The Mystery of Ultra-High Energy Cosmic Rays

A. V. OLINTO
Department of Astronomy & Astrophysics,
& Enrico Fermi Institute,
The University of Chicago, Chicago, IL 60637, USA
E-mail: olinto@oddjob.uchicago.edu

The origin of cosmic rays with energies higher than $10^{20}$ eV remains a mystery. Accelerating particles up to these energies is a challenge even for the most energetic astrophysical objects known. While the isotropy in arrival directions argues for an extra-galactic origin, the photon-pion production off the cosmic background radiation limits the sources of such particles to systems less than 50 Mpc away from us. The combination of large gyroradii, efficient energy losses, and isotropic arrival directions defies most of the proposed astrophysical accelerators as well as the more exotic alternatives. I briefly review theoretical models for the acceleration and propagation of ultra-high-energy cosmic-rays and discuss the potential for future observatories to resolve this cosmic mystery.

1 Introduction

The origin of cosmic rays with energies above $10^{20}$ eV is an intriguing mystery. At present, about 20 events above $10^{20}$ eV have been reported worldwide by experiments such as the High Resolution Fly’s Eye, AGASA, Fly’s Eye, Haverah Park, Yakutsk, and Volcano Ranch. (For recent reviews of these observations see, e.g., [1]). The unexpected flux above $\sim 7 \times 10^{19}$ eV shows no sign of the Greisen-Zatsepin-Kuzmin (GZK) cutoff A cutoff should be present if these ultra-high energy particles are protons, nuclei, or photons from extragalactic sources. Cosmic ray protons of energies above a few $10^{19}$ eV lose energy to photopion production off the cosmic microwave background (CMB) and cannot originate further than about 50 Mpc away from Earth. Nuclei are photodisintegrated on shorter distances due to the infrared background while the radio background constrains photons to originate from even closer systems.

In addition to the presence of events past the GZK cutoff, the arrival directions of the highest energy events show no clear angular correlation with any of the plausible optical counterparts such as sources in the Galactic plane, the Local Group, or the Local Supercluster. If these events are protons, their arrival direction should point back to their sources, but unlike luminous structures in a 50 Mpc radius around us, the distribution of the highest energy events is isotropic.

At these high energies the Galactic and extragalactic magnetic fields should not affect the orbits significantly. Protons at $10^{20}$ eV propagate mainly in
straight lines as they traverse the Galaxy since their gyroradii are $\sim 100$ kpc in $\mu G$ fields which is typical in the Galactic disk so they should point back to their sources within a few degrees. Extragalactic fields are expected to be $\ll \mu G$, and induce at most $\sim 1^\circ$ deviation from the source. Even if the Local Supercluster has relatively strong fields, the highest energy events may deviate at most $\sim 10^\circ$.

If astrophysical sources cannot explain these observations, the exciting alternative involves physics beyond the standard model of particle physics. Not only the origin of these particles may be due to physics beyond the standard model, but their existence can be used to constrain extensions of the standard model such as violations of Lorentz invariance.

The absence of a GZK cutoff and the isotropy of arrival directions are some of the challenges that models for the origin of UHECRs face. This mystery has generated a number of proposals but no model can claim victory at this point. The exact shape of the spectrum at the highest energies as well as a clear composition determination awaits future observatories such as the Pierre Auger Project and the proposed satellites OWL and Airwatch.

In this talk, I briefly review the models that attempt to solve this mystery. For more extensive reviews, see [5].

2 Astrophysical Zevatrons

These challenging observations have generated two different proposals to reaching a solution: A bottom-up approach involves looking for Zevatrons, possible acceleration sites in known astrophysical objects that can reach ZeV energies, while a top-down approach involves the decay of very high mass relics from the early universe and physics beyond the standard model of particle physics.

Cosmic rays can be accelerated in astrophysical plasmas when large-scale macroscopic motions, such as shocks and turbulent flows, are transferred to individual particles. The maximum energy of accelerated particles, $E_{\text{max}}$, can be estimated by requiring that the gyroradius of the particle be contained in the acceleration region: $E_{\text{max}} = Z e B L$, where $Z e$ is the charge of the particle, $B$ is the strength and $L$ the coherence length of the magnetic field embedded in the plasma. For $E_{\text{max}} \geq 10^{20}$ eV and $Z \sim 1$, the only known astrophysical sources with reasonable $BL$ products are neutron stars ($B \sim 10^{13}$ G, $L \sim 10$ km), active galactic nuclei (AGNs) ($B \sim 10^4$ G, $L \sim 10$ AU), radio lobes of AGNs ($B \sim 0.1 \mu G$, $L \sim 10$ kpc), and clusters of galaxies ($B \sim \mu G$, $L \sim 100$ kpc).

