Modelling High Energy Monopole Induced Air Showers

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Abstract

Following the recent revival of the idea that the highest energy cosmic rays might be magnetic monopoles which gain their energy from the galactic magnetic field, we study the electromagnetic and hadronic interactions of monopoles and model their interactions with the atmosphere. We find a strong dependence of the sort of induced shower on the monopole mass, and discuss the possibilities of distinguishing monopole-induced showers from those due to conventional particles.

1 Introduction

The origin of the highest energy cosmic rays is, at present, a deep mystery. Protons with energies above the GZK (Greisen 1966, Zatsepin and Kuz'min, 1996) cutoff (about 5×10^{19} eV) lose energy rapidly via inelastic collisions with the cosmic microwave background radiation and thus must come from a nearby source, which seems unlikely. Nuclei, though heavier, are subject to photo-disintegration from red-shifted microwave photons and will lose energy rapidly with distance. Gamma rays of appropriate energy have short mean free paths to create electron-positron pairs and, again, are unlikely candidates. Neutrinos have lower interaction cross-sections, so if they are the particles that make up the highest energy cosmic rays there are a lot of them, and in any case they would likely have to come from the decay of other highly accelerated charged particles. Given the difficulties in identifying a known particle as a candidate, it seems reasonable to turn to exotic candidates. In this paper, we consider the possibility that the highest energy cosmic rays are magnetic monopoles.

2 Monopoles as UHECR Primaries

The idea that UHECR's might be monopoles is an old one due to Porter (1960), and revived recently by Kephart and Weiler (1996). There are two considerations that make the monopole hypothesis attractive: 1) The energy that a monopole with Dirac charge $q_m = e/2\alpha$ would acquire crossing the 3μGauss galactic magnetic field is about 10^{20} eV – surely an intriguing coincidence at least, and 2) the observed flux of the highest energy cosmic rays is consistent with the Parker bound which requires that there not be so many magnetic monopoles around as to effectively "short out" the galactic magnetic field.

While no reliable direct observations have yet been made of magnetic monopoles, they are attractive objects from a theoretical point of view as the existence of just one automatically implies the quantization of electric charge. Many theories of physics beyond the standard model contain magnetic monopoles naturally; any theory with a simple grand unification (GUT) group that breaks leaving an unbroken $U(1)$ (*i.e.* electromagnetism) will contain magnetic monopoles with masses around the scale of symmetry breaking. While it is possible to imagine models with lighter monopoles, and indeed even to simply postulate the existence of pointlike Dirac monopoles, direct searches at accelerators pretty much exclude masses below a few tens of GeV. Strict model-independent limits are difficult to set for many reasons including difficulties in treating pointlike monopoles in quantum field theory, and estimating form-factors for non-pointlike monopoles which arise as solitons.

3 Interactions of Monopoles with Matter

The interactions of monopoles with matter can be broken down into two general classes – the obvious electromagnetic interaction, and a much less obvious strong interaction which violates both lepton and baryon numbers.

3.1 Electromagnetic Interactions At high energies, a magnetic monopole can be thought of as carrying an electric field with it of $\gamma\vec{v}\times\vec{B}$, where γ is the usual Lorentz contraction factor, $\vec{v}$ is the velocity, and $\vec{B}$ is the magnetic field of the monopole at rest. As $\vec{v}\to c$ (the highly relativistic limit), the monopole then looks like a charge of $Z=1/2\alpha\sim 137/2$. (Here and hence we consider the lowest magnetic charge possible). This leads one to think of a relativistic monopole as a minimum-ionizing charged particle depositing about 6 GeV/(g cm^{-2}). A horizontal shower would them deposit 240 TeV, mainly in the form of ionization, and this would look nothing like a high energy proton or nuclear interaction.

3.2 Monopole–Proton Interactions Far more promising as signatures are the strong-interaction processes in which a monopole can participate. The generic process is one of

$$p+\text{Monopole}\to\ell+\text{Monopole}+X$$

where X is a collection of other particles with net baryon and lepton number equal to zero and ℓ is a lepton. This is an extension of the celebrated "monopole-catalyzed baryon number violation" giving $p\to e^+\pi^0$, but, as we shall see, can be rather more dramatic when the centre-of-mass energy is high. We will discuss this process in more detail in section 4.

