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II-4-9. Cosmic Ray Evidence for a Ring Current

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Many observations show that low rigidity protons from solar flares are permitted entry at Minneapolis only during the main phase of magnetic storms. The measured energy is much below the normal Störmer cutoff at that time. This paper develops the idea that a ring current responsible for the main storm field reduces the Störmer cosmic ray cutoffs. The model of the ring chosen is actually an azimuthal current on the surface of a sphere with current intensity proportional to $\sin\theta$ where θ = co-latitude. It is shown that this mathematical form permits great simplicity in the analysis and leads to essentially the same result as a diffuse ring corresponding to the actual trapped radiation. The magnetic moment of the ring required to produce the cutoff change can be provided by reasonable intensities of very low-energy trapped radiation. It is shown that the cosmic ray data permit one to evaluate both the moment (M') and radius (R) of the ring, whereas the surface magnetic measurements determine only the quantity M'/R^3. Since observation shows that the cosmic ray cutoffs return to normal during the main phase, it must be assumed that the ring shrinks inward so that the surface field is maintained negative. Cosmic ray evidence concerning the presence of a permanent ring current is discussed. Such a ring is measured directly by satellites during quiet times.

Cosmic Ray Evidence for a Ring Current

On several occasions during the past three years, cosmic ray protons have been observed at balloon altitudes at Minneapolis (56°N geomagnetic) which have energies much lower than those normally allowed by the earth's magnetic field[1,7,8,23].

During some of these events, protons of energies down to 75 Mev have been observed. At other times it is clear that a cutoff is imposed by the earth's field and has a value of 250-400 Mev. The low rigidity protons are observed at Minneapolis only during magnetic storms and an important step in the interpretation of these events was made when one of us (JRW) noticed that the arrival of low energy protons coincided not with the commencement, but with the main phase of the storm, which is defined as the time when the horizontal component of the field

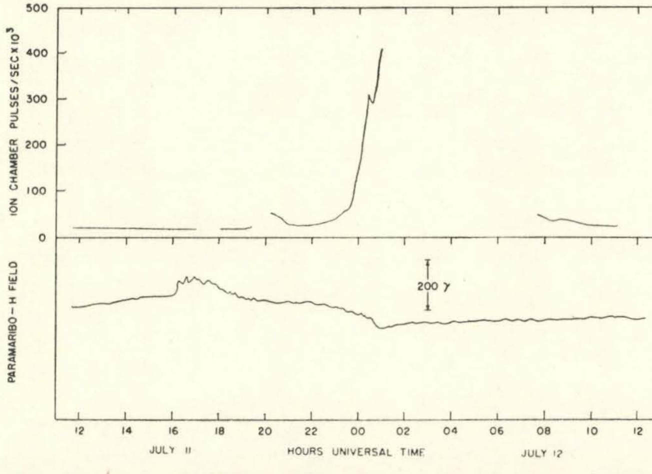

Fig. 1. Solar protons at Minneapolis and equatorial magnetic field for July 11-12. (For details see Winckler, *et al.*[23])

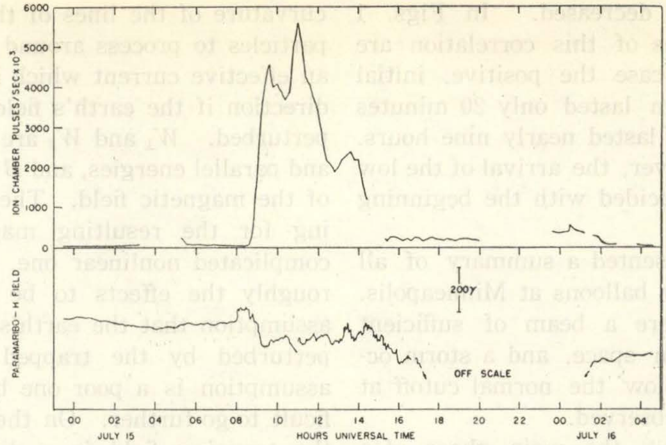

Fig. 2. Solar protons at Minneapolis and equatorial magnetic field for July 15–16. (For details see Winckler, *et al.*[23])

Table I. Correlation of Cutoff Changes and Magnetic Field at Minneapolis.

