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ULTRA HIGH ENERGY COSMIC RAYS AND CLUSTERS

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ABSTRACT

I briefly review the current theoretical status of the origins of ultrahigh energy cosmic rays with special emphasis on models associated with galaxy clusters. Some basic constraints on models are laid out, including those that apply both to so-called "top-down" and "bottom-up" models. The origins of these UHECRs remain an enigma; no model stands out as a clear favorite. Large scale structure formation shocks, while very attractive conceptually in this context, are unlikely to be able to accelerate particles to energies much above 10^{18}eV. Terminal shocks in relativistic AGN jets seem to be more viable candidates physically, but suffer from their rarity in the local universe. Several other, representative, models are outlined for comparison.

Key words : cosmic rays – clusters of galaxies

I. INTRODUCTION

The existence of cosmic rays (CRs) with energies approaching 10^{21}eV is experimentally now well accepted, although the composition and especially the origins of these "ultra high energy" cosmic rays (UHECRs) are still not resolved. Above $\sim$ a few $\times$ 10^{18}eV, CRs of unit charge (e.g., protons) in the galactic magnetic field have gyroradii too large to confine them to the galaxy. On the other hand, the observed distribution of those CRs appears to be almost isotropic, so at least the highest energy UHECRs are likely to come from sources not concentrated in the Milky Way. Clusters of galaxies, by the violence of their formation and the galaxies collected inside them, are likely sources of high energy CRs by a variety of physical and astrophysical processes. Observations confirm the existence of CR electrons, at least, filling some clusters, as has been widely discussed at this meeting. Coming generations of space telescopes may be able to establish a baryonic component that should theoretically also be present in clusters.

In that context my task here is to review briefly some of the theoretical issues that underlie the acceleration of the highest energy CRs. Recent, more extensive theoretical reviews have been written, for example, by Bhattacharjee & Sigl (2000), Stecker (2002), Protheroe & Clay (2003) and by Torres & Anchoroqui (2004). Other presentations at this meeting dealt with the current observational UHECR story (Olinto), while numerous presentations touched on the observational and theoretical pictures of CRs in clusters and their propagation (numerous presentations). In what follows I consider UHECRs to be particles with energies above roughly 10^{18}eV and will assume that these UHECRs are composed primarily of protons, since that seems to be the most consistent interpretation of current data. I will also assume that the sources are primarily, if not necessarily entirely outside our galaxy.

II. BASIC MODEL CONSTRAINTS

Before discussing constraints on specific models it is useful to mention one critical constraint that applies to all extragalactic models for UHECRs, independent of the details of the physics of their origins. In particular propagating UHECRs interact inelastically with cosmic background radiation fields, such as the microwave background. In the process they lose energy and generate secondaries that may, in some cases, be detectable. So, for instance, CR protons colliding with background photons will create e^+/e^- pairs when the proton energy exceeds the threshold

$$\begin{aligned} E_t^{\pm} &\approx m_p c^2 m_e c^2/\epsilon_\gamma \\ &\approx 5\times 10^{17}(1/\epsilon_{-3})\ \text{eV}, \end{aligned} \tag{1}$$

where $\epsilon_\gamma = 10^{-3}\epsilon_{-3}$ is the characteristic incident photon energy. At somewhat higher energies these collisions can excite the Δ^+ resonance leading to photopion production. This has a threshold

$$\begin{aligned} E_t^{\pi} &= \frac{m_\Delta^2 c^4 - m_p^2 c^4}{4\epsilon_\gamma} \\ &\approx m_p c^2 m_\pi c^2 (1 + m_\pi/(2m_p))/(2\epsilon_\gamma) \\ &\approx 7\times 10^{19}(1/\epsilon_{-3})\ \text{eV}. \end{aligned} \tag{2}$$

For the CMB $\epsilon_{-3} \sim 1$. On average each collision leading to photopion generation costs the CR of order 10% of its energy, which led Greisen (1966) and Zatsepin & Kuz'min (1966) independently to predict that no UHECRs would exist above that threshold. Clearly such UHECRs do exist, but this "GZK cutoff" just below 10^{20}eV represents a serious constraint on the distance

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more energetic CRs can travel. Roughly speaking it limits the average propagation distance of a 10^{20}eV CR to about 100 Mpc, or alternatively its propagation time to about 300 Myr. The latter concept is more generally useful, in fact, particularly if magnetic fields are sufficient to deflect the particle motions from rectilinear.

