The origin of the highest energy cosmic rays
Do all roads lead back to Virgo?

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Introducing a simple Galactic wind model patterned after the solar wind we show that back-tracing the orbits of the highest energy cosmic events suggests that they may all come from the Virgo cluster, and so probably from the active radio galaxy M87. This confirms a long standing prediction, as well as a theoretical model for the radio galaxy jet emission of M87. With this picture in hand, one clear expectation is that those powerful radio galaxies that have their relativistic jets stuck in the interstellar medium of the host galaxy, such as 3C147, will yield limits on the production of any new kind of particle, expected in some extensions of the standard model in particle physics.

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I. INTRODUCTION

The origin of the highest energy particles observed in the universe continues to present a major enigma to physics. These particles reach energies as high as \(3 \times 10^{20}\) eV. The flux of such nuclei is expected to drop sharply at \(5 \times 10^{19}\) eV due to the interaction with the microwave background, commonly referred to as the GZK-cutoff after its discoverers\textsuperscript{[1]}. However, the number of particles to particles to overcome losses within the space limitations and the particle orbits are bent. In the second option there are two extreme explanations of the isotropy, one is to argue that we have many sources contributing, even at the highest particle energies, and the other is that we have one source dominating at the maximum energies, and the particle orbits are bent. In the second option the bending should not add substantially to the travel time.

There are several ways out of these difficulties. The highest energy particles could be particles generated by topological defects\textsuperscript{[3]} or from extensions of supersymmetry\textsuperscript{[12]}. Alternatively, they could be cosmologically local\textsuperscript{[13,14]}. If many sources contribute to the observed particle fluxes they have to be fairly common in space, as in the scenarios of accelerating such particles in the environment of quiescent black holes\textsuperscript{[14]}, or gamma ray bursts\textsuperscript{[16]}

Here we present the consequences of introducing a magnetic Galactic wind in analogy to the solar wind.

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The magnetic field of the wind bends the particle orbits without adding substantial travel time.

II. A MODEL FOR A MAGNETIC GALACTIC WIND

It has long been expected that our Galaxy has a wind \(^{17}\) akin to the solar wind \(^{18}\). Recent modeling \(^{19}\) shows that such winds can be quite fast, and ubiquitous.

It seems plausible that this wind is powered by the combined action of cosmic rays and magnetic fields \(^{19}\) and starts in the hot phase of the interstellar medium seen in X-rays by ROSAT. This phase has a density of \(3 \times 10^{-3}\) particles per cc, a temperature of about \(4 \times 10^6\) K, a radial scale of about 5 kpc, and an exponential scale in \(z\), perpendicular to the disk, of almost 2 kpc \(^{21}\). We note that the corresponding equipartition magnetic field strength is 10 microGauss.

Parker has shown \(^{18}\) that in a spherical wind the poloidal component of the magnetic field becomes negligible rather quickly with radius \(r\), the radial component decays with \(1/r^2\), but the azimuthal part of the magnetic field quickly becomes dominant with \(B_\phi \sim \sin \theta / r\) in polar coordinates.

An available measure of magnetic field along any line of sight is the Rotation Measure: It is proportional to the line of sight integral of the product of electron density and magnetic field component (including the sign) from us to a distant linearly polarized radio source. We verified that the magnetic field topology of the Parker model is consistent with the data \(^{21}\) for a base density below that of the hot interstellar medium.

Cosmic ray driving is similar to radiation driving of winds in massive stars, and so \(^{22}\) magnetic fields can lead to an increase of the momentum of the wind. For a steady wind and Parker topology the Alfvén speed in the wind becomes independent of radius \(r\) for large distances. The ultimate wind velocity is then a small multiple of the Alfvén velocity, suggesting a rather strong magnetic field. On this basis we have adopted here a magnetic field somewhat higher than in other current models \(^{19}\).

The data on the sign of the azimuthal component show that in the disk of the Galaxy there are reversals but in the direction of the anti-center, the part of the sky most relevant for calculating orbits of energetic charged particles, the field points to the direction of galactic longitude about 90 degrees \(^{23,24}\). That means immediately that positively charged particles traced backwards have their origin above us, at high positive galactic latitudes.

There is one additional observational argument in favor of such a topology of the magnetic field: Krause & Beck \(^{22}\) have found that the dominant magnetic field symmetry in spiral galaxies points approximately along the local spiral arms inwards towards the center. This effect is unexplained at present, but it seems nevertheless to be observationally well established. One might expect that magnetic field sign reversals in the disk should translate into similar reversals in the wind. However, if the dominant directionality is established by the most active spirals arms, then the symmetry as found by Krause & Beck should prevail well outside the disk. We will assume this to be the case. This symmetry implies an overall current in the Galaxy possibly driven by star formation through stellar winds and cosmic rays.

If the entire disk has this symmetry, then there cannot be a sign reversal of the azimuthal component close to the disk along the direction perpendicular to the disk. This implies that the radial magnetic field component \(B_r \sim 1/r^2\) is pointed inwards inside the disk and in its immediate neighborhood below and above. However, considering all of \(4\pi\) the radial component has to be pointed outwards roughly over half the sky, and pointed inwards in the other half in order to satisfy the condition of a source free magnetic field. Thus, one possible and simple configuration is that \(B_r\) is pointed inwards within 30 degrees of the disk both above and below the disk, and pointed outwards within 60 degrees of both poles. Such a pattern is different from the Solar wind, where the components change sign in mid-plane.