The cross section expected is a typical strong interaction cross section of about 10^{-26} cm^2. The reason for this is the following: the s-wave wavefunction for a charged fermion in the field of a magnetic monopole is infinite at the origin. Any wavefunction then with any admixture of s-wave will then get "sucked into the monopole" with infinite probability.

This infinity, of course, indicates a pathology in the theoretical description of a monopole-fermion interaction, but we can imagine introducing a cutoff at some scale characteristic of the monopole to regularize the result. In the event of a GUT monopole, the scale is the GUT scale, and represents the fact that a GUT monopole is not pointlike, but rather an extended object with length scale the inverse of the GUT scale. For a Dirac monopole one might use the Compton wavelength of the monopole, or some other reasonable guess. In any case, the characteristic scale must be much smaller than a proton, so the net result is that the cross section for a proton to interact with a monopole must be given by the proton – the interaction takes place with a cross section typical of the strong interaction.

4 Baryon and Lepton Number Violation in Monopole Interactions

The process described in the previous section may seem rather bizarre, since lepton and baryon number are strictly conserved in perturbation theory in the standard model. The origin of the phenomenon is in a nonperturbative effect in the Standard Model, but may arise due to tree level processes in GUT's.

4.1 The Standard Model In the standard model, baryon and lepton number are not conserved. The origin of this phenomenon is the chiral anomaly. Imposition of ordinary current conservation $\partial_\mu j^\mu=0$ leads to a divergence in the chiral current

$$\partial_\mu j^{\mu 5}=\frac{g^2}{32\pi^2}\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$$

where g is the gauge coupling constant and F the field strength associated to the gauge field. In the standard model, the $SU(2)$ gauge field only couples to left-handed quark and lepton doublets. Writing baryon and lepton currents as sum of left- and right-handed components then leads to

$$\partial_\mu b^\mu=\partial_\mu \ell^\mu=\frac{n_f}{16\pi^2}\epsilon^{\mu\nu\alpha\beta}\left(-g_2^2 tr(F_{\mu\nu}^{SU(2)}F_{\alpha\beta}^{SU(2)})+g_1^2F_{\mu\nu}^{U(1)}F_{\alpha\beta}^{U(1)}\right)$$

where and $F_{\mu\nu}^{U(1)}$ is the $U(1)$ field strength, $F_{\mu\nu}^{SU(2)}$ is the $SU(2)$ field strength, g_1 and g_2 are the corresponding coupling constants, and n_f is the number of fermion generations, and the trace is taken in the $SU(2)$ adjoint

representation in which the gauge fields lie. Electroweak baryon and lepton number violations are then essentially a consequence of the chiral anomaly and the left-right asymmetric electroweak gauge couplings.

This sort of violation of lepton and baryon number was first considered by 't Hooft (1976), who noted that fluctuations in the gauge fields could, in principle, induce proton-decay amplitudes which are suppressed by a factor of $\exp(-4\pi \sin^2 \theta_W/\alpha) \sim 10^{-170}$, and thus quite unobservable.

The combination of field tensors that appears in the above expressions is essentially $\vec{E}\cdot\vec{B}$, leading to the idea that one might be able to get baryon and lepton number violation with nothing more than electric and magnetic fields. The problem in the laboratory is that it is hard to get the required field strength, though very high energy particle collider experiments might be able to achieve this sort of effect (Mattis & Mottola, 1990).

In the presence of a monopole, however, the effect is huge. The monopole has a $\vec{B}$ that falls as $1/r^2$ and points radially out. It will effectively suck in a proton (or, rather, a quark from a proton) and in combination with its electric field also falling as $1/r^2$, one gets $\vec{E}\cdot\vec{B} \sim 1/r^4$ and thus the net baryon number change per unit time obtained by integrating the divergences given above is singular, or, more precisely, huge with a cutoff that depends on the details of the monopole.