The consequences to the spectrum of CRs incident at earth depend on both the spatial distribution of sources and the energy distribution of CRs as they are produced. CRs originating at great distance with energies well above the GZK cutoff will end up with energies below the cutoff. The energy loss process is stochastic, however, not smooth, so CRs originating not too far beyond the nominal distance limit still have a reasonably good chance of arriving with little or loss in energy. If the source spectrum is relatively hard, then, the incident spectrum is expected to exhibit a bump just below the GZK cutoff and continue to higher energies with an increased slope. So, as others have pointed out before, it is really more appropriate to label the onset of photopion production as the "GZK feature", rather than a cutoff. Existing data are not yet adequate to confirm nor deny existence of a GZK feature (de Marco et al. 2003). In addition to its influence on the incident UHECR spectrum, the decay of photopions represents a source of high energy neutrinos and γ-rays that may provide additional observational constraints on the distribution and nature of UHECRs. Some notes about that follow shortly. Finally, I comment for later reference that both photo pair and photopion production also need to be considered as loss mechanisms inside particle accelerators in models where protons are accelerated from low energies to energies above their thresholds.

There is one rather exotic "out" from the GZK cutoff, as pointed out by Coleman and Glashow (1999). In particular if Lorentz invariance is slightly broken at high energies, the photopion production behind the GZK cutoff could become kinematically forbidden, and there would be no GZK cutoff. This is allowed within the standard model and the required breakage is very small. Simply put, the suggestion is that massive particles might have slightly different maximum velocities than photons. If so, then the threshold energy in equation 3 picks up a term proportional to $E(E/\epsilon_\gamma)(c_\Delta - c_p)$, where c_Δ and c_p are the limiting speeds for the Δ and the proton. A difference in those speeds of order 10^{-23} is sufficient to forbid photopion production. Current experimental limits do not exclude this possibility.

Models for UHECR origins generally fall into either "top-down" or "bottom-up" scenarios. The top-down approach considers UHECRs as the by-products of the decay of superheavy dark matter particles or topological defects such as monopoles, all typically relics from the very early universe; e.g., particles associated with grand unification or GUT phase transitions. Bottom-up scenarios consider UHECRs as constituents of ordinary matter accelerated from low energies in some kind of "cosmic zevatron", assuming that they must somehow be accelerated to energies exceeding $1ZeV = 10^{21}$. These models are also frequently termed "astrophysical".

The superheavy particles or topological features in top-down models characteristically have masses in excess of 10^{23}eV. They can decay or annihilate to produce so-called "X-particles", which in turn, should decay into leptons and quarks, eventually generating a population of ultra ultrahigh energy pions (which then decay to ultra high energy γ-rays and neutrinos) and a few baryons. There are many variations on this theme (see, e.g., Bhattacharjee & Sigl (2000)). Models involving ultraheavy weakly interacting particles (a.k.a. "wimpzillas"), which are part of the dark matter halo of the galaxy, predict that the decay-product UHECRs should show some concentration toward the galactic center (e.g., Berezinski et al. 1997). It has been argued that existing data exclude this (Kachelriess & Semikoz (2003)), and the coming generation of observatories, such as Auger, should have sufficient sensitivity to see it clearly or exclude it with high confidence. Topological defect models predict a more isotropic distribution, so not so easily tested in this way. On the other hand they do predict large fluxes of high energy γ-rays and neutrinos. Semikoz & Sigl (2004) have recently explored observational γ-ray and neutrino constraints on topological defect models. The decay-product γ-rays are in the ultrahigh energy regime, but they also lose energy through photo pair production in interaction with cosmic background microwave and infrared radiation fields. So, "cosmogenic" γ-rays should quickly degrade to the GeV range, where the universe is relatively transparent and where they are detectable by experiments such as EGRET and GLAST. Semikoz & Sigl argue that the existing EGRET limit on the cosmic γ-ray background already disfavors some extragalactic topological defect models and point out that the next generation of ultrahigh energy neutrino telescopes, such as ICECUBE, should provide definitive tests.

