The supergalactic structure and the origin of the highest energy cosmic rays

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Abstract

The recent discoveries of several reliable events of high energy cosmic rays at an energy above 10^{20} eV raise questions about their path through the nearby universe. The two analyses of, on the one hand, the Haverah Park data set including a limited set of further events and, on the other hand, the Akeno data set appear to have an inconsistent pattern of arrival directions. Both data sets showed some measure of a correlation with the supergalactic plane, the locus of cosmologically nearby galaxies, radio galaxies and clusters of galaxies. In order to be able to interprete such findings, we need a reasonable model of the true intergalactic magnetic field and then can expect to make further progress on the propagation of energetic charged particles. Using recent cosmological simulations of structure formation in the universe, we estimate the magnetic fields which correspond to the upper limits in the Rotation Measure to distant radio sources. Using the one single direct measurement of such a magnetic field, near the Coma cluster, we thus estimate that the magnetic field strength in supergalactic sheets and filaments may be in the range of 0.1 to 1 microgauss. If such strengths are realized inside our Local Supercluster, this opens up the possibility to focus charged particles in the direction perpendicular to the supergalatic plane, analoguously but in the opposite direction to solar wind modulation. If focusing exists, it means that for all particles captured into the sheets, the dilution with distance d is $1/d$ instead of $1/d^2$, increasing the cosmic ray flux from any source appreciably with respect to three-dimensional expansion. This means in effect, that we may see sources to much larger distances than expected sofar. This effect is relevant only for energies for which the possible distances are smaller than the void scale of the cosmological galaxy distribution, in the range possibly up to 100 Mpc, but presumably less than this distance.

1 Introduction

The discovery of cosmic rays early this century [22, 27] spawned many observations of these high energy particles, right up to the recent detection [20, 9, 14] of a significant number of particles beyond the energy of 10^{20} eV; for general reviews of these questions see, e.g., [23, 2, 17, 18, 7, 8].

While the search into the origin of cosmic rays still awaits the final resolution, there are many successful steps that have been taken, from the original Fermi-acceleration process [15, 16] via the argument that the high energy particles ought to be extragalactic [11, 3, 12] to the more recent discoveries already mentioned.

In this brief discussion we propose to concentrate on the arrival directions of the most energetic cosmic rays, and their possible correlation with the matter distribution in the nearby universe [6, 35, 36, 21].

2 Expectations for high energy cosmic rays

For the source region or in our Galaxy the Larmor radius r_g is given by

$$r_g \approx 10\ E_{20}\, B_{-5}^{-1}\ \mathrm{kpc}, \tag{1}$$

where E_{20} is the particle energy in 10^{20} eV, and B_{-5} is the magnetic field in units of 10^{-5} Gauss.

This means that the Larmor radius is larger than the thickness of the Galactic cosmic ray disk (about a kpc; for a review of the Galactic magnetic field see [1]), and of the order of the size of the source region if radio galaxy hot spots of very high luminosity are considered [3]. Thus, at such energies, propagation through the Galaxy is nearly in a straight line path.

Other important limitations are obviously losses against photon or magnetic field backgrounds, and the time required for acceleration (for a review, see [8]). Detailed calculations for the propagation have been done by a variety of scientists, e.g., Stanev [37], and several others.

For intergalactic space the Larmor radius is conveniently scaled to other units and can be written as

$$r_g \approx 100\ E_{20}\, B_{-9}^{-1}\ \mathrm{Mpc}, \tag{2}$$

where the magnetic field strength is obviously given in units of 10^{-9} Gauss. This means that for the typical upper limits derived from Rotation Measure observations (for a review see Kronberg [28]), the intergalactic propagation is also in a nearly straight line path. Therefore, it is meaningful to ask for the arrival directions on the sky, and whether they correlate with any known objects or structures.

However, losses in the bath of the microwave background radiation (MBR) limit the distance from which particles can realistically come to less than $\lesssim 50$ to 100 Mpc. In other words, integrating over a presumed cosmologically homogeneous source distribution leads to a cutoff in the summed contributions from all sources near 5×10^{19} eV. This is the GZK cutoff, named after Greisen, Zatsepin and Kuzmin [19, 42, 38].