Clusters of Galaxies: Cluster shocks are reasonable sites to consider for ultra-high energy cosmic ray (UHECR) acceleration, since particles with en-
ergy up to \( E_{\text{max}} \) can be contained by cluster fields. However, efficient losses due to photopion production off the CMB during the propagation inside the cluster limit UHECRs in cluster shocks to reach at most \( \sim 10 \ \text{EeV} \).

**AGN Radio Lobes:** Next on the list of plausible Zevatrons are extremely powerful radio galaxies. Jets from the central black-hole of an active galaxy end at a termination shock where the interaction of the jet with the intergalactic medium forms radio lobes and ‘hot spots’. Of special interest are the most powerful AGNs where shocks can accelerate particles to energies well above an EeV via the first-order Fermi mechanism. These sources may be responsible for the flux of UHECRs up to the GZK cutoff.

A nearby specially powerful source may be able to reach energies past the cutoff. However, extremely powerful AGNs with radio lobes and hot spots are rare and far apart. The closest known object is M87 in the Virgo cluster (\( \sim 18 \ \text{Mpc} \) away) and could be a main source of UHECRs. Although a single nearby source can fit the spectrum for a given strength and structure of the intergalactic magnetic field, it is unlikely to match the observed arrival direction distribution. After M87, the next known nearby source is NGC315 which is already too far at a distance of \( \sim 80 \ \text{Mpc} \).

A recent proposal tries to get around this challenge by invoking a Galactic wind with a strongly magnetized azimuthal component. Such a wind can significantly alter the paths of UHECRs such that the observed arrival directions of events above \( 10^{20} \ \text{eV} \) would trace back to the Virgo cluster close to M87. If our Galaxy has a such a wind is yet to be determined. The proposed wind seems hard to support physically and would focus most events into the northern Galactic pole and render point source identification fruitless. Future observations of UHECRs from the Southern Hemisphere by the Southern Auger Site will provide data on previously unobserved parts of the sky and help distinguish plausible proposals for the effect of local magnetic fields on arrival directions. Full sky coverage is a key discriminator of such proposals.

**AGN - Central Regions:** The powerful engines that give rise to the observed jets and radio lobes are located in the central regions of active galaxies and are powered by the accretion of matter onto supermassive black holes. It is reasonable to consider the central engines themselves as the likely accelerators. In principle, the nuclei of generic active galaxies (not only the ones with hot spots) can accelerate particles via a unipolar inductor not unlike the one operating in pulsars. In the case of AGNs, the magnetic field is provided by the infalling matter and the spinning black hole horizon provides the imperfect conductor for the unipolar induction.

The problem with AGNs as UHECR sources is two-fold: first, UHE particles face debilitating losses in the acceleration region due to the intense ra-
diation field present in AGNs, and second, the spatial distribution of objects should give rise to a GZK cutoff of the observed spectrum. In the central regions of AGNs, loss processes are expected to downgrade particle energies well below the maximum achievable energy. This limitation has led to the proposal that quasar remnants, supermassive black holes in centers of inactive galaxies, are more effective UHECR accelerators. In this case, losses are not as significant but the distribution of sources should still lead to a clear GZK cutoff unless the spectrum is fairly soft.

Neutron Stars Another astrophysical system capable of accelerating UHECRs is a neutron star. Acceleration processes inside the neutron star light cylinder are bound to fail much like the AGN central region case: ambient magnetic and radiation fields induce significant losses. However, the plasma that expands beyond the light cylinder is freer from the main loss processes and may be accelerated to ultra high energies.

One possible source of UHECR past the GZK cutoff is the early evolution of neutron stars. In particular, newly formed, rapidly rotating neutron stars may accelerate iron nuclei to UHEs through relativistic MHD winds beyond their light cylinders. In this case, UHECRs originate mostly in the Galaxy and the arrival directions require that the primaries be heavier nuclei. Depending on the structure of Galactic magnetic fields, the trajectories of iron nuclei from Galactic neutron stars may be consistent with the observed arrival directions of the highest energy events. Moreover, if cosmic rays of a few times $10^{18}$ eV are protons of Galactic origin, the isotropic distribution observed at these energies is indicative of the diffusive effect of the Galactic magnetic fields on iron at $\sim 10^{20}$ eV. This proposal awaits a clear composition determination.