For bottom-up, astrophysical UHECR models there are several general constraints we can lay down, beginning with basic energy requirements needed to account for the observed incident flux, which is about 4×10^{-14} J m^{-2} s^{-1} at 10^{20}eV. That translates into a local UHECR energy density of roughly 10^{-22} J m^{-3}, or 10^{-21}erg cm^{-3}. Since the lifetime of these UHECRs is around 300 Myr, we can estimate the required minimum source luminosity per unit volume to be about 10^{-37} W m^{-3} $\sim$ 10^{45} erg Mpc^{-3} yr^{-1}. The last expression is the easiest to compare, since it is roughly equivalent to the luminosity of a high luminosity AGN, or the expected accretion power onto a moderately rich galaxy cluster (inside 100 Mpc), or the cosmic γ-ray burst rate without cosmic evolution. That fact appears encouraging, since it would seem to keep open a range of possible sources. We should keep in mind, however, that this estimate is conservative, since it ignores energy inputs at lower energy, which, depending on the source spectrum, could be substantially larger than our simple estimate.

A second fundamental constraint on astrophysical UHECR accelerators is the maximum energy for individual CRs that can be produced. In the absence of losses, there are several simple ways to approach this question, but all lead to approximately the same answer; namely, the famous "Hillas" constraint (Hillas 1984), which can be expressed as,

$$E_{max} < 9 \times 10^{20} \beta \Gamma Z B_{Gauss} R_{pc} \mathrm{eV}, \qquad (3)$$

where B is the magnetic field inside the accelerating environment, R is its characteristic size, while βc is a characteristic velocity within the accelerator and $\Gamma = 1/\sqrt{1-\beta^2}$. The simplest version of this constraint comes from the need to confine the particles within the accelerator during the time they are being accelerated. In particular we expect the particle gyroradius, $r_g = E/(ZeB)$ to be smaller than the size of the accelerator. That leads to equation 3 with $\beta\Gamma = 1$. The emf of a unipolar inductor, such as a rotating neutron star or Kerr black hole, could be as large as $E < ZeBR(\Omega R/c) \sim \beta ZeBR$, where Ω is the angular rotation frequency of the object. This also expresses the Hillas constraint. Similarly, we must demand that the acceleration time is less than the lifetime of the accelerator. For an expanding object the latter can be expressed roughly as $R/(\beta c)$, of course. Supposing the acceleration is due to diffusive shock acceleration, the acceleration time scales as κ/v^2, where κ is a representative value for the spatial diffusion coefficient of the CRs. This behavior comes from the fact that the time between shock crossings for relativistic CRs during diffusive shock acceleration is measured by $\kappa/(vc)$, while the fractional energy gain per crossing scales as v/c in a first order Fermi process. Making the common assumption of Bohm diffusion for the particles, which applies for strong, isotropic MHD turbulence, $\kappa = (1/3)Ec/(ZeB)$. Then, the acceleration time is given by

$$\begin{aligned} t_{da} &\approx C_d Ec/(3ZeBv^2) \qquad (4) \\ &\approx 10^5 \frac{C_d E_{20}}{ZB_\mu \beta^2}\ \mathrm{yr}, \end{aligned}$$

where $C_d \sim 10 - 20$ is a factor that depends on the strength of the shock, E_{20} is the CR energy expressed in units of 10^{20}eV and B_μ is the magnetic field expressed in μG. Then, demanding that the acceleration time is less than the expansion time leads once again to equation 3 within a factor of order unity. The relativistic correction represented by the term $\beta\Gamma$ in equation 3 is meant to extend the equation to include diffusive acceleration at a relativistic shock (e.g., Gallant & Achterberg 1999).