Probable sources at distances < 100 Mpc are distributed in the supergalactic plane sheet [40, 39, 32, 33], which is defined by the Local Supercluster of nearby galaxies ($< 30h^{-1}$Mpc). Therefore arrival directions should cluster toward the supergalactic plane from energies, where MBR losses become important. Or, in other words, from near 5×10^{19} eV the arrival directions should cluster just as the sources in our neighborhood do. However, there should be no clustering below this energy.

3 Test of prediction

This prediction was made and explored in various lectures late 1994 and early 1995 [4, 5, 6, 35], and has been tested using several data sets.

First, the Haverah Park Array data set was used, and also combined with a fraction of other data available at the time [36]. In this test the question was asked in the following way: Given very limited statistics, we can test whether the arrival directions cluster better towards the Galactic plane, or the supergalactic plane. The measure of success was the distance of the arrival directions to the reference plane, and the distance for homogeneously scrambled data (in order to allow for all selection effects). This test showed an effect of a correlation at a level somewhat below 3 sigma.

Thus, the effect was consistent with the prediction and was visible from 4×10^{19} eV.

Second, the Akeno Array data set was used [21]. These authors found another measure to be better as a test: The distance to the Galactic and supergalactic plane did not yield any better result than the analysis of the Haverah Park data, but using pairs of events there appeared a tantalizing excess of pairs lying directly on the supergalactic plane sheet. Thus, here again the effect was consistent with the prediction, however, using pairs of events, from 5×10^{19} eV.

Third, as presented at this meeting, the combination of all events and again using pairs and triplets of events suggested that the supergalactic plane is the region of origin of ultrahigh energy cosmic ray events, for a fraction of maybe 15 - 20 %, or possibly more, of all events beyond 5×10^{19} eV.

However, as pointed out by Waxman et al. [41], not only is there a seeming inconsistency between the first two analyses, but there is also a deeper difficulty: When one uses the actual distribution of galaxies farther beyond the Local Supercluster as a measure of possible source directions and distances, the supergalactic plane is not such a good approximation anymore, and so one would not really simply expect a direct straightforward correlation. The observed correlation is apparently better with the geometric sheet corresponding naively to the cosmologically nearby galaxy population, rather than with the actual large-scale galaxy distribution.

4 The supergalactic Plane

Galaxies are distributed in the observed universe in a non-homogeneous pattern, in what may loosely be described as a network of filamentary superclusters encompassing voids, with typical void scales of (30-100) h^{-1} Mpc [34, 13]. We live in one of the superclusters, namely the Local Supercluster [39]. It is a flattened condensation of nearby galaxies centered at the Virgo cluster extending to $30h^{-1}$ Mpc with a scale height of $5h^{-1}$ Mpc. It is also connected to several nearby superclusters by filaments of galaxies and clusters. This observed structure of supercluster-void networks can now be well simulated in large computers and also be interpreted [10]: The large scale structure forms as the result of gravitational instability, and then the matter flows into the potential wells, into the sheets, filaments, where sheets intersect, and nodes, where filaments intersect. This means that there is baryonic accretion flow towards the nonlinear structures in cosmological structure formation. The velocity of this accretion flow can be as large as about 1000 km/sec, independent of the Hubble constant [30].

As a consequence of the accretion flow, the cosmological magnetic field is expected to lie mostly along sheets and filaments. Assuming uniformity, Kronberg et al. had derived an upper limit for the true intergalactic magnetic field of $B < 10^{-9} L_{rev,Mpc}^{-1/2}$ Gauss; here $L_{rev,Mpc}$ is the reversal scale of the magnetic field. Allowing for the correlation of magnetic field to cosmic structures we can rederive this limit and it transforms an upper limit to $B < 10^{-6\pm0.5}$ Gauss along sheets and filaments [29, 31]. Interestingly there is confirmation of a definitive strength of such a magnetic field in one case, in the plane of the Coma/A1367 supercluster [26]. This supercluster is about $90h^{-1}$Mpc away from the edge of the Local Supercluster and they are connected by filaments of galaxies.

Figure 1. A two-dimensional cut in a simulation of the evolution of the cosmological flow in a standard cold dark matter (SCDM) universe with total $\Omega = 1$ and baryonic $\Omega_b = 0.06$. The calculation has been done in a box of $(32h^{-1}\mathrm{Mpc})^3$ volume, and the plot includes a region of $(16h^{-1}\mathrm{Mpc})^2$ with a thickness of $0.25h^{-1}$Mpc. The first panel shows density contours, the second panel shows velocity vectors, and the third panel shows magnetic field vectors. In the third panel, the vector length is proportional to the log of magnetic field strength.

