We suggest that the highest energy $> \sim 10^{20}$ eV cosmic ray primaries may be relativistic magnetic monopoles. Motivations for this hypothesis are twofold: (i) conventional primaries are problematic, while monopoles are naturally accelerated to $E \sim 10^{20}$ eV by galactic magnetic fields; (ii) the observed highest energy cosmic ray flux is just below the Parker limit for monopoles. By matching the cosmic monopole production mechanism to the observed highest energy cosmic ray flux we estimate the monopole mass to be $\sim 10^{10}$ GeV.

The recent discoveries by the AGASA [1], Fly’s Eye [2], Haverah Park [3], and Yakutsk [4] collaborations of cosmic rays with energies above the GZK [5] cut–off at $E_c \sim 5 \times 10^{19}$ eV present an intriguing challenge to particle astrophysics. The origin of the cut–off is degradation of the proton energy by resonant scattering on the $3K$ cosmic background radiation; above threshold, a $\Delta^*$ is produced which then decays to nucleon plus pion. For every mean free path $\sim 6 M_p$ of travel, the proton loses 20% of its energy on average. So if protons are the primaries for the highest energy cosmic rays they must either come from a rather nearby source ($\sim 50$ to $100$ Mpc [6]) or have an initial energy far above $10^{20}$ eV. Neither possibility seems likely, although the suggestion has been made that radio galaxies at distances $10$ to $200 h^{-1}$ Mpc in the supergalactic plane may be origins [7]. A primary nucleus mitigates the cut–off problem (energy per nucleon is reduced by $1/A$), but has additional problems: above $\sim 10^{19}$ eV nuclei should be photo–dissociated by the $3K$ background [8], and possibly disintegrated by the particle density ambient at the astrophysical source.

Gamma–rays and neutrinos are other possible primary candidates for these highest energy events. However, the gamma–ray hypothesis appears inconsistent [9] with the time–development of the Fly’s Eye event. In addition, the mean free path for a $\sim 10^{20}$ eV photon to annihilate on the radio background to $e^+e^-$ is believed to be only $10$ to $40$ Mpc [9], and the density profile of the Yakutsk event [4] showed a large number of muons which argues against gamma–ray initiation. Concerning the neutrino hypothesis, the Fly’s Eye event occurred high in the atmosphere, whereas the expected event rate for early development of a neutrino–induced air shower is down from that of an electromagnetic or hadronic interaction by six orders of magnitude [9]. Moreover, the acceleration problem for $\gamma$ and $\nu$ primaries is as daunting as for hadrons, since $\gamma$’s and $\nu$’s at these energies are believed to originate in decay of $\sim 10^{20}$ eV pions.

Given the problems with interpreting the highest energy cosmic ray primaries as protons, nuclei, photons, or neutrinos, we rekindle the idea [10] that the primary particles of the highest energy cosmic rays may be magnetic monopoles [11]. Two “coincidences” in the data support this hypothesis. The first is that the energies above the cut–off are naturally attained by monopoles when accelerated by known cosmic magnetic fields. The second is that the observed cosmic ray flux above the cut–off is of the same order of magnitude as the theoretically allowed “Parker limit” monopole flux.

To impart its kinetic energy to the induced air–shower, the monopole must be relativistic. This bounds the monopole mass to be $\sim 10^{10}$ GeV. The Kibble mechanism [12] for monopole generation in an early–universe phase transition establishes a monotonic relationship between the monopole’s flux and mass. There results, then, a second upper bound on the monopole mass, which turns out to be similar. The consistency of these

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two bounds is a third “coincidence.” Thus, we arrive at a flux of monopoles of mass $M \sim 10^{10}$ GeV as a viable explanation the highest energy cosmic ray data. This hypothesis has testable signatures, as we shall see.

The kinetic energy of cosmic monopoles is easily obtained. As pointed out by Dirac, the minimum charge for a monopole is $q_M = e/2\alpha$ (which implies $\alpha_M = 1/4\alpha$). In the local interstellar medium, the magnetic field $B$ is approximately $3 \times 10^{-6}$ gauss ($\equiv B_{-6}$) with a coherence length $L \sim 300$ pc ($\equiv L_{300}$) [13]. Thus, a galactic monopole will typically have kinetic energy:

$$E_K \sim q_M B L \sqrt{N} \sim 6 \times 10^{20} \left( \frac{B}{B_{-6}} \right) \left( \frac{L}{L_{300}} \right)^{1/2} \left( \frac{R_M}{R_{30}} \right)^{1/2} \text{eV},$$

where $N \sim R_M/L \sim 100 (R_M/R_{30})/(L/L_{300})$ is the number of magnetic domains encountered by a typical monopole as it traverses the galactic magnetic field region of size $R_M \equiv R_{30} \times 30$ kpc. Note that this energy is above the GZK cut–off. Thus, the “acceleration problem” for $E \sim 10^{20}$ eV primaries is naturally solved in the monopole hypothesis.