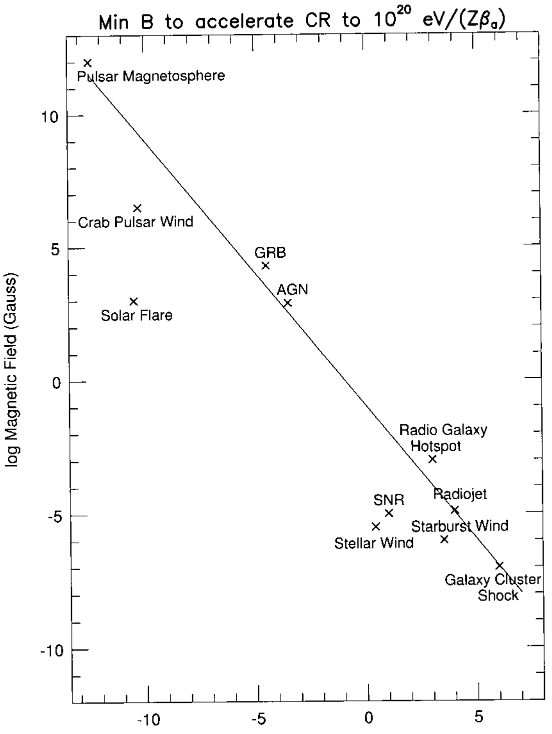

Fig. 1.— A "Hillas diagram" comparing various astrophysical objects to the minimum requirements to accelerate particles of charge Ze to 10^{20}eV.

Figure 1 shows the Hillas constraint for a $10^{20}/(Z\beta)$eV UHECR proton. Crude loci of various plausible astrophysical accelerators are included for comparison. Only points above the line satisfy the constraint. Most galactic accelerators, with the exception of pulsar magnetospheres, would be excluded by this constraint. On other grounds (specifically, isotropy considerations) I have excluded galactic sources, anyway. Several extragalactic possibilities seem to be in the running still, on this basis. I will comment on several of these individually, below.

There are further basic constraints, however, that must be met before a model can be taken as a serious candidate for UHECRs. In particular the Hillas constraint ignores energy losses during the acceleration process, and those can be severe. Synchrotron emission and photon scattering generally are the most serious losses to consider. Photon scattering includes inverse Compton scattering, pair production and photopion production, depending on the energy of the ambient photon field. Compton scattering resembles synchrotron emission, so they are usually lumped together. Synchrotron/Compton losses scale as E^2, so become continuously more important as the CR energy increases. As we saw earlier in this section, energy losses from inelastic collisions jump sharply in two stages, as first pair production, then photopion production turn on according to equations 2 and 3.

The energy loss lifetime of a particle from synchrotron/Compton emission is simply

$$t_{sc} = \frac{3}{2} \frac{m^4 c^7}{Z^4 e^4 (B^2 + B_{eq}^2)} \frac{1}{E} \qquad (5)$$

$$\approx \left(\frac{A}{Z}\right)^4 \frac{10^{12}}{B_{T,\mu}^2 E_{20}} \text{ yr},$$

where $m = Am_p$ is the CR mass, $B_{T,\mu}^2 = B^2 + B_{eq}^2$, expressed in μG, and $B_{eq} = \sqrt{6\pi u_{rad}}$ is sometimes called the equivalent isotropic magnetic field for the incident photon field for Compton losses. For a black body radiation field, $B_{eq} = 0.38T^2\mu$G. Inelastic scattering losses are usually dominated by photopion production, which sets in above $E_t^\pi \approx 2\times10^{20}/T$eV for a blackbody radiation field. The energy loss lifetime above this threshold can be approximated as

$$t_\pi \sim 10^9 \frac{1}{T} \text{ yr}. \tag{6}$$

The minimum constraint would demand that the lesser of these times exceed the acceleration time. These limitations can become effective under a variety of circumstances, but especially when the particle accelerator is associated with an intense magnetic field or "hot" radiation field, or if the acceleration is slow. The former condition is a concern in AGNs, γ-ray bursts, pulsar magnetospheres or any young neutron star. For instance, the 10^7K radiation field around a young neutron star limits to a few km the propagation of CRs above $\sim$ 10 TeV. Similarly, the radiation field close to a luminous AGN will limit the escape energy of protons to less than a few hundred TeV. In either case plausible UHECR sources would have to be farther out from the central object.

III. SOME ASTROPHYSICAL UHECR MODELS

There have been many bottom-up models proposed to explain the existence of UHECRs. All seem to push the envelope of plausibility, so none is yet obviously the correct one, if indeed there is a single source. I will comment here on a few that are illustrative of both the ideas that have been introduced and some of the concerns they must overcome.