We adopt the simplest possible model. We assume that the magnetic field in the galactic wind has a dominant azimuthal component, and ignore all other components. We assume that this azimuthal component has the same sign everywhere. This then means that the strength of this azimuthal component at the location of the Sun is the first key parameter, and the distance to which this wind extends is the second one. Since the irregularities in magnetic fields should decay into the halo, the total magnetic field strength near the Sun may be used as an approximation to the local halo wind field, and in fact one might expect a lower limit. Most measures of magnetic field underestimate its strength. Therefore we will consider for reference a model which has a field strength near the Sun of 7 microGauss \(^{23}\). The second parameter, the distance to which this wind extends, is more uncertain: Our Galaxy dominates its near environment well past our neighbor, M31, the Andromeda galaxy, and might well extend its sphere of influence to half way to M81. Therefore we will adopt as outer the halo wind radius half the distance to M81, 1.5 Mpc.

III. TRACING THE PATH BACKWARDS

To follow the particle trajectories in the Galactic halo we trace protons backwards \(^{20}\) from their arrival direction at Earth. We use the 14 published cosmic ray events above \(10^{20}\) eV, the list from Watson (included in \(^{27}\)) and the new list from AGASA \(^{28}\). There is a big uncertainty with the energy estimate of the highest energy Yakutsk \(^{2}\) event, which we therefore exclude from the present analysis, and hence we arrive at a final tally.
of 13 events used.

Fig. 1 shows the directions of the events at that point when they leave the halo wind of our Galaxy in a polar projection. For reference we show the direction to the active galaxy M87 (Virgo A), the dominant radio galaxy in the Virgo cluster. We show the two highest energy events twice: under the assumption, (i) that they are protons, and (ii) that they are Helium-nuclei (filled black symbols). We also show the supergalactic plane as a shaded band.

The interesting result of these model calculations is that the directions of all tracks point North. With the exception of the two events having the highest energy, all other 11 events can be traced to within less than about 20 degrees from Virgo A. Considering the uncertainty of the actual magnetic field distribution, we find then that all events are consistent with arising originally from Virgo A. Since these particles are assumed to be accelerated out of cosmic gas, about 1/10 of all particles may be Helium nuclei with the same energy per particle. If the two highest energy events are in fact He nuclei, all 13 events point within 20° of Virgo A.

If Virgo A is indeed the acceleration site of the highest energy cosmic ray events when they leave the halo of our Galaxy.

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IV. DISCUSSION AND IMPLICATIONS

This particular model can be tested in several ways:

It has been suggested repeatedly in the literature, that radio galaxies may inject a major fraction of the total energy output (of order 0.1) in energetic particles [7,30–32]. In order to determine this fraction for M87 we need a model for the magnetic field structure along the supergalactic sheet, and test it with orbit calculations.

Second, if the appearance of pairs and triplets of events [11] along the supergalactic sheet is confirmed, then clearly the magnetic field structure along the sheet may be the reason in that it gives rise to some caustics with an enhancement just along the sheet direction. Again, orbit calculations will be able to test this.

Third, the very concept of a magnetic wind, driven by cosmic rays, but with an initial magnetic field as strong as in the disk, needs to be examined more closely. The conditions to be met are a) the available energetics, b) agreement with the Rotation Measure data, c) the condition that the wind be super-Alfvénic, and d) that the wind does extend to large scales. The model for Wolf Rayet star winds [22] gives us some confidence, that this is indeed reasonable. Since this should be true for any galaxy with a high star formation rate and therefore, presumably with a high rate of cosmic ray production, this latter condition may be the easiest to test with sensitive absorption line data at high redshift, with observations of the shell of gas around these extended winds.

Fourth, the current experimental statistics cover only a fraction of the Southern sky. We would expect some asymmetry between the Northern and Southern hemispheres of our sky. How much asymmetry depends again on the more detailed magnetic field configurations, but
the data from the Auger observatory will clearly provide stringent conditions on this as on any other model.

Fifth, if the model proposed here could be confirmed, then it would constitute strong evidence that all powerful radio galaxies produce high energy cosmic rays, and that they do this at a level of $\approx 0.1$ of their total power output. This then implies that compact radio galaxies do provide a good test bed for particle interactions, since they have a large screen of interstellar gas around the radio hot spots and jets as seen in mm-wavelength radio data. There the paradigm is materialized of having a gigantic accelerator, and a beam dump. These radio galaxies may be used for particle interaction experiments in the sky. If a significant correlation in arrival direction between ultra high energy cosmic rays and this specific class of radio quasars could be confirmed, then properties of new particles could be constrained.

In summary, we propose here that a very simple model for a Galactic wind rather analogous to the Solar wind, may allow particle orbits at $10^{20}$ eV to be bent sufficiently to allow “super-GZK” particles to get here from M87, and also explains the apparent isotropy in arrival directions.

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