Event No	Cosmic Ray Flare Date	Time	Related Sudden Commencement Date	Time	Begin Negative Phase Date	Time	Low Energy Cosmic Ray Increase Date	Time	Notes
1	23 Mar 1958	0950	25 Mar	1540	26 Mar	1300	26 Mar	1330	*Event includes evidence for trapping in solar cloud
2	22 Aug 1958	1417	24 Aug	0140	24 Aug	0330	Undetected		Free space intensity probably too low to detect during main phase
3	10 May 1959	2055	11 May	2320	12 May	0430	12 May	0400–0500	Inferred from total difference between two flights
4	10 July 1959	0210	11 July	1623	11 July	2300	11 July	2330	
5	14 July 1959	0325	15 July	0802	15 July	0830	15 July	0830	
6	16 July 1959	2114	17 July	1638	17 July	1900	17 July	1900	
7	1 April 1960	0843	31 Mar	0800	31 Mar	1600	1 April	0945	Main phase already in progress at time of cosmic ray flare
8	5 April 1960	0215	None		None		Undetected		Although free space rates high, no cosmic rays at Minneapolis
9	28 April 1960	0130	27 April	2000	27 April	2100	28 April	0315	Main phase in progress at time of cosmic ray flare
10	29 April 1960	0107	30 April	0130	30 April	0330	30 Apr	before 0600	Very weak event in >100 Mev range
11	4 May 1960	1340	None		None		No low energy particles		All particles measured were above normal cutoff
12	3 Sept 1960	0040	4 Sept	0230	4 Sept	0400	4 Sept	about 0400	
13	12 Nov 1960	1322	12 Nov	1348	12 Nov	1740	12 Nov	before 2000	*Main phase in progress at time of balloon ascent
14	15 Nov 1960	0207	15 Nov	1303	Uncertain	1400	15 Nov	1400–1500	*Sudden commencement and storm from previous flare. Interpretation difficult.

* Evidence indicates trapping in solar cloud, producing possible increases at time of sudden commencement associated with beam in space.

at the equator is decreased. In Figs. 1 and 2 two examples of this correlation are presented. In one case the positive, initial phase of the storm lasted only 20 minutes and in the other it lasted nearly nine hours. In each case, however, the arrival of the low energy protons coincided with the beginning of the main phase.

In Table I is presented a summary of all events observed by balloons at Minneapolis. In every case where a beam of sufficient intensity existed in space, and a storm occurred, protons below the normal cutoff at Minneapolis were observed.

For a long time[18] the main phase of a magnetic storm has been attributed to the formation of a ring current around the earth, but there has been little proof of this hypothesis. The effect of a ring current on cosmic rays has been discussed by C. Störmer[21] and by Ray[16]. We shall now apply their analysis to the events under discussion and show that the observed effects may be reasonably attributed to a ring current and further that observations at a northerly latitude like that of Minneapolis give new information on its size.

The ring current is presumably due, as was first suggested by Singer[19], to charged particles trapped in the earth's magnetic field in the same way that the Van Allen radiation belts are trapped. Trapped particles contribute to the earth's field in three ways; (1) their spiral motion around lines of magnetic field gives them a magnetic moment $W_\perp/B$; and (2) the gradient and (3) the curvature of the lines of the field cause the particles to process around the earth, giving an effective current which is in the westward direction if the earth's field is not seriously perturbed. $W_\perp$ and $W_\parallel$ are the perpendicular and parallel energies, and B is the magnitude of the magnetic field. The problem of solving for the resulting magnetic field is a complicated nonlinear one. We may discuss roughly the effects to be expected on the assumption that the earth's field is not much perturbed by the trapped particles. This assumption is a poor one but it is very difficult to go further. On the assumption that the trapping field is a dipole field, effects (2) and (3) give contributions to the magnetic moment of the ring of (2) $3/2 \cdot W_\perp/B$ and (3) $2\,W_\parallel/B$, for particles at the equator. All three contributions to the magnetic moment of the ring have the same direction. If the ring is large compared to the earth, then the fields produced at the earth are inversely proportional to the cube of the ring radius so the three fields are (1) $W_\perp/B_0$, (2) $3/2 \cdot W_\perp/B_0$ and (3) $2 \cdot W_\parallel/B_0$ where B_0 is the magnitude of the earth's surface field at the equator. The field produced by the intrinsic magnetic moment (1) is opposite to the fields (2) and (3) and the latter are opposed to the earth's own field. At the earth all three contributions to the field are of the same order of magnitude. This is not true near the trapping region however, since the field of a magnetic moment varies inversely as the cube of distance while that of a current element varies only inversely as the square.