The focus of this meeting has been clusters of galaxies, so it is appropriate to put this discussion in that context, as well. Consequently, I mention first the possibility that UHECRs might be the results of large scale cosmic structure formation shocks ("structure shocks" for short). On the face of it, they are very natural candidates, being enormous ($\sim$Mpc in scale), reasonably fast ($\sim 10^3$ km s^{-1}, so comparable to SNRs, which are thought to accelerate CRs to energies around 10^{15}eV), and very long lived ($\sim 10^8 - 10^9$ yr). Additionally, recent simulations have shown these shocks to be more common than one might guess from simple considerations of cluster accretion and merger shocks (Miniati et al. 2000; Ryu et al. 2003). While most of the shocks deep inside clusters should be relatively weak, since they involve largely virialized gas, the so-called "external" shocks involving matter entering from voids can be very strong, as can the shocks formed by gas streaming toward clusters from filaments and sheets. Indeed, numerical estimates suggest that those structure shocks may be the most important ones for dissipation of gravitational energy, and that as much as several tens of percents of the dissipated energy may be transferred to CRs (e.g., Miniati 2002; Ryu et al. 2003; Kang & Jones 2005). Figure 2 illustrates the distribution of shocks and their Mach numbers for one cluster formed in a large ΛCDM simulation.

Figure 1 includes a point to represent structure formation shocks that fell close to the nominal Hillas constraint line. The point assumes Bohm diffusion with a conservative magnetic field estimate, $B \sim 0.1\mu$G, so there is considerable latitude in its placement. On the other hand, the line actually applies the constraint to the energy $10^{20}/(Z\beta)$eV, where β is the shock speed in units of c. In this context $\beta \lesssim 3 \times 10^{-3}$, so we have really tested Bohm diffusion against a CR energy closer to 10^{18}eV. Kang et al. (1997) have argued that magnetic fields near structure shocks may be aligned close to the shock faces, in which case the relevant spatial diffusion is that across the magnetic field. If the upstream MHD turbulence is weak, the effective diffusion coefficient can be much smaller than that for Bohm diffusion (Jokipii 1987), potentially increasing the possible energy of UHECR from structure shocks by perhaps two orders of magnitude.

There are at least two remaining difficulties with this model, however. Even if we reduce the acceleration time from that for Bohm diffusion as given in equation 5 by two orders of magnitude, at least 10^9yrs are required to accelerate protons above 10^{20}eV. Recall that the lifetime against photopion production at these energies is only about 300 Myr, making it extremely difficult to reach higher energies. Furthermore, Ostrowski & Siemieniec-Ozieblo (2002) have pointed out for quasiperpendicular MHD fields with weak turbulence that CRs diffuse rapidly parallel to the magnetic field, and, thus, along the shock face. Limiting the acceleration time by the time for the CRs to traverse the shock width returns something close to the original Hillas constraint. I conclude, somewhat sadly, that unless magnetic fields reach into the range of tens of μG *outside* of clusters, where the strongest shocks are likely to be found, structure shocks are not viable candidates for UHECRs, even as they are good candidates for CRs of lower energy. Galactic wind termination shocks, which are also sometimes mentioned (e.g., Jokipii et al. 1989), fail more severely on grounds similar to those of structure shocks.

Probably the most attractive cluster-related candidate UHECR accelerators are the interaction regions between AGNs and ICM plasmas in clusters (e.g. Biermann & Strittmatter 1987; Rachen & Biermann 1993). In particular, if AGN jets penetrating the ICM are relativistic, their termination shocks should be relativistic, making the factor $\beta\Gamma > 1$ in equation 3. Characteris-

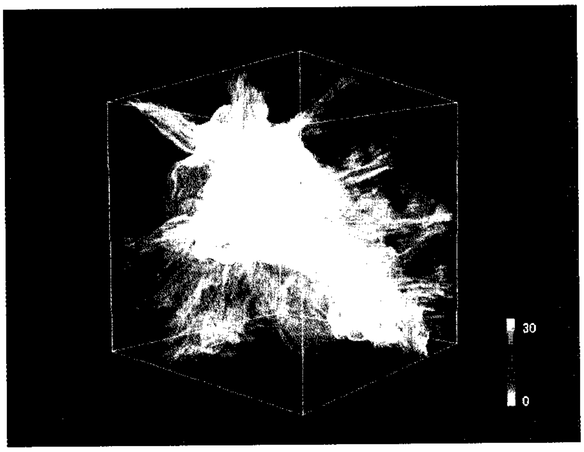

Fig. 2.— Volume rendering of the shocks at $z = 0$ in association with a cluster formed in a ΛCDM cosmological simulation (Ryu et al. 2003)

