Frontiers: Ultra High Energy Cosmic Rays

We now focus on cosmic rays with almost unimaginable energies: 10^{19} eV and beyond. The very highest energy cosmic rays have energies in excess of 50 Joules(!), which is comparable to a tennis ball hit at 150 km hr^{-1}! The particulars of the UHECR spectrum give tantalizing hints that these may be caused by a completely new mechanism, and may hint at physics beyond the Standard Model. This, of course, would be an extremely big deal. The Standard Model of particle physics has been amazingly successful in describing the interactions between known particles. However, it is aesthetically not satisfying that there are so many "fundamental" particles, or that there are so many free parameters in the model (the masses of the fundamental particles, for example). Thus, much of the theoretical particle physics community is working on understanding a grander theory of everything, which may put back the simplicity expected to be there! Such a model is also expected to predict other, as yet unobserved particles. These developments are, however, difficult to observe in the laboratory because most of the predictions suggest they could only be observed at energies too high to see in a lab. Therefore, the field of particle astrophysics may be our only hope to see observational confirmation of these predictions. This would include the nature of dark matter as well as what makes UHECRs.

Of course, a more prosaic explanation for UHECRs is also possible, so before striding off into the land of tachyons and violation of Lorentz invariance it's a good idea to think about how these particles propagate and what is known about them observationally. It is also useful to remember that the amazingly low fluxes of UHECRs (one event per sq. km per century above 10^{20} eV!) make statistics poor, so we could be fooled that way as well.

Observational properties

Ask class: what are some of the things we'd like to know about UHECRs observationally? Spectrum, fluxes, limits to energy, composition, arrival directions.

In addition to the high energies and low fluxes, the spectrum of UHECRs suggests that there may be a new component entering at very high energies. The number between energies E and $E + dE$ is $N(E)dE$, with $N(E)$ usually characterized by a local power law: $N(E) \propto E^{-\gamma}$. Below the "knee" at $E \approx 10^{15}$ eV, $\gamma \approx 2.7$. Between the knee and the "ankle" at $E \approx 10^{19}$ eV, $\gamma \approx 3.1$. Above $\approx 10^{19.5}$ eV, the spectrum is much flatter, with $\gamma \approx 1 - 2$. The uncertainty in slope is much larger, of course, due to the small flux. The flatness of the spectrum means that a new component could come in; at lower energies, the flux of this new component would be small compared to the flux of the steeper component between the knee and ankle, and hence would not be seen.

A potentially crucial diagnostic of the nature and origin of UHECRs would be their composition. At such unbelievably high energies, interactions for photons, neutrinos, protons, and heavier nuclei are different, but not by nearly as much as their differences at lower energies. One of the difficulties is that for an air shower produced by a given event, fluctuations are significant, meaning that one must wait for the better statistics provided by large air shower arrays before definitive judgments can be made. In general, the discriminants available from an air shower tend to be the muon content and the depth of shower maximum in fluorescence detectors. The current data suggests that the composition is constant from 10^{18-20} eV, and disfavors photon primaries but cannot distinguish between protons and heavier nuclei. This does help somewhat, because some top-down models (in which a superheavy particle decays) tend to produce photons. More data are needed. The latest from the Pierre Auger Array (the 500 pound gorilla of UHECRs) suggests a mixed composition at all energies, but a lot more work is required.

Another question is whether the arrival directions of the highest energy cosmic rays are distributed uniformly or are clustered in some way (the latter would suggest specific sources).

Propagation of UHECRs

Deflection by magnetic fields.—One of the themes of cosmic rays is deflection by magnetic fields. In particular, the source of an individual cosmic ray particle is unknown if the energy is low, because deflection is substantial. For very high energy cosmic rays, however, this is not necessarily the case. The deflection angle of a particle of charge Ze and energy E propagating a distance d through a magnetic field with a component $B_\perp$ perpendicular to the direction of motion is

$$\theta(E,d) \approx \frac{d}{r_g} \approx 0.5^\circ Z \left(\frac{E}{10^{20}\text{ eV}}\right)^{-1} \left(\frac{d}{1\text{ Mpc}}\right) \left(\frac{B_\perp}{10^{-9}\text{ G}}\right) . \tag{1}$$