Another monopole acceleration mechanism of the right order of magnitude is provided by the surface magnetic field of a neutron star. At the neutron star’s surface, a monopole acquires a kinetic energy $E_K \equiv q_M B L \sim 2 \times 10^{21}$ eV ($B/10^{12}$ gauss) ($L$/km). However, it is thought to be unlikely that objects as small as stars would contain a population of bound monopoles large enough to generate a measurable flux.

To obtain the theoretically predicted monopole flux, it is worthwhile to review how and when a monopole is generated in a phase transition [12, 13]. The topological requirement for monopole production is that a semisimple gauge group changes so that a $U(1)$ factor becomes unbroken. If the mass or temperature scale at which the symmetry changes is $\Lambda$, then the monopoles appear as topological defects, with mass $M \sim \alpha^{-1} \Lambda$. We use $M \sim 100 \Lambda$ in the estimates to follow. All that is necessary to ensure that the monopoles are relativistic today, i.e. $M \sim 10^{10}$ GeV, and so produce relativistic air showers, is to require this symmetry breaking scale associated with the production of monopoles to be at or below $\sim 10^8$ GeV.

This $M \sim 10^{10}$ GeV restriction also serves to ameliorate possible overclosure of the universe by an excessive monopole mass density. At the time of the phase transition, roughly one monopole or antimonopole is produced per correlated volume [12]. The resulting monopole number density today is

$$n_M \sim 0.1 \left( \frac{\Lambda/10^{17}\text{GeV}}{l_H/\xi_c} \right)^3 \text{cm}^{-3},$$

where $\xi_c$ is the phase transition correlation length, bounded from above by the horizon size $l_H$ at the time of the phase transition, or equivalently, at the Ginsburg temperature $T_G$ of the phase transition. The correlation length may be comparable to the horizon size (second order or weakly first order phase transition) or considerably smaller than the horizon size (strongly first order transition). The resulting monopole mass density today relative to the closure value is

$$\Omega_M \sim 0.1 \left( \frac{M/10^{13}\text{GeV}}{l_H/\xi_c} \right)^4,$$

Monopoles less massive than $\sim 10^{13}(\xi_c/l_H)^{3/4}$ GeV do not overclose the universe.

From Eq. (1), the general expression for the relativistic monopole flux may be written

$$F_M = c n_M/4\pi \sim 0.2 \left( \frac{M/10^{16}\text{GeV}}{l_H/\xi_c} \right)^3,$$

per cm$^2$-sec-sr. The “Parker limit” on the galactic monopole flux [14] is $F_M^{PL} \leq 10^{-15}$/cm$^2$/sec/sr. It is derived by requiring that the measured galactic magnetic fields not be depleted (by accelerating monopoles) faster than the fields can be regenerated by galactic magneto-hydrodynamics. Comparing this Parker limit with the general monopole flux in Eq. (3), we see that the Parker bound is satisfied if $M \sim 10^{11}(\xi_c/l_H)$ GeV. From Eqs. (2) and (3) we may also write for the relativistic monopole closure density

$$\Omega_{RM} \sim 10^{-8} \left( \frac{E_M}{10^{20}\text{eV}} \right) \left( \frac{F_M^{PL}}{F_M} \right),$$

which shows that the hypothesized monopole flux does not close the universe regardless of the nature of the monopole–creating phase transition (parameterized by $\xi_c/l_H$).
There is no obvious reason why monopoles accelerated by cosmic magnetic fields should have a falling spectrum, or even a broad spectrum. So we assume that the monopole spectrum is peaked in the energy half-decade $10^{19}$ to $5 \times 10^{20}$ eV. With this assumption, the monopole differential flux is

$$\frac{dF_M}{dE} \sim 4 \times 10^{-40} \left( \frac{M}{10^{10} \text{ GeV}} \right)^3 \left( \frac{l_H}{\xi_c} \right)^3$$