In principle, the process should be $q + \mathrm{Monopole} \rightarrow \mathrm{Monopole} + (3n_f - 1)\bar{q} + n_f\ell$ where q represents a quark, $\bar{q}$ an antiquark, and ℓ a lepton and there should be one representative from each generation. In fact, as discussed by Nair (1983), the number of generations seen is energy-dependent and with the known generational mixing, one expects to see just one generation at energies too low to produce more. Note that the process violates neither colour, nor charge conservation.

4.2 Grand Unified Theories In GUT's, quarks and leptons appear in the same multiplets. The reason that baryon and lepton number violation don't take place at a noticeable rate is that the GUT group is supposed to be broken to a smaller one which does not mix quarks and leptons. The gauge bosons acquire masses of order the GUT-breaking scale m_{GUT}, and all processes they mediate are suppressed by powers of m_p/m_{GUT}.

While all that was said in the foregoing section remains as true for a GUT monopole as for pointlike Dirac one, there is a different way of looking at the baryon and lepton number violation in the GUT case. A proton, or one of its quarks falls into a monopole and gets sucked to the centre. A GUT monopole is a topologically nontrivial object in whose centre the Higgs field that broke the GUT symmetry and gave the gauge bosons that correspond to broken directions masses vanishes. This in turn means that the all the baryon and lepton number violation processes become unsuppressed there.

4.3 Modelling Baryon and Lepton Number Violating Interactions Despite the slightly different perspectives of the two approaches to monopoles described above, the net result is, fortunately, quite model-independent. The basic process as we model it is the following: 1) Start with a nucleon (proton or neutron) 2) Decide whether or not to interact based on the proton-proton cross section. 3) Select a quark at random and have it fall into the monopole 4) The quark now disappears and is replaced by two antiquarks and a lepton. In principle one might see more generations at once, but this is a later extension of the work which is yet to be performed. In fact, once one has charged fermions around the monople baryon and lepton number are no longer conserved and the net effect one would expect is that the the whole proton disappears and is replaced by several quarks and leptons with total charge and colour zero, and keeping baryon number minus lepton number conserved. The energies and momenta of the particles are chosed according the phase space with the centre-of-mass energy calculated for the collision. The LUND fragmentation model (Andersson *et al.*,1983) as realized in JETSET (Sjöstrand, 1986 and Sjöstrand & Bengtsson, 1987) is then used to fragment the system.

Work on handling multiply-wounded nuclei in analogy to what is done in SIBYLL (Fletcher *et al.*, 1994 and Engel *et al.*, 1992) is in progress. We expect little change to the results since the main effect will be to increase the number of partons in the initial state, an effect which is mimicked by the fragmentation process described above.

5 A Modified Version of AIRES

Code to perform the above calculations has been incorporated into an extended version of AIRES (S. Sciutto, 1997) in order to study extensive air showers which are caused by an energetic monopole primary. In addition to changes for kinematics and tracking of the monopole, all other particles are handled by the standard AIRES code, with nuclear interactions done using SIBYLL (*op. cit.*).

6 Qualitative Results

While a detailed comparison of results for various monopoles is the subject of a more detailed paper (Dova & Swain, 1999), several qualitative feature of the process are immediately apparent:

- The monopoles must be highly relativistic (mass much less than 10^{20} eV) in order to transfer energy efficiently to nuclei in the atmosphere – otherwise simple kinematics does not allow them to lose much energy
- If the monopoles are very light, they can lose most of their energy in the first collision and generate a proton-like shower.
- If the monopoles are intermediate in mass range, they may initiate several showers, each of somewhat less (again, this depends on kinematics) energy than the previous one making the profile seem more like a stack of proton showers, each started at different depths.
- With the possibility at each interaction to direcly produce a highly energetic neutrino, we expect fluctuations to be larger in monopole-induced showers. High statistics MC studies are underway to check this claim.

Of course one might also hope that monopole primaries would show some directional preferences as they are accelerated by the galactic magnetic field.

7 Conclusions

The idea that the highest energy cosmic rays might be magnetic monopoles is an exciting one, but a difficult one to test. While extensive airshowers they produce can be quite different from proton or nucleus initiated showers, the details are highly dependent on kinematics – in particular the monopole mass and energy. A more detailed study can be found in Dova & Swain (1999).

8 References

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