above $10^{10}$ eV (where the Sun’s magnetic field is no longer a concern) can be described by a series of power laws with the flux falling about 3 orders of magnitude for each decade increase in energy \[ \text{eV} \]. Above $10^{14}$ eV, the flux becomes so low that direct measurements using sophisticated equipment on satellites or high altitude balloons are limited in detector area and in exposure time. Ground-based experiments with large apertures make such a low flux observable after a magnification effect in the upper atmosphere: the incident cosmic radiation interacts with atomic nuclei of the air molecules and produces extensive air showers which spread out over large areas. Continuously running monitoring through ingenious installations has raised the maximum observed primary particle’s energy to higher than $10^{20}$ eV \[ \text{eV} \].

While theoretical subtleties surrounding CR acceleration provide ample material for discussion, the debate about the origin of CRs up to the knee ($\sim 10^{15.5}$ eV) has reached a consensus that they are produced in supernova explosions \[ \text{eV} \]. The change of the spectral index (from $-2.7$ to $-3.0$) near the knee, presumably reflects a change in origin and the takeover of another, yet unclear type of source. The spectrum steepens further to $-3.3$ above $\sim 10^{17.7}$ eV (the dip) and then flattens to an index of $-2.7$ at $\sim 10^{18.5}$ eV (the ankle). A very widely held interpretation of the modulation features is that above the ankle a new population of CRs with extragalactic origin begins to dominate the more steeply falling Galactic population \[ \text{eV} \]. The origin of the extragalactic channel is somewhat mysterious.

CRs do not travel unhindered through intergalactic space, as there are several processes that can degrade the particles’ energy. In particular, the thermal photon background becomes highly blue shifted for ultrarelativistic protons. The reaction sequence $p\gamma \rightarrow \Delta^+ \rightarrow \pi^0 p$ effectively degrades the primary proton energy providing a strong constraint on the proximity of CR-sources, a phenomenon known as the Greisen-Zatsepin-Kuz’min (GZK) cutoff \[ \text{eV} \]. Specifically, fewer than 20\% of $10^{20.5}$ eV ($10^{20}$ eV) protons can survive a trip of 18 Mpc (60 Mpc) above $\sim 10^{18}$ eV – 10\(^3\) eV \[ \text{eV} \]. A heavy nucleus undergoes photodisintegration in the microwave and infra-red backgrounds; as a result, iron nuclei do not survive fragmentation over comparable distances \[ \text{eV} \]. Ultra high energy gamma rays would travel even shorter paths due to pair production on radio photons \[ \text{eV} \].

In order to analyze the effect of energy losses in the observed spectrum, it is convenient to introduce the accumulation factor $f_{\text{acc}}$, defined as the ratio of energy-weighted fluxes for low ($10^{18.7}$ eV $- 10^{19.5}$ eV) and high ($> 10^{20}$ eV) energy CRs above the ankle. In the case where the cosmic rays are protons from a uniform distribution of sources active over cosmological times, the cutoff due to the photopion processes relates the accumulation factor to a ratio of the GZK distances \[ \text{eV} \] and leads to $f_{\text{acc}} \sim 100$. A similar value for $f_{\text{acc}}$ is obtained for nuclei due to photodisintegration. Therefore, in the case of ordinary baryonic CRs, if Earth is located in a typical environment and all CR-sources have smooth emission spectra, the observed spectrum above the ankle should have an offset in normalization between low and high energy given by $f_{\text{acc}}$. To reproduce the recorded spectrum (i.e., $f_{\text{acc}} \sim 1$), the power of nearby sources (say, 10 Mpc or so) should be comparable to that of all other sources (redshift $z > 0.5$) added together. This condition imposes stern constraints on models describing the origin of baryonic ultra high energy CRs. For instance, “top down” models (with hard injection spectra $\propto E^{-1}$) \[ \text{eV} \] would fail to reproduce the detected population of CRs below the GZK energy by more than an order of magnitude. For models that rely on GZK-evading messengers \[ \text{eV} \], $f_{\text{acc}}$ depends on the details of the model. In the case of messengers which can induce showers across the entire energy spectrum, one expects enhancement on the low energy side only from the baryonic component, and $f_{\text{acc}}$ depends on the interaction length in the cosmic microwave background and on the relative energy spectra at the source. For messengers whose attenuation length is comparable to the horizon, and which do not shower at the lower energies, $f_{\text{acc}} \ll 1$. Summing up, the smoothness of the observed CR spectrum suggests, as the simplest explanation, that nearby sources should be significantly more concentrated or more powerful than
average.