per cm$^2$·sec·sr·eV. Comparing this monopole flux to the measured differential flux $(dF/dE)_{Exp} \sim 10^{-38 \pm 2}$ per cm$^2$·sec·sr·eV above $10^{20}$ eV (summarized in [9]), we infer $M \sim (\xi_c / l_H) \times 10^{10 \pm 1}$ GeV. We note that the monopole mass derived here from the flux requirement is remarkably consistent with the three prior mass requirements, namely that the $E \sim 10^{20}$ eV monopoles be relativistic, that they not overclose the universe, and that they obey the Parker limit. It is very interesting that the observed highest energy cosmic ray flux lies just below the Parker limit for monopole flux. A slightly larger observed flux would exceed this limit, while a slightly lower flux would not have been observed. If the monopole hypothesis is correct, it is possible that we are seeing evidence for some dynamical reason forcing the monopole flux to saturate the Parker bound.

Let us analyze the monopole hypothesis in detail by focussing on some more salient features of the data. There appears to be an event pile-up just below and above the gap (with low statistical significance). Except for the highest energy cosmic ray events, the spectrum is well fit [1] by a diffuse population of protons distributed isotropically in the universe. The apparent pile-up of events between $10^{19}$ eV and $6 \times 10^{19}$ eV is explained by the pion photo-production mechanism of GZK [15]. For the events above $10^{20}$ eV, a different origin seems to be required. That the galactic magnetic fields naturally impart $10^{20}$ to $10^{21}$ eV of kinetic energy to the monopole, and that there appears to be an absence of events above and just below this energy, we find very suggestive. A monopole with $\gamma_M = E_M / M$ will forward-scatter atmospheric particles to $\gamma = 2 \gamma_M^2$. Consequently, there is an effective energy threshold of $E_M \sim 10M$ for relativistic air showers induced by monopoles. Thus, an apparent threshold in the data at $E \sim 10^{20}$ eV may also be explained if the monopole mass is $\sim 10^{10}$ GeV.

Any proposed primary candidate must be able to reproduce the observed shower evolution of the $3 \times 10^{20}$ eV Fly’s Eye event. The shower peaks at $815 \pm 55$ g/cm$^2$, which is marginally consistent with that expected in a proton–initiated shower. Does a monopole–induced air shower fit the Fly’s Eye event profile? We do not know. The hadronic component of the monopole shower is likely to be complicated. The interior of the monopole is symmetric vacuum, in which all the fermion, Yang–Mills, and Higgs fields of the grand unified theory coexist. Thus, even though the Compton size of the monopole is incredibly tiny, its strong interaction size is the usual confinement radius of $\sim 1$ fm, and its strong interaction cross-section is indeed strong, $\sim 10^{-20}$ cm$^2$, and possibly growing with energy like other hadronic cross-sections. Furthermore, a number of unusual monopole–nucleus interactions may take place, including enhanced monopole–catalyzed baryon–violating processes with a strong cross-section $\sim 10^{-27}$ cm$^2$ [16]; catalysis of the inverse process $e^- + M \rightarrow M + p + (\bar{p} \text{ or } n)$, followed by pion/antibaryon initiation of a hadronic shower; binding of one or more nucleons by the monopole [17], in which case the monopole–air interaction may resemble a relativistic nucleus–nucleus collision; strong polarization of the air nuclei due to magnetic interaction with the individual nucleon magnetic moments and electric $(E = \gamma_M e / 2 \alpha r^2 \phi)$ interaction with the proton constituents, possibly causing fragmentation [17]; hard elastic magnetic scattering of ionized nuclei (in the rest frame of the monopole the charged nuclei will see the monopole as a reflecting magnetic mirror); and possible electroweak–scale sphaleron processes [18] at the large Q-value of the monopole–air nucleus interaction $(\sim \gamma_M A m_N \sim \text{TeV})$. Clearly, more theoretical work is required to understand a monopole’s air shower.
development.

On the other hand, the monopole’s electromagnetic showering properties are straightforward. A magnetic monopole has a rest–frame magnetic field \( B_{RF} = q_M \hat{r}/r^2 \). When boosted to a velocity \( \beta_M \), an electric field \( E_M = \gamma_M \beta_M \times B_{RF} \) is generated, leading to a “dual Lorentz” force acting on the charged constituents of air atoms. The electromagnetic energy loss of a relativistic monopole traveling through matter is very similar to that of a heavy nucleus with similar \( \gamma \)-factor and charge \( Z = q_M/e = 1/2\alpha = 137/2 \). One result is a \( \sim 6 \text{ GeV}/(g \text{ cm}^{-2}) \) “minimum–ionizing monopole” electromagnetic energy loss. Integrated through the atmosphere, the total electromagnetic energy loss is therefore \( \sim (6.2/\cos \theta_z) \) TeV, for zenith angle \( \theta_z \lesssim 60^\circ \). For a horizontal shower the integrated energy loss is \( \sim 240 \) TeV.

