Propagation of UHE cosmic rays in a structured universe

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In a gravitationally unstable universe, the structure of dark matter and galaxies, intergalactic gas and magnetic field can have severe impact on the propagation of ultra high energy cosmic rays (UHECR). The possible effects include spatial confinement and directional focusing along the supergalactic matter sheets, as well as universal re-acceleration at large scale shock fronts, and spectral modification due to energy dependent leakage into cosmic voids. As a result, the GZK-cutoff may be less pronounced and occur at a higher energy, where the stochastic nature of both acceleration and energy loss processes has to be taken into account.

1 Supergalactic magnetic field structure and cosmic ray confinement

Very little is known about the strength and orientation of the magnetic field outside our galaxy. For cosmic ray transport calculations, one mostly uses the assumption of a nanogauss field, which is homogeneous over cells with some reversal scale of order 1 Mpc. In such fields, the highest energy cosmic ray protons have a gyro-radius \( r_g \sim 300 \text{ Mpc} \), thus propagate almost in straight lines; this opens the possibility of an “UHECR astronomy”, as anticipated by the Pierre Auger Project.

Models of structure formation in cosmology, however, draw a quite different picture: The magnetic field is aligned with the matter sheets, where it can reach a field strength up to \( \sim \mu G \), while in the large cosmic voids the field drops to its primordial value of \( \lesssim \text{pG} \); this scenario is fully consistent with existing observations. In the sheets, which have a typical thickness of \( \sim 10 \text{ Mpc} \), the highest energy cosmic rays have \( r_g \sim 1 \text{ Mpc} \), and are thus confined. Outside the sheets, the accretion flow of intergalactic gas drives the cosmic rays back, but the rapidly decreasing magnetic field may allow diffusive losses in upstream direction, which can imply spectral modifications due to a “leaky box” mechanism. Fringe field effects may additionally focus and align the cosmic rays with the field direction in the sheets; this might explain the apparent correlation of UHECR arrival directions with the local sheet, the “supergalactic plane”. Since the universe needs no longer to be homogeneously filled with cosmic rays, the total energy budget for UHECR sources is strongly diminished.

2 Large scale shocks and universal acceleration

Another prediction in a structured universe is the existence of large scale shock fronts, providing the possibility of cosmic ray acceleration by the very effective shock-drift acceleration mechanism. In a global picture, the matter sheets form the collective downstream region, and the voids the collective upstream region in a foam-like shock
topology. The cosmic rays, sliding sideways along the shock, never effectively leave the acceleration region. The spatial extension of the acceleration region in the direction of the flow can be estimated by the diffusion length, $l_D$, which depends on particle energy for quasi-perpendicular shocks and a Kolmogoroff turbulence spectrum as $l_D \propto E^{5/3}$. At the highest energies, $l_D$ can become comparable to the sheet thickness, and the particles scatter freely between the boundary shock fronts. In this case, a stationary particle spectrum will no longer be obtained by the balance of diffusion over the shock front and downstream advection, but rather by the balance of energy gains and losses due to MBR interactions; here, the stochastic nature of the loss process turns out to be important.

3 The stochastic nature of MBR pion production losses

The transport of a proton in the MBR which is subject to pion production losses has to be described by a Markov point process, where the energy loss occurs randomly in distinct steps of random-distributed width. We may simplify the process to a pure counting process of unit steps, which is in case of a constant interaction rate known as a Poisson process. In photopion interactions, particles lose energy fractionally, i.e $\Delta E/E \approx \Delta \ln E = \text{const} \approx 0.2$. For a Poisson process, one can show that an initial spectrum power law spectrum, $f \propto E^{-a}$, of a source at distance $D$, suffers an energy independent reduction by a factor $M = \exp[-(D/\lambda)(1 - e^{-\alpha})]$, if $\lambda$ is the mean interaction length and $\alpha = a(\Delta \ln E)$. For a linearly increasing interaction rate, $\rho = c/\lambda = \rho' \ln(E/E_0)$, the modified spectrum can be approximately described as a power law steepened by $\Delta a = (D\rho'/c)(1 - e^{-\alpha})$.

The interaction rate in the microwave background can be best modeled relative to the maximum rate $\rho_1$, which is reached for $E > E_1 \approx 1\text{ ZeV}$ and corresponds to $\lambda_1 \approx 4\text{ Mpc}$. For $E_0 \approx 30\text{ EeV} < E < E_1$, it is linearly increasing, $(\rho/\rho_1) \approx 0.3 \ln(E/E_0)$, and $\rho = 0$ for $E < E_0$. A continuing initial power law spectrum maps then to a piecewise power law with index $a$ for $E < E_0$ and $E > E_1$, and $a + \Delta a$ in between. A spectral cutoff in the source maps to an exponential decline of the observed spectrum somewhat below the source cutoff energy. We may give two numerical examples: A radio galaxy at $D = 30\text{ Mpc}$, producing a spectrum $f \propto E^{-2}$ with a sharp cutoff at 1 ZeV, is observed with a power law index $a' \approx 2.75$ between 30 and 300 EeV, followed by an exponential cutoff. A topological defect at $D = 100\text{ Mpc}$, producing a $f \propto E^{-1.3}$ spectrum, is observed with a power law index $a' \approx 3$ between 30 EeV and 1 ZeV, flattening back to $a = 2$ for higher energies.

4 Consequences for the GZK cutoff and cosmic ray observatories

The time scale of large scale shock acceleration, $t_\alpha$, is generally larger than the time scale for MBR photopion losses, $t_\pi$; depending on magnetic field strength and shock
velocity, we may find ratios $t_a/t_\pi \sim 1-100$ at $\gtrsim 100 \text{ EeV}$. Thus the acceleration is not really effective in the ordinary sense; however, considering the stochastic nature of energy losses and the breakdown of advection at the highest energies, the resulting stationary spectrum can still be relatively flat for $E \gtrsim 100 \text{ EeV}$. In the simple case of a constant acceleration time scale, interaction loss balanced shock acceleration leads to power laws $f \propto E^{-b}$, and the relation $t_a/t_\pi = b[1 - \exp(-0.2b)]^{-1}$ holds. Spectral indices as observed in the UHECR spectrum are obtained for $t_a/t_\pi \approx 4$, but steepen very fast for larger values; under realistic conditions, the equilibrium spectrum is probably concave and too steep to explain the highest energy event rates.

Therefore, the existence of large scale shocks in the universe does not make cosmic ray point sources unnecessary; radio galaxies, AGN, gamma ray bursters or topological defects may still contribute as UHECR sources. Clusters of galaxies, which are the sites of the strongest large scale shocks and well located in the universe, can play an intermediate role between point sources and large scale acceleration. The importance of large scale shocks is rather that they provide a re-acceleration mechanism which is as universal as the GZK process, and thus may lead to revised estimates of the maximum distance of the possible sources of highest energy cosmic rays. Consequently, the pros and cons for the various source models have to be reconsidered in a structured universe. For the Pierre Auger UHECR observatory, the large values of the magnetic field arising from large scale structure simulations give little hope to see point sources of charged cosmic ray particles; however, UHECR events are likely to occur in clusters and map the local large scale structure of the magnetic field.

Acknowledgements

Work of JPR is funded by NASA grant 5-2857. This work is based on a PhD thesis supervised by P.L. Biermann at the MPIfR Bonn, and a collaboration with H. Kang. T. Stanev is acknowledged for discussions.

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