tic sizes for these shocks are tens of kpc, and various arguments suggest magnetic fields $\sim$ mG. These conditions applied to equation 5 allow UHECR protons to be accelerated to $E \sim 10^{21}$eV on timescales of $\sim 10^4$ yr. Proton-photon interaction losses according to equations 6 and 6 for these magnetic fields and for radiation fields at distances of kpc from the AGN are at least this long, so these accelerators seem viable. There are several caveats that must be dealt with, however. The most commonly cited concern is the rarity of high luminosity AGN in the local universe. In fact, there are probably only one of two suitable candidates inside 100 Mpc; the best being M87, as emphasized by Biermann and collaborators. In that case it becomes difficult to explain the near isotropy of detected UHECRs unless the local intergalactic magnetic field is quite strong, so it is able to deflect the particles into a quasi-random pattern (Biermann et al. 2001).

The above UHECR models are the ones most directly associated with clusters, per se. There are, on the other hand, many source models based on phenomena associated with individual galaxies, more or less independent of their residence in clusters. For completeness, I mention briefly a small sampling of these ideas. Long duration γ-ray bursts (GRBs) are now generally seen to be a consequence of ultrarelativistic fireballs associated with the core collapse of massive stars; that is a "hypernova". Since they involve ultrarelativistic shocks, they have been suggested by several authors as possible accelerators of UHECRs. (e.g., Waxman 1995, Vietri 1995). Gallant and Achterberg (1999) pointed out, however, that these shocks decelerate too fast to produce UHECRs unless they take place in a strongly decreasing external density, such as that in a pre-existing stellar wind. A more serious concern comes from the realization that most GRBs are seen at large redshift; that is, they were much more common in the early universe than they are today. Photopion losses would be enormous for protons reaching us from cosmological GRBs, leading Scully and Stecker (2002), for example, to argue that the full energy requirements to explain observed UHECR would exceed realistic estimates for GRBs by at least two orders of magnitude. On the other hand, more local GBR sources, being discrete rather than continuous events, should lead to correlated UHECRs, which are not seen.

Arons (2003) recently proposed a model for UHECR protons based on "wind surfing" of the relativistic wind of nascent magnetars, which are born with both very fast rotation and ultrastrong magnetic fields. These produce an emf easily great enough to account for observed UHECR energies. Like a similar model for UHECR iron based on young galactic pulsars (Blasi et al. 2000), the acceleration takes place outside the magnetosphere, so avoids the severe energy losses expected close to the neutron star. The sources are also discrete, since magnetars are spinning fast enough only for a few hours after they form. It is also not clear if the UHECR can penetrate the surrounding stellar matter without losses. In a somewhat similar twist on the AGN hypothesis that seeks also to avoid large energy losses in a strong radiation field, Boldt & Ghosh (1999) proposed that UHECRs might be accelerated by the emf of a magnetized, Kerr black hole that was inactive, "dead" in the AGN sense. Those authors estimated that there might be a sufficient local density of dead quasars in the nuclei of galaxies to account for the observed energy flux of UHECRs. The strongest criticism of this idea comes from the lack of evidence that non-accreting black holes can or do maintain strong magnetic fields (e.g., Krolic 1999).

IV. CONCLUSION

The existence of cosmic rays up to energies approaching 10^{21}eV is now well established experimentally. Although the point is argued, it seems likely that these ultrahigh energy CRs are primarily protons. The energies of these particles are macroscopic; that is, of the order of 10 Joules. We still have no clear picture of how they are produced or where they come from. They appear to be approximately isotropic above energies where the galactic magnetic field would significantly influence their trajectories, so are mostly likely not produced primarily inside the Milky Way. On the other hand, if they are produced primarily at cosmological distances, they suffer major energy losses through inelastic collisions with the cosmic microwave background, especially at energies above the so-called "GZK cutoff", near 6×10^{19}eV. There are a multitude of suggested models that depend either on the decay or annihilation of supermassive relic particles or topological defects, or on the acceleration of protons from thermal plasma by very fast (perhaps relativistic) shocks, or enormous emfs associated with rapidly rotating highly magnetized objects of various origins. Their existence may or may not directly relate to phenomena on galaxy cluster scales. The coming generation of cosmic ray observatories, beginning with Auger, promise to provide us with much more definitive constraints on their energy spectrum, as well as their spatial distribution and any indications of correlations between events. One thing is certain. Resolution of this puzzle is going to be interesting to watch.

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