On a different track, any candidate model addressing the origin of ultra high energy CRs should properly match the main features of the observed extensive air showers. As the cascade develops in the atmosphere, the number of particles in the shower increases until the secondary particles’ energy is degraded to the point where ionization losses dominate, and the density of particles starts to decline. The number of particles as a function of the amount of atmosphere penetrated by the cascade in g cm\(^{-2}\) becomes a smooth curve, the so-called “longitudinal profile”. The atmospheric depth at which the shower reaches its maximum size is referred to as the depth of shower maximum \(X_{\text{max}}\), and is often regarded as the most basic parameter of the shower. It increases with primary energy as more cascade generations are required in the cooling of secondary products. For a given total energy \(X_{\text{max}}\) is related to the energy per nucleon of the shower progenitor. Unfortunately, extracting information on the nature of the primaries from the air shower they produce has proved to be exceedingly difficult. The most fundamental drawback is that the first few cascade steps are subject to large inherent fluctuations and consequently this limits the event-by-event mass resolution of the experiments. In addition, the center of mass energy of the first interactions is well beyond those reached in collider experiments. Thus, one needs to rely on hadronic interaction models that attempt to extrapolate (using different mixtures of theory and phenomenology) our understanding of particle physics.

An analysis of the histogram of \(X_{\text{max}}\), observed by the Fly’s Eye experiment, indicates that there is a significant fraction of nuclei with charge greater than unity in the energy range \((10^{18.5}\text{ eV} - 10^{19}\text{ eV}, \text{ and somewhat above})\) \([12]\). To examine the situation above the GZK-energy, simulations of giant air shower evolution have been performed by means of the code AIRESQ (version 2.1.1) \([13]\). Several sets of protons and iron nuclei were injected at 100 km above sea level. The geomagnetic field was set to reproduce that in the Utah desert. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons and nuclei. The charged multiplicity, essentially electrons and positrons, was used to determine the number of charged particles and the location of the shower maximum by means of 4-parameter fits to the Gaisser-Hillas function. In Fig. 1 we show the evolution of \(X_{\text{max}}\) above the GZK-energy for protons and iron nuclei. For comparison, we also show the depth of shower maxima of the two highest energy events recorded by Fly’s Eye and HiRes experiments \([14]\). The observed values of \(X_{\text{max}}\) are consistent with both proton and iron primaries, perhaps (speculatively) suggestive of a medium mass nucleus \([15]\).

In the search for the trans-GZK-sources another observable that one has to take into account is the CR arrival directions. The observed events above \(\approx 10^{20}\text{ eV}\)
are distributed widely over the sky, with no plausible counterparts (such as sources in the Galactic Plane or in the Local Supercluster). Moreover, the data are consistent with an isotropic distribution of sources in sharp contrast to the anisotropic distribution of light within 50 Mpc. At first glance, this seems to contradict any explanation based on nearby sources. However, if the highest energy CRs are heavy nuclei, one cannot yet rule out that extragalactic/galactic magnetic fields could tangle up the particle paths, camouflaging the exact location of the sources. Intergalactic field strengths and coherent lengths are not well established, but it is plausible to assume that fields have coherent directions on scales of $\ell \sim 0.5 - 1$ Mpc. A recent estimate on the extragalactic magnetic field in the neighborhood of the Milky Way suggests $B > 10$ nG \cite{10}. However, magnetic fields of a few $\mu G$ structured in cells of $\sim 1$ Mpc cannot be excluded \cite{17}. Such a large field would completely deflect trans-GZK proton orbits. For a CR nucleus of charge $Z$ in a magnetic field $B_{\mu G} = B/10^{-9}$ G, the Larmor radius is
\begin{equation}
R_L \approx \frac{E_{18}}{Z B_{\mu G}} \text{ Mpc ,}
\end{equation}
where $E_{18} = E/10^{18}$ eV. Therefore, the assumption that the giant air showers $E > 10^{20}$ eV were triggered by heavy nuclei implies ordered ($\ell \sim 1$ Mpc) extragalactic magnetic fields $B_{\mu G} < 15$ (at least in the outskirts of the Galaxy), or else nuclei would be trapped in magnetic subdomains suffering catastrophic spallations \cite{18}.