5 Supergalactic Modulation and Confinement

Suppose we approximate the Local Supercluster as a cosmological sheet bounded by two plane parallel accretion shocks. Then in the accretion flow and in the sheet we can again write the Larmor radius

$$r_{g\perp} \approx 0.05 \; E_{19.7} \, B_{-6}^{-1} \, (\frac{p_\perp}{p_{tot}}) \text{ Mpc}, \tag{3}$$

and notice that the Larmor radius for the highest energy particles is smaller than the thickness of the supergalactic sheets for $B_{-6} \gtrsim 0.02 \, h \, E_{19.7} \, p_\perp / p_{tot}$. This means a rather small strength of the magnetic field may be sufficient to contain high energy particles in the sheets.

Then the question arises : Is modulation possible in the accretion flow analogous to solar wind modulation of cosmic rays? Of course, if such a modulation were possible, it would only pertain to the momentum component perpendicular to the sheet.

The transport equation for energetic particles with z along $\perp$-direction to the sheet can be written as

$$F_\perp \; = \; N \, v_\perp \; - \; \kappa_\perp \, \frac{\partial}{\partial z} \, N. \tag{4}$$

$$N \; = \; N_o \, \exp[-\frac{\mid v_\perp \mid}{\kappa_\perp} \, z] \tag{5}$$

Note $v_\perp < 0$ for z positive, where $v_\perp$ is the accretion velocity perpendicular to the sheet, and $\kappa_\perp$ the transport coefficient perpendicular to the sheet.

The critical question is then: What numerical value can $\kappa_\perp$ possibly have? The transport coefficient can be written as (the characteristic length scale) $\times$ (the characteristic velocity scale). If all the magnetic field is perpendicular to the sheet, then the Larmor radius and the speed of particle, c, are the relevant scales, then we have a very large $\kappa_\perp$, and no modulation is effectively possible. But if the magnetic field has large parallel components, then convective turbulence is dominant probably. It means that velocity and length scales of transport are of the order of the accretion velocity ($v_\perp$) to the supergalactic plane sheet and the scale height of sheet (H_{sgp}), respectively. Then for particles with $r_{g\perp} < H_{sgp}/2 \sim 2.5 \, h^{-1}$Mpc modulation is possible. Thus, if supergalactic modulation can exist, then we can have weak confinement along the supergalactic sheet.

In three-dimensional expansion $1/d^2$ dilution and a gradual weakening of the particle flux by interaction with the MBR lead at large distances to a total cutoff above 5×10^{19} eV. If some fraction of the particles originated from the sources in the Local Supercluster are confined along the sheet, we have only a two-dimensional $1/d$ dilution but also interaction with the MBR. This effect is clearly relevant only beyond 5×10^{19} eV, since at lower energies we can see sources beyond the Local Superclusters. In other words, for confined particles focusing along the two-dimensional sheet is possibly stronger than original source distribution beyond 5×10^{19} eV.

We offer this possibility as a potential solution to the conundrum posed by the two data analyses about arrival directions in the literature. This is a possible explanation for the Haverah Park and Agasa results.

6 Tests

There are a number of tests that can be done in the next few years, or could be done now:

- In such a picture we have stronger magnetic fields along sheets/filaments of super-clusters, of order

$$B \lesssim 10^{-6\pm 0.5}\,\mathrm{Gauss} \tag{6}$$

  Radio polarization observations of cosmologically distant radio sources (group of Phil P. Kronberg) will provide the most stringent check.

- All present and future events beyond 4×10^{19} eV from the various arrays Akeno, Haverah Park, Fly's Eye, Yakutsk, Volcano Ranch, and in the future Auger should be combined to repeat the analysis: At this meeting there was a first report of such an attempt, with very interesting results.

- We need to verify specific source candidates, such as the radio galaxies 3C134, NGC315, and M87. We also suggested the accretion shocks around the large scale structure as a possible candidate [24, 25].

The future of our attempts to understand the origin of these very high energy particles promises to be challenging.

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