Gamma-Ray Bursts Transient high energy phenomena such as gamma-ray bursts may accelerate protons to ultra-high energies. Aside from both having unknown origins, GRBs and UHECRs have some similarities that argue for a common origin. Like UHECRs, GRBs are distributed isotropically in the sky, and the average rate of $\gamma$-ray energy emitted by GRBs is comparable to the energy generation rate of UHECRs of energy $> 10^{19}$ eV in a redshift independent cosmological distribution of sources, both have $\approx 10^{44}$ erg/Mpc$^3$/yr.

However, the distribution of UHECR arrival directions and arrival times argues against the GRB–UHECR common origin. Events past the GZK cutoff require that only GRBs from $\lesssim 50$ Mpc contribute. Since less than about one burst is expected to have occurred within this region over a period of 100 yr, the source would appear as a concentration of UHECR events. Therefore, a very large dispersion of $\gtrsim 100$ yr in the arrival time of protons produced in a single burst is necessary. The deflection by random magnetic fields combined with the energy spread of the particles is usually invoked to reach the
required dispersion. If the dispersion in time and space is achieved, the energy spectrum for the nearby source(s) becomes very narrowly peaked $\Delta E/E \sim 1$. Finally, if the observed small scale clustering of arrival directions is confirmed by future experiments with clusters having lower energy events precede higher energy ones, bursts would be invalidated.

3 Hybrid Models

The UHECR puzzle has inspired proposals that use Zevatrons to generate UHE particles other than protons, nuclei, and photons. These use physics beyond the standard model in a bottom-up approach, thus, named hybrid models.

The most economical among such proposals involves a familiar extension of the standard model, namely, neutrino masses. If some flavor of neutrinos have masses $\sim 1$ eV, the relic neutrino background will cluster in halos of galaxies and clusters of galaxies. High energy neutrinos ($\sim 10^{21} \text{ eV}$) accelerated in Zevatrons can annihilate on the neutrino background and form UHECRs through the hadronic Z-boson decay.

This proposal is aimed at generating UHECRs nearby (in the Galactic halo and Local Group halos) while using Zevatrons that can be much further than the GZK limited volume, since neutrinos do not suffer the GZK losses. The weak link in this proposal is the nature of a Zevatron powerful enough to accelerate protons above ZeVs that can produce ZeV neutrinos as secondaries. This Zevatron is quite spectacular, requiring an energy generation in excess of presently known highest energy sources.

Another suggestion is that the UHECR primary is a new particle. The mass of a hypothetical hadronic primary can be limited by the shower development of the Fly’s Eye highest energy event to be below $\lesssim 50 \text{ GeV}$. Both a long lived new particle and the neutrino Z-pole proposals involve neutral particles which are usually harder to accelerate (they are created as secondaries of even higher energy charged primaries) but can traverse large distances without being affected by the cosmic magnetic fields. Thus, a signature of such hybrid models for future experiments is a clear correlation between the position of powerful Zevatrons in the sky such as distant compact radio quasars and the arrival direction of UHE events.

Another exotic primary that can use a Zevatron to reach ultra high energies is the vorton. Vortons are small loops of superconducting cosmic string stabilized by the angular momentum of charge carriers. Vortons can be a component of the dark matter in galactic halos and be accelerated in astrophysical Zevatrons. Although not yet clearly demonstrated, the shower development profile is also the likely liability of this model.
4 Top-Down Models

It is possible that none of the astrophysical scenarios are able to meet the challenge posed by the UHECR data as more observations are accumulated. In that case, one alternative is to consider top-down models. This proposal dates back to the work on monopolonia of Hill and Schramm. Other top-down proposals involve the decay of ordinary and superconducting cosmic strings, cosmic necklaces, vortons, and superheavy long-lived relic particles. The idea behind these models is that relics of the very early universe, topological defects (TDs) or superheavy relic (SHR) particles, produced after or at the end of inflation, can decay today and generate UHECRs. Defects, such as cosmic strings, domain walls, and magnetic monopoles, can be generated through the Kibble mechanism as symmetries are broken with the expansion and cooling of the universe. Topologically stable defects can survive to the present and decompose into their constituent fields as they collapse, annihilate, or reach critical current in the case of superconducting cosmic strings. The decay products, superheavy gauge and higgs bosons, decay into jets of hadrons, mostly pions. Pions in the jets subsequently decay into $\gamma$-rays, electrons, and neutrinos. Only a few percent of the hadrons are expected to be nucleons. Typical features of these scenarios are a predominant release of $\gamma$-rays and neutrinos and a QCD fragmentation spectrum which is considerably harder than the case of shock acceleration.