In a previous paper \cite{19}, there was explored the hypothesis that CRs above the ankle are (mostly) protons from the nearby radio galaxy Centaurus A \cite{9}, accelerated in a “hot spot” in the northern middle lobe. These protons were assumed to diffuse in a magnetic field of $O(\mu G)$ over the transit distance $\sim 3.4$ Mpc to Earth. In this work, in view of the possibility raised by the air shower profiles, we examine an alternate hypothesis: that the composition of CRs above the ankle are largely heavy nuclei which originate in two nearby sources, and traverse extragalactic magnetic fields which conform to the restriction outlined in the previous paragraph. As will be seen, this hypothesis (as well as the previous one involving Cen A), will be subject to specific testing in the coming array of high statistics cosmic ray observations.

II. STARBURST-HYPOTHESIS

If the trans-GZK particles are heavy nuclei, then the nearby ($\sim 3$ Mpc \cite{20}) starburst galaxies M82 ($\ell = 141^\circ, b = 41^\circ$) and NGC 253 ($\ell = 89^\circ, b = -88^\circ$) would probably be the sources of most ultra high energy CRs observed on Earth. Starbursts are galaxies undergoing a massive and large-scale star formation episode. Their characteristic signatures are strong infrared emission (originated in the high levels of interstellar extinction), a very strong HII-region-type emission-line spectrum (due to a large number of O and B-type stars), and a considerable radio emission produced by recent supernova remnants (SNRs). Typically, the starburst region is confined to the central few hundreds of parsecs of the galaxy, a region that can be easily 10 or more times brighter than the center of normal spiral galaxies. In the light of such a concentrated activity, the existence of galactic superwinds is not surprising \cite{20}.

Galactic-scale superwinds are driven by the collective effect of supernovae and massive star winds. The high supernovae rate creates a cavity of hot gas ($\sim 10^8$ K) whose cooling time is much greater than the expansion time scale. Since the wind is sufficiently powerful, it can blow out the interstellar medium of the galaxy avoiding it remaining trapped as a hot bubble. As the cavity expands a strong shock front is formed on the contact surface with the cool interstellar medium. The shock velocity can reach several thousands of kilometers per second and ions like iron nuclei can be then efficiently accelerated in this scenario up to ultra high energies by Fermi’s mechanism \cite{21}.

In a first stage, ions are diffusively accelerated at single supernova shock waves within the nuclear region of the galaxy. Energies up to $\sim 10^{15}$ eV can be achieved in this step \cite{3}. Heavy nuclei are not photodissociated in the process despite the large photon energy densities (mostly in the far infrared) measured in the central region of the starburst. The escape of the CR outflow is convection dominated. In fact, the presence of several tens of young SNRs with very high expansion velocities and thousands of massive O stars (with stellar winds of terminal velocities up to 3000 km s$^{-1}$) must generate collective plasma motions of several thousands of km per second. Then, due to the coupling of the magnetic field to the hot plasma, the magnetic field is also lifted outwards and forces the CR gas to stream along from the starburst region. Most of the nuclei escape in opposite directions along the symmetry axis of the system, as the total path traveled is substantially shorter than the mean free path \cite{24}.

Once the nuclei escape from the central region of the galaxy (with energies of $\sim 10^{15}$ eV) they are injected into the galactic-scale wind and experience further acceleration at its terminal shock. For this second step in the acceleration process, the photon field energy density drops to values of the order of the microwave background radiation (we are now far from the starburst region), and consequently, iron nuclei are safe from photodissociation while energy increases from $\sim 10^{15}$ to $10^{20}$ eV. In terms of parameters that can be determined from observations, the nucleus maximum energy is given by
\begin{equation}
E_{\text{max}} \approx \frac{1}{2} Z e B \frac{E_{\text{sw}}}{M} T_{\text{on}} ,
\end{equation}
where $E_{\text{sw}} \sim 2.7 \times 10^{42}$ erg s$^{-1}$ is the superwind kinetic energy flux and $M = 1.2 M_\odot$ yr$^{-1}$ is the mass flux gener-
ated by the starburst \[20\]. The age \( T_{on} \) can be estimated from numerical models that use theoretical evolutionary tracks for individual stars and make sums over the entire stellar population at each time in order to produce the galaxy luminosity as a function of time \[22\]. Fitting the observational data, these models provide a range of suitable ages for the starburst phase that goes from 50 Myr to 160 Myr \[24\]. These models must assume a given initial mass function (IMF), which usually is taken to be a power-law with a variety of slopes. Recent studies have shown that the same IMF can account for the properties of both NGC 253 and M82 \[23\]. Besides, a region (referred to as M82 “B”) near the galactic center of M82, has been under suspicion to be a fossil starburst site in which an intense episode of star formation occurred over 100 Myr ago \[24\]. The derived age distribution suggests steady, continuing cluster formation at a modest rate at early times (> 2 Gyr ago), followed by a concentrated formation episode 600 Myr ago and more recent suppression of cluster formation. In order to get some estimates on the maximum energy, let us assume \( T_{on} = 50 \) Myr one obtains