The contribution to the deflection from our Galactic field ($d \approx 1$ kpc, $B \approx 3 \times 10^{-6}$ G) is comparable to the contribution per Mpc from larger-scale fields, which are poorly known but may typically be 10^{-9} G or so. The net result is that if the particles are protons ($Z = 1$) the arrival directions of such UHECRs will point fairly accurately to their sources. This means that UHECR observations are much more in the realm of normal astronomy than are observations of lower-energy cosmic rays. It is this fact more than anything that suggests to most people that UHECRs are extragalactic in origin. The argument is that if they came from specific Galactic sources then we'd see clustering on the sky, and in particular would see far more sources towards the Galactic center than away from it.

Greisen-Zatsepin-Kuzmin cutoff.—When the energy per nucleon is greater than about 7×10^{19} eV, a new effect is expected to appear. This is the Greisen-Zatsepin-Kuzmin (GZK) cutoff, and prior to the existence of the Pierre Auger Array the lack of definitive evidence for this cutoff was the main reason that there was consideration of unusual sources and new physics for the highest energy cosmic rays. The effect is that above those energies, in the rest frame of the nucleon(s) the photons of the CMB are at a high enough energy to photoproduce pions during a scattering. **Ask class:** will this happen suddenly at a particular energy per nucleon, or will it be an effect that becomes gradually more important with increasing energy? The latter, because the CMB photons have an energy distribution. This dramatically reduces the energy of the cosmic rays. The mean free path of this process is a few Mpc (lower at higher energies), and is expected to limit the distance traveled by UHECRs to $<$100 Mpc. **Ask class:** if UHECRs are produced uniformly everywhere in the universe, what should this do to the observed spectrum? It should create a strong cutoff, because the available volume for production is diminished above the GZK cutoff.

What have we learned from the Pierre Auger Observatory?

Some of the key points, adapted from the online slides of Antonella Castellina's presentation at the Paris High Altitude Workshop, May 2014:

1. The spectral cutoff is definitively seen, at more than 20σ significance, and the energy is $10^{19.6}$ eV. Yay! GZK confirmation, right?
2. ...not so fast. Remember, the GZK cutoff comes in at about 7×10^{19} eV *per nucleon*. If cosmic rays at those high energies are essentially protons, then cosmic rays with total energies above 7×10^{19} eV satisfy the criterion, and we'd expect a GZK cutoff. Since we see a cutoff at about the expected energy, that might suggest a proton-dominated composition. However, various pieces of evidence from Auger suggest that in fact at higher energies the composition tends toward a mixed composition of heavier nuclei from helium to iron. From the acceleration standpoint this makes sense; given a particular electrical potential, you get Z times as much energy per nucleus for a nucleus of charge Z than you would for a proton. But then the cutoff being near the GZK level is a coincidence! Perhaps the cutoff indicates the limits of the accelerators, rather than propagation effects?
3. Directionality of UHECRs. Another hope of the Pierre Auger Observatory was that it would identify individual sources of ultra-high energy cosmic rays. If enough UHECRs are observed, then particularly bright individual sources should give us enough that they show up in a statistically significant way. But this hope has not been realized. In fact, there aren't really even any statistically significant deviations from isotropy; people thought early on that the distribution of UHECRs was more consistent with nearby large-scale structure of visible matter than with actual isotropy, but that might not be true anymore. Cen A could be a source, but the significance isn't high once you

take trials into account (that is, you have to take into account that you would have been impressed by an apparent excess in any of a large number of directions). Perhaps the sources are very common? If neutron stars can do this somehow, that would make it less likely that individual bright AGN are responsible. Also, a larger nuclear charge means greater deflection, which would reduce the significance of individual point sources.

Thus the observational status remains frustratingly inconclusive. Time to retreat into some comforting theory :).