ZeV energies are not a challenge for top-down models since symmetry breaking scales at the end of inflation typically are $\gg 10^{21}$ eV (typical X-particle masses vary between $\sim 10^{22} - 10^{25}$ eV). Fitting the observed flux of UHECRs is the real challenge since the typical distances between TDs is the Horizon scale, $H^{-1}_0 \approx 3h^{-1}$ Gpc. The low flux hurts proposals based on ordinary and superconducting cosmic strings. Monopoles usually suffer the opposite problem, they would in general be too numerous. Inflation succeeds in diluting the number density of monopoles usually making them too rare for UHECR production. To reach the observed UHECR flux, monopole models usually involve some degree of fine tuning. If enough monopoles and antimonopoles survive from the early universe, they may form a bound state, named monopolonium, that can decay generating UHECRs. The lifetime of monopolonia may be too short for this scenario to succeed unless they are connected by strings.

Once two symmetry breaking scales are invoked, a combination of horizon scales gives room to reasonable number densities. This can be arranged for cosmic strings that end in monopoles, making a monopole string network or even more clearly for cosmic necklaces. Cosmic necklaces are hybrid de-
ffects where each monopole is connected to two strings resembling beads on a cosmic string necklace. Necklace networks may evolve to configurations that can fit the UHECR flux which is ultimately generated by the annihilation of monopoles with antimonopoles trapped in the string. In these scenarios, protons dominate the flux in the lower energy side of the GZK cutoff while photons tend to dominate at higher energies depending on the radio background. If future data can settle the composition of UHECRs from 0.01 to 1 TeV, these models can be well constrained. In addition to fitting the UHECR flux, topological defect models are constrained by limits on the flux of high energy photons, from 10 MeV to 100 GeV, observed by EGRET.

Another interesting possibility is the recent proposal that UHECRs are produced by the decay of unstable superheavy relics that live much longer than the age of the universe. SHR s may be produced at the end of inflation by non-thermal effects such as a varying gravitational field, parametric resonances during preheating, instant preheating, or the decay of topological defects. These models need to invoke special symmetries to insure unusually long lifetimes for SHRs and that a sufficiently small percentage decays today producing UHECRs. As in the topological defects case, the decay of these relics also generate jets of hadrons. These particles behave like cold dark matter and could constitute a fair fraction of the halo of our Galaxy. Therefore, their halo decay products would not be limited by the GZK cutoff allowing for a large flux at UHEs.

Future experiments should be able to probe these hypotheses. For instance, in the case of SHR and monopolonium decays, the arrival direction distribution should be close to isotropic but show an asymmetry due to the position of the Earth in the Galactic Halo. Studying plausible halo models and the expected asymmetry will help constrain halo distributions especially when larger data sets are available from future experiments. High energy gamma ray experiments such as GLAST will also help constrain the SHR models due to the products of the electromagnetic cascade.

5 Conclusion

Next generation experiments such as the High Resolution Fly’s Eye which recently started operating, the Pierre Auger Project which is now under construction, the proposed Telescope Array, and the OWL and Airwatch satellites will significantly improve the data at the extremely-high end of the cosmic ray spectrum. With these observatories a clear determination of the spectrum and spatial distribution of UHECR sources is within reach.

The lack of a GZK cutoff should become clear with HiRes and Auger and
most extragalactic Zevatrons may be ruled out. The observed spectrum will distinguish Zevatrons from top-down models by testing power laws versus QCD fragmentation fits. The cosmography of sources should also become clear and able to discriminate between plausible populations for UHECR sources. The correlation of arrival directions for events with energies above $10^{20}$ eV with some known structure such as the Galaxy, the Galactic halo, the Local Group or the Local Supercluster would be key in differentiating between different models. For instance, a correlation with the Galactic center and disk should become apparent at extremely high energies for the case of young neutron star winds, while a correlation with the large scale galaxy distribution should become clear for the case of quasar remnants. If SHRs or monopoleia are responsible for UHECR production, the arrival directions should correlate with the dark matter distribution and show the halo asymmetry. For these signatures to be tested, full sky coverage is essential. Finally, an excellent discriminator would be an unambiguous composition determination of the primaries. In general, Galactic disk models invoke iron nuclei to be consistent with the isotropic distribution, extragalactic Zevatrons tend to favor proton primaries, while photon primaries are more common for early universe relics. The hybrid detector of the Auger Project should help determine the composition by measuring simultaneously the depth of shower maximum and the muon content of the same shower. The prospect of testing extremely high energy physics as well as solving the UHECR mystery awaits improved observations that should be coming in the next decade with experiments under construction or in the planning stages.