\[ E_{Fe}^{\text{max}} > 10^{20} \ \text{eV}. \] (3)

Now, we could use the rates at which starbursts inject mass, metals and energy into superwinds to get an estimate on the CR-injection spectra. Let us introduce \( \epsilon \), the efficiency of ultra high energy CR production by the superwind kinetic energy flux. Using equal power per decade over the interval \( 10^{18.5} \text{eV} < E < 10^{20.6} \text{eV} \), we obtain a source CR-luminosity

\[ \frac{E^2 dN_0}{dE dt} \approx 3.5 \epsilon \times 10^{53} \text{eV/s} \] (4)

where the subscript “0” refers to quantities at the source. The density of CRs at the present time \( t \) of energy \(< 10^{20} \text{eV} \) at a distance \( r \) from a source (assumed to be continuously emitting at a constant spectral rate \( dN_0/dE dt \) from time \( t_{on} \) until the present) is \[19\]

\[
\frac{dn(r,t)}{dE} = \frac{dN_0}{dE dt} \frac{1}{[4\pi D(E)]^{3/2}} \int_{t_{on}}^{t} dt' e^{-r^2/(4D(t-t'))} (t-t')^{3/2}
= \frac{dN_0}{dE dt} \frac{1}{4\pi D(E)r} I(x),
\] (5)

where \( D(E) \) stands for the diffusion coefficient, \( x = 4DT_{on}/r^2 \equiv T_{on}/\tau_D \), \( t = t_{on} \), and

\[ I(x) = \frac{1}{\sqrt{\pi}} \int_1^{\infty} du \frac{1}{\sqrt{u}} e^{-u}. \] (6)

In each “scatter”, the diffusion coefficient describes an independent angular deviation of particle trajectories whose magnitude depends on the Larmor radius. CRs with energies \( E < 10^{18} \ell_{Mpc} Z B_{nG} \text{eV} \) remain trapped inside cells of size \( \ell_{Mpc} = \ell/(1 \text{Mpc}) \), attaining efficient diffusion when the wave number of the associated Alfvén wave is equal to the gyroradius of the particle \[26\]. It may be plausible to assume a Kolmogorov form for the turbulent magnetic field power spectrum, this gives for a diffusion coefficient \[27\]

\[ D(E) \approx 0.048 \left( \frac{E_{18} \ell^2_{Mpc}}{Z B_{nG}} \right)^{1/3} \text{Mpc}^2/\text{Myr}. \] (7)

For \( T_{on} \to \infty \), the density approaches its time-independent equilibrium value \( n_{eq} \), while for \( T_{on} = \tau_D = r^2/4D, n/n_{eq} = 0.16 \). To further constrain the parameters of the model, we evaluate the energy-weighted approximately isotropic proton flux at \( 10^{19} \text{eV} \), which lies in the center of the flat “low energy” region of the spectrum:

\[ E^3 J(E) = \frac{E c}{(4\pi)^2 d D(E)} \frac{E^2 dN_0}{dE dt} I_\star \approx 2.3 \times 10^{26} \epsilon I_\star \text{eV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}, \] (8)

where \( I_\star = I_{M82} + I_{NGC 253} \). In the second line of the equation we used \( B_{nG} = 15 \), \( \ell_{Mpc} = 0.5 \), and an average \( Z = 20 \). We fix

\[ \epsilon I_\star = 0.013, \] (9)

after comparing Eq. (8) to the observed CR-flux:

\[ E^3 J_{\text{obs}}(E) = 10^{24.5} \text{eV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \]. \[1\]. Note that the contribution of \( I_{M82} \) and \( I_{NGC 253} \) to \( I_\star \) critically depends on the age of the starburst. In Fig. 2 we show the relation “starburst-age/superwind-efficiency” derived from Eq. (8). We have assumed that both M82 and NGC 253 were active for 115 Myr (\( \epsilon \approx 10\% \)), beyond this epoch CR-emission must be associated to M82 “B”.