Potential sources: acceleration

If the cosmic ray particles are accelerated from a low energy to the observed energy, then general considerations that we discussed earlier in the course indicate that electromagnetic acceleration is the only possibility. A handy estimate of the maximum energy possible comes from the (plausible) assumption that acceleration ceases or becomes very inefficient when the gyroradius of the particle exceeds the size of the acceleration region. Putting this together, for a charge Ze in a field B of size L the maximum energy is $E_{\rm max} = ZeBL$. Suppose that $E > 10^{20}$ eV particles are protons, $Z = 1$. Then the only plausible astrophysical sources with a high enough BL are (1) neutron stars ($B \sim 10^{13}$ G, $L \sim 10^6$ cm), (2) active galactic nuclei ($B \sim 10^4$ G, $L \sim 10^{14}$ cm), and (3) clusters of galaxies ($B \sim 10^{-6}$ G, $L \sim 10^{23-24}$ cm). Clusters of galaxies are not especially promising, because in the time that the particle would take to be accelerated to the required energies, photopion losses would dominate. The maximum energy then turns out to be about 10^{19} eV. Radio lobes of AGN may do it, but sources are few and far between. The nearest one is M87 in the Virgo cluster, which is 16 Mpc away. If a single source like this is the cause of the UHECRs, the intergalactic magnetic fields must be large enough to scramble the arrival directions. **Ask class:** if the central regions of AGN or the region near neutron stars is the source, what are some of the problems? If the central regions of AGN are the source, an apparently serious problem is that the high radiation intensity environments are deadly for high-energy particles (energy losses are tremendous, via many processes). Neutron stars also face this problem, in spades because their magnetic fields are high enough that many of the processes in ultrastrong fields (e.g., trident pair production) can decrease the energy significantly within a few Compton wavelengths. It may be that iron nuclei "surf" field lines away from the star, avoiding some of the loss processes, but there are many things that can go wrong.

All of these processes therefore face difficulties, although maybe not insurmountable difficulties. Note, however, that if much higher energy cosmic rays are ever detected (10^{22-23} eV, for example) then the sources discussed above no longer have enough energy to generate them, and some other process must be considered.

Possible sources: new physics

The lack of observational understanding of the type of particles composing UHECRs leaves freedom for broader speculation about their origin. In particular, perhaps the particles are heavier hadrons. These models come in two flavors: hybrid models, in which other particles are accelerated, and top-down models, in which superheavy particles decay and produce the observed cosmic rays.

The most conservative such possibility is that since some neutrinos have mass (as demonstrated by various experiments), ultrahigh energy neutrinos accelerated in some way can annihilate on the background of massive neutrinos, and form hadrons by Z-boson decay. Problems with this include the energy generation rate required to get protons that have ZeV neutrinos as secondaries (10^{48} erg Mpc^{-3} yr^{-1}!). It could instead be that there is a new particle that decays to hadrons as necessary, or that topological defects (e.g., monopoles) do the same. The point for some of these more exotic suggestions is that acceleration to high energies is not necessary. Instead, the particles are created with approximately the right energy, or perhaps an order of magnitude greater energy. These are therefore called "top-down" models, in contrast to the "bottom-up" models in which a low energy particle is accelerated to high energies in some fashion.

Another possibility to mention is that some people have suggested that Lorentz invariance might be broken at the highest energies, as a symptom of new physics involved at GUT scales, and that these might be manifest even at lower energies such as the center-of-mass energies involved in UHECR interactions. This was suggested as a way to bypass the GZK cutoff, but as it has now been observed the idea has to go back into storage.

Future observations

If any of these exciting possibilities are realized, it will be a major step forward in understanding grand unified theories, reaching new physics, and possibly solving a number of other questions, such as the nature of dark matter. However, the only way to test any of this is to have more extensive observations. In particular, much larger area is required. This can be seen simply from the low fluxes observed at ultrahigh energies (one per sq. km per century is tiny!). This is why experiments such as the Pierre Auger Array are being conducted. Even more ambitious plans are in the works. A NASA project called OWL-Airwatch has been suggested, which will look for flashes of fluorescence in the Earth's atmosphere caused by high energy cosmic rays. This would, at least in principle, increase the effective area another couple of orders of magnitude.