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1. J. W. Cronin, *Nucl. Phys.* B X. Bertou, M. Boratav, and A. Letessier-Selvon, astro-ph/001516, *Int. J. of Modern Physics A* (2000).
2. M. Takeda et al., *Phys. Rev. Lett.*
3. K. Greisen, *Phys. Rev. Lett.* 16 748 (1966); G. T. Zatsepin and V. A. Kuzmin, *Sov. Phys. JETP Lett.* 4 78 (1966).
4. D. Ryu, H. Kang and P. L. Bierman, *Astron. Astrophys.* 335 (1998) 19; G. Sigl, M. Lemoine, and P. Biermann, *Astropart. Phys.* 10 (1999) 141.
5. A. M. Hillas, *ARAA* 22 (1984) 425; V. S. Berezinsky, et al., *Astrophysics of Cosmic Rays*, (Amsterdam: North Holland, 1990); R. D. Blandford, *Particle Physics and the Universe*, eds. Bergstrom, Carlson and Fransson (World Scientific, 1999); V. S. Berezinsky, *Nucl. Phys.* B 70 (1999) 419; P. Bhattacharjee and G. Sigl, *Phys. Reps.* in press. (2000); A.V. Olinto,
6. H. Kang, D. Ryu, T.W. Jones, Astropart. Phys. MNRAS, **286** (1997) 257.
7. P.L. Biermann and P. Strittmatter, Astropart. Phys. **322** (1987) 643; P. L. Biermann, J. Phys. G: Nucl. Part. Phys. **23** (1997) 1.
8. J. P. Rachen and P. L. Biermann, Astron. Astrophys. **272** (1993) 161.
9. P. Blasi and A. V. Olinto, Phys. Rev. D **59**, 023001 (1999).
10. E. J. Ahn, et al., astro-ph/9911123
11. P. Billoir and A Letessier-Selvon, astro-ph/000142 (2000).
12. K.S. Thorne, R.M. Price, and D. MacDonalds, *Black Holes: The Membrane Paradigm* (New Haven: Yale Press) (1986).
13. E. Boldt and P. Ghosh, Mon. Not. R. Astron. Soc., in press (1999).
14. A. R. Bell, Mon. Not. R. Astron. Soc. **257**, 493 (1992).
15. A. V. Olinto, R. I. Epstein, and P. Blasi, Proceedings of 26th ICRC, Salt Lake City, 4, 361 (1999); P. Blasi, R. I. Epstein, and A. V. Olinto, astro-ph/9912240.
16. V. N. Zirakashvili, et al., Astron. Lett. **24**, 139 (1998).
17. E. Waxman, Phys. Rev. Lett. **75**, 386 (1995); ibid., Astrophys. J. **452**, L1 (1995); M. Vietri, Astrophys. J. **453**, 883 (1995).
18. G. Sigl, M. Lemoine, and A. V. Olinto, Phys. Rev. D
19. D. Fargion, B. Mele, and A. Salis, astro-ph/9710029; T. Weiler, Astropar. Phys. **11**, 303 (1999).
20. I. F. M. Albuquerque, G. R. Farrar, and E. W. Kolb, Phys. Rev. D **59**, 015021 (1999).
21. G. R. Farrar and P. L. Biermann, Phys. Rev. Lett. **81**, 3579 (1998).
22. R. L. Davis and E. P. S. Shellard, Nucl. Phys. B
23. S. Bonazzola and P. Peter, Astropart. Phys. **7**, 161 (1997).
24. C. T. Hill, Nucl. Phys. B **224**, 469 (1983); D. N. Schramm and C.T. Hill, Proc. 18th ICRC (Bangalore) **2**, 393 (1983); C. T. Hill and D. N. Schramm, Phys. Lett. B **131**, 247 (1983).
25. J. J. Blanco-Pillado and K. D. Olum, astro-ph/9904312.
26. V. Berezinsky and A. Vilenkin, Phys. Rev. Lett. **79**, 5202 (1997).
27. V. Berezinsky, P. Blasi, and A. Vilenkin, Phys. Rev. D **58**, 103515-1 (1998).
28. V. Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997); V. Kuzmin and V. Rubakov, Yad. Fisika **61**, 1122 (1998).
29. D. J. H. Chung, E. W. Kolb, and A. Riotto, Phys. Rev. D **59**, 023501 (1999); Phys. Rev. Lett. **81**, 4048 (1998); V. Kuzmin and I. Tkachev, Phys. Rev. D **59**, 123006 (1999); JETP. Lett.
30. P. Blasi, Phys. Rev. D **60**, 023514 (1999).