Above \( > 10^{20.2} \text{eV} \) iron nuclei do not propagate diffusively. Moreover, the CR-energies get attenuated by photodisintegration off the microwave background radiation and the intergalactic infrared background photons. The disintegration rate of \(^{56}\text{Fe}\) as a function of the Lorentz factor \( \Gamma \) can be parametrized as follows \[28\],

\[ R(\Gamma) = 3.25 \times 10^{-6} \Gamma^{-0.643} \times \exp(-2.15 \times 10^{10}/\Gamma) \text{s}^{-1}, \] (10a)

if \( \Gamma \in [1, 10^3, 3.68 \times 10^{10}] \), and

\[ R(\Gamma) = 1.59 \times 10^{-12} \Gamma^{-0.698} \text{s}^{-1}, \] (10b)

if \( \Gamma \in [3.68 \times 10^{10}, 1 \times 10^{11}] \). At this stage it is worthwhile to point out that the knowledge of \(^{56}\text{Fe}\) effective nucleon loss rate is enough to obtain the corresponding value of \( R \) for any other nuclei \[7\].

\[ \frac{dA}{dt} \approx \frac{dA}{dt} \text{Fe} \left( \frac{A}{56} \right), \] (11)
This means that $A(t)$ is an exponential function of time with an $e$-folding time of $56 \ dA/dt|_{\gamma^*}$. Now, since the emission of nucleons is isotropic in the rest frame of the nucleus, the average fractional energy loss is equal to the fractional loss in mass number of the nucleus (i.e., $\Gamma$ is conserved). The relation that determines the energy attenuation length of iron as a function of the time flight $t$ is then

$$E(t) = 938 \ A(t) \ \Gamma \ \text{MeV}$$

$$= E_0 \exp \left[ -R(\Gamma) t \right], \quad (12)$$

where $E_0 \equiv 938 \ A_0 \ \Gamma \ \text{MeV}$, denotes the nucleus' emission energy. This relation imposes a strong constraint on the location of nucleus-sources: note that less than 1% of iron nuclei (or any surviving fragment of their spallations) can survive more than $3 \times 10^{14} \ \text{s}$ with an energy $> 10^{20.5} \ \text{eV}$.

In the non-diffusive regime, the accumulated deflection angle $\theta(E)$ from the direction of the source, located at a distance $d$, can be estimated assuming that the particles make a random walk in the magnetic field $\vec{B}$

$$\theta(E) \approx 0.54^\circ \left( \frac{d}{1 \ \text{Mpc}} \right)^{1/2} \left( \frac{\ell}{1 \ \text{Mpc}} \right)^{1/2} Z \frac{B_{nG}}{E_{20}}, \quad (13)$$

where $E_{20} \equiv E/10^{20} \ \text{eV}$. Therefore, if $B \sim 15 \ \text{nG}$ all directionality is lost. The resulting time delay with respect to linear propagation is given by

$$\tau_{\text{delay}}(E) \approx \frac{d \ \theta^2}{4 \ c}, \quad (14)$$

and the total travel time is

$$t \approx \frac{d}{c} \left( 1 + \frac{1}{4} \theta^2 \right) \quad . \quad (15)$$

As an example, we apply these considerations to the highest energy Fly's Eye event. Including statistical and systematic uncertainties, the energy of this event is $3.2 \pm 0.9 \times 10^{20} \ \text{eV}$. Eqs. (14) and (15) relate the uncertainty in energy to the uncertainty in the attenuation time:

$$\frac{\delta t}{t} \approx \left( \frac{11.3}{E_{20}} \right) \left( \frac{\delta E}{E} \right) \quad . \quad (16)$$

From these considerations, we find that the upper limit on the transit time for a nuclear candidate for the highest energy Fly's Eye event is $\sim 6 \times 10^{14} \ \text{s}$. The arrival direction of the highest energy Fly's Eye event is $37^\circ$ from M82 [31]. With $d \approx 3 \ \text{Mpc}$ and $\theta = 37^\circ$, we find from Eq. (14) a transit time $t \approx 3.4 \times 10^{14} \ \text{s}$, well within the stated upper limit [32].