A second electromagnetic prediction is Cerenkov radiation at the usual angle but enhanced by \((137/2)^2 \sim 4700\) compared to a proton primary. This enhanced Cerenkov radiation may help in the identification of the monopole primary.

We can derive useful information on some of the characteristics of the monopole shower simply from kinematics. For relativistic monopoles with mass \( M \) greatly exceeding the masses of the target air atoms and their constituent nucleon masses \( m \), the maximum energy transfer occurs via forward (in the lab frame) elastic scattering. This maximum is

\[
E_m/E_M = (1 + M^2/2mE_M)^{-1}.
\]

In contrast, the maximum energy transfer for a relativistic particle of energy \( E \) and mass \( m \) scattering on a stationary target particle of the same mass is

\[
E_m/E_m = 1 - m/2E \sim 1.
\]

We see that a relativistic nucleon or light nucleus primary will transfer essentially all of its energy in a single forward scattering event. If the monopole has \( M \lesssim \sqrt{2mE_M} \), i.e. \( \lesssim 10^6 \) GeV for \( E_M \sim \text{few} \times 10^{20} \) eV, it too will transfer most of its energy in the first forward–scattering event, possibly mimicking a standard air shower. On the other hand, a relativistic monopole primary with \( M > 10^6 \) GeV will retain most of its energy per each scattering, and so will continuously “initiate” the shower as it propagates through the atmosphere. For this reason, we refer to the monopole shower as “monopole–induced” rather than “monopole–initiated.” The smaller energy transfer per collision for a \( M > 10^6 \) GeV monopole as compared to that of the usual primary candidates may constitute a signature for heavy monopole primaries. Moreover, the back–scattered atmospheric particles in the center–of–mass system (which is roughly half of the scattered particles) are forward–scattered in the lab frame into a cone of half–angle \( 1/\gamma_M \); at the given energy of \( E \sim 10^{20} \) eV, this angle will be large for a heavy monopole primary compared to the angle for a usual primary particle, possibly offering another monopole signature.

Simple GUT models may be constructed in which a \( U(1) \) symmetry first appears at a cosmic temperature far below the initial GUT–breaking scale, signaling the appearance of monopoles with mass \( M \) far below the initial GUT scale. Indeed, there are several published models in which exactly this happens, the most recent being [19].

The utility of an intermediate breaking scale has been invoked before in many contexts, including the Peccei–Quinn solution to the strong CP problem, the right–handed neutrino scale in “see–saw” models of neutrino mass generation, and supersymmetry breaking in a hidden sector.

To conclude, we suggest that the primary particles of the highest energy cosmic rays discovered in the past several years are relativistic magnetic monopoles of mass \( M \lesssim 10^{10} \) GeV. Energies of \( \sim 10^{20} \) eV can easily be attained via acceleration in a typical galactic magnetic field, and the observed highest energy cosmic ray flux (just below the Parker limit) can be explained within the monopole hypothesis by the Kibble mechanism. Fortunately, there are some possible tests of this monopole hypothesis. First of all, the monopole primaries should be asymmetrically distributed on the sky, showing a preference for the direction of the local galactic magnetic field. Secondly, the characteristics of air showers induced by monopoles may carry distinctive signatures: The electromagnetic shower and Cerenkov cone...
should develop as if the relativistic monopole carried $\sim 137/2$ units of electric charge. In addition, there may be several strong interaction aspects of the monopole, each contributing to monopole–induced air shower development. Finally, the energy transfer per scatterer will be smaller for a $M \gtrsim 10^6$ GeV monopole compared to that of a standard primary, and the scattering angle will be larger.

There are good prospects for more cosmic ray data at these highest energies. The present cosmic ray detection efforts are ongoing, and the “Auger Project” has been formed to coordinate an international effort to instrument a 5,000 km$^2$ detector and collect five thousand events per year above $10^{19}$ [20].

REFERENCES


18 A sphaleron is the minimum–energy baryon– and lepton–number violating classical field configuration of the standard model. An overview of sphaleron physics can be found in ref. [13].


20 J. W. Cronin and A. A. Watson, announcement from the Giant Air Shower Design Group (recently renamed the “Auger Project”), October 1994.