For average deflections of $60^\circ$, the time of flight is $\sim 3.9 \times 10^{14} \ \text{s}$, and consequently there is a sharp end of the CR-spectrum near the maximum observed energy. Indeed, this leads to a slight anisotropy just before the cutoff, and eventually to a north-south asymmetry on the tail [35]. It is rather difficult to assess whether events with energies $> 10^{20.5} \ \text{eV}$ are plausible. This would require an event-by-event analysis because the maximum energy strongly depends on $\tau_{\text{delay}}$. We do not attempt to make yet another estimate in the present article and only note that the energy-weighted flux beyond the GZK-energy (due to a single M82 flare) [36]

$$E^3 J(E) = \frac{E}{(4\pi d)^2} \left( \frac{d \ \text{d}N_0}{dE \ dt} \right) e^{-Rt/56}$$

$$\approx 2.7 \times 10^{25} E_{20}^5 e^{-R t/56} \ \text{eV}^2 \ \text{m}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1}, \quad (17)$$

is easily consistent with observation [37]. The analytical study outlined in this paper should be followed up by numerical studies, especially to refine our estimates above the GZK-energy.

III. CONCLUSION

We have shown that the nucleus-emitting-sources of our backyard have enough power to produce all CRs observed above the ankle. Starburst galaxies can accelerate iron nuclei above the GZK-energy if a two-step process is involved. The crucial point is that for energies $> 10^{15} \ \text{eV}$, acceleration occurs in the terminal shock of the starburst superwind, well outside the problematic central region.

Below $10^{15} \ \text{eV}$, the distribution of the CR arrival directions is expected to be completely isotropic because of Kolmogorov diffusion in ordered ($\ell_{\text{Mpc}} = 0.5$) extra-galactic magnetic fields $10 < B_{nG} < 15$. In addition, (de)magnification of the fluxes by lensing effects are expected due to deflections in the regular Galactic magnetic
field. Furthermore, medium mass and heavy nuclei with energies < 10^{19.7} eV would also have an isotropic distribution in the sky.

On the other hand, ultra high energy (E > 10^{19.7} eV) light nuclei (Z < 10) do not propagate diffusively. However, as can be seen in Eq. (2), light nuclei are not copiously accelerated to ultra high energies in the starburst. Note also that the nucleons (α-particles) emitted in the photodisintegration process have energies well below 10^{19} eV and consequently do not produce any anisotropy.

It should be noted that several groups have recently reported evidence of clustering (6 doublets and 1 triplet, with the chance probability 7 \times 10^{-4}). Magnetic focussing in the magnetic field structure could – in principle – account for directional clustering to explain the current sparse data. However, if not a statistical fluctuation, and clusters are well established in very much larger data sets, they would constitute a serious objection to the model.

All in all, within this scenario almost all CRs above the GZK-energy would be medium mass and heavy nuclei, yielding a small rate of change of composition (in agreement with observation). In addition, the model predicts a slight anisotropy above 10^{20.4} eV produced by non-diffusive iron debris. This makes the model capable of being proven false. The limited statistics in the observed data make it impossible to definitively test the “starburst-hypothesis” at this time. The coming avalanche of high quality CR-observations promises to give the final verdict on these speculations.

ACKNOWLEDGMENTS

The work was partially supported by CONICET (Argentina) and the National Science Foundation (USA).

[1] S. Yoshida, and H. Dui, J. Phys. G 24, 905 (1998); M. Nagano and A. A. Watson, Rev. Mod. Phys. 72, 689 (2000).

[2] Very recently, the AGASA Collaboration reported the highest energy event ever detected on Earth (with an energy ∼ 10^{20.52} eV). M. Teshima, talk presented at the Summer study on the future of Particle Physics (Snowmass 2001) (Snowmass, Colorado, 2001).

[3] P. O. Lagage and C. J. Cesarsky, Astron. Astrophys. 118, 223 (1983); P. L. Biermann, Astron. Astrophys. 271, 649 (1993).

[4] This hypothesis is supported by AGASA data, N. Hayashida et al., Astropart. Phys. 10, 303 (1999).

[5] K. Greisen, Phys Rev. Lett. 16, 748 (1966); G.T. Zatsepin and V.A. Kuz'min, Pis’ma Zh. Eksp. Teor. Fiz. 4, 114 (1966) [JETP Lett. 4, 78 (1966)].

[6] F. W. Stecker, Phys. Rev. Lett. 21, 1016 (1968); T. Staney, R. Engel, A. Muecke, R. J. Protheroe and J. P. Rachen, Phys. Rev. D 62, 093005 (2000) [astro-ph/0003484].

[7] J. L. Puget, F. W. Stecker and J. H. Bredekamp, Astrophys. J. 205, 638 (1976). Updated in, L. N. Epele and E. Routine, JHEP 10, 009 (1998); F. W. Stecker and M. H. Salamon, Astrophys. J. 512, 521 (1999).

[8] R. J. Protheroe and P. Johnson, Astropart. Phys. 4, 253 (1996).

[9] G. R. Farrar and T. Piran, [astro-ph/0010371].

[10] P. Bhattacharjee and G. Sigl, Phys. Rep. 327, 109 (2000), and references therein.

[11] D. J. H. Chung, G. R. Farrar and E. W. Kolb, Phys. Rev. D57, 4606 (1998); T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982); Astrophys. J 285, 495 (1984); Astropart. Phys. 11, 303 (1999); D. Fargion, B. Mele and A. Salis, Astrophys. J. 517, 725 (1999); S. Nussinov and R. Shrock, Phys. Rev. D 59, 105002 (1999); G. Domokos and S. Kovess-Domokos, Phys. Rev. Lett. 82, 1366 (1999); P. Jain, D. W. McKay, S. Panda, and J. P. Ralston, Phys. Lett. B 484, 267 (2000); C. Tyler, A. Olinto and G. Sigl, Phys. Rev. D 63, 055001 (2001); L. Anchordoqui, H. Goldberg, T. McCauley, T. Paul, S. Reucroft and J. Swain Phys. Rev. D 63, 124009 (2001) [hep-ph/0011079]; A. Jain, P. Jain, D. W. McKay and J. P. Ralston [hep-ph/0013116].

[12] T. Wibig and A. W. Wolfendale, J. Phys. G 25, 1099 (1999).

[13] S. J. Sciutto, in Proc. 26th International Cosmic Ray Conference, (Edts. D. Kieda, M. Salamon, and B. Dingus, Salt Lake City, Utah, 1999) vol.1, p.411, [hep-ph/9905185].

[14] D. J. Bird et al., Astrophys. J. 441, 144 (1995); C. C. H. Jui (HiRes Collaboration), in 26th International Cosmic Ray Conference: Invited, Rapporteur, and Highlight Papers, (Edts. B. L. Dingus, D. B. Kieda, M. H. Salamon, American Institute of Physics), AIP Conference Proceedings 516, 370 (2000).

[15] Previous analyses of the highest energy Fly's Eye event are suggestive of this composition. F. Halzen, R. A. Vázquez, T. Staney and H. P. Vankov, Astropart. Phys. 3, 151 (1995); L. A. Anchordoqui, M. Kirasirova, T. P. McCauley, S. Reucroft and J. D. Swain, Phys. Lett. B492, 237 (2000).

[16] L. A. Anchordoqui and H. Goldberg, [hep-ph/0106217].

[17] T. E. Clarke, P. P. Kronberg and H. Boehringer, [astro-ph/9912240].

[18] Naturally, this supposes an extragalactic origin for the CRs detected above the GZK energy. Recently, an argument has been advanced suggesting that young strongly magnetized neutron stars could accelerate iron nuclei to greater than 10^{20} eV. Note that this implies a slight (yet unobserved) correlation between the arrival directions and the Galactic center. P. Blasi, R. I. Epstein, and A. V. Olinto, Astrophys. J. 533, L123 (2000) [astro-ph/9912240].
A point worth noting at this juncture: For propagation times $< 10^{15}$ s, the average values $\bar{A}(t)$ of disintegration histories obtained using Monte Carlo simulations are in very good agreement with the analytic approximations given by Eq. (12). (L. A. Anchordoqui, PhD. Thesis, UNLP, Argentina 1998, summary electronically available from \[\text{astro-ph/9812445}\].) Deviations from Eq. (11) arise because the actual dependence of the photodisintegration cross section on $A$ has a non-monotonic variation across the periodic table. However, fluctuations due to the different disintegration histories are larger. The latter lead to a spread in $A$ of the order of 10%. For details, see Ref. [7].