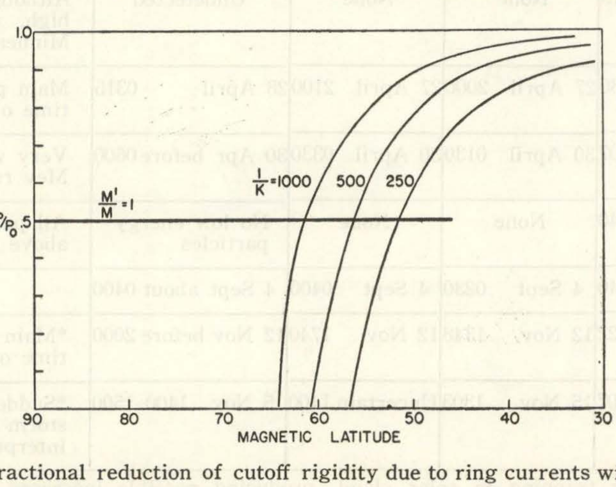

Fig. 3. Fractional reduction of cutoff rigidity due to ring currents with various parameters.

In the trapping region, the intrinsic magnetic moment produces most of the perturbation field, provided that the particle distribution is not too diffuse.

In spite of this we shall take as a model for the field of trapped particles the field produced by a simple ring current which cannot represent the intrinsic magnetic moment contribution. Great simplicity is gained, and the error introduced is probably not as large as might appear at first sight. It will turn out that the cosmic ray effects depend only on the vector potential, and this, being the integral of the field, is not so strongly changed by the intrinsic moment field which is dominant in a fairly small region. Further, some of our results will be independent of the model.

In this rough approximation the ring current may be described by giving its radius and its magnetic moment. In Fig. 3, results of calculations are presented for a model in which the current is not a ring but an azimuthal current on the surface of a sphere of radius R, the current being proportional to $\sin\theta$ (θ=co-latitude). The effect of such a ring current on the cutoff rigidity for cosmic ray particles may be described as follows: The curve of critical rigidity versus latitude has two parts, depending on whether the Störmer pass closes inside or outside the ring current. The part of the curve pertaining to high latitudes corresponds to closing of the pass outside of the ring current. For this branch of the curve the cutoff rigidity is reduced from the Störmer value by a factor of $(1+M'/M)$

$$P=\frac{P_0}{1+M'/M} \qquad P_0C=\frac{ZeM}{4R^2_E}\sin^4\theta$$

where M' is the magnetic moment of the ring and M is the magnetic moment of the earth. The branch of the curve which applies to more equatorial latitudes depends only on the parameter M'/R^3 and has a more complicated form. As one proceeds southward from the intersection of the two curves the cutoff rises rapidly toward the Störmer cutoff P_0. $2M'/R^3$ is just the magnetic field at the center of the ring current and is therefore the magnetic storm field. Thus at middle and low latitudes the reduction in cosmic ray cutoff is a function of the storm field. This agrees with the observations of Yoshida[24]. At higher latitudes the reduction of cutoff is not a function of the storm field, though we expect the two to be correlated.

Ray[16] has calculated the effect of a current which flows is a ring. His results are similar to those for the model presented here.

We now show how this analysis can be used to determine the parameters of the ring. Suppose that during a magnetic storm the cutoff rigidity at Minneapolis is reduced by a factor of 2. Then (see Fig. 3) two things are necessary. First, the magnetic moment of the ring must be at least equal to or greater than the magnetic moment of the earth and second, the parameter M'/R^3 must also be sufficiently large. If we take the latitude of Minneapolis to be 56° then we need $M'/R^3 > 1/500\, M/R_E^2$. The parameters of the ring which give a cutoff at Minneapolis reduced by a factor of 2 are those with values in the shaded area on Fig. 4. Additional information on ring parameters is given by observations of the earth's magnetic field, which determine the quantity M'/R^3. Suppose that the storm field at the equator has a value of 125 γ. The parameters of the ring must then fall on the indicated curve in Fig. 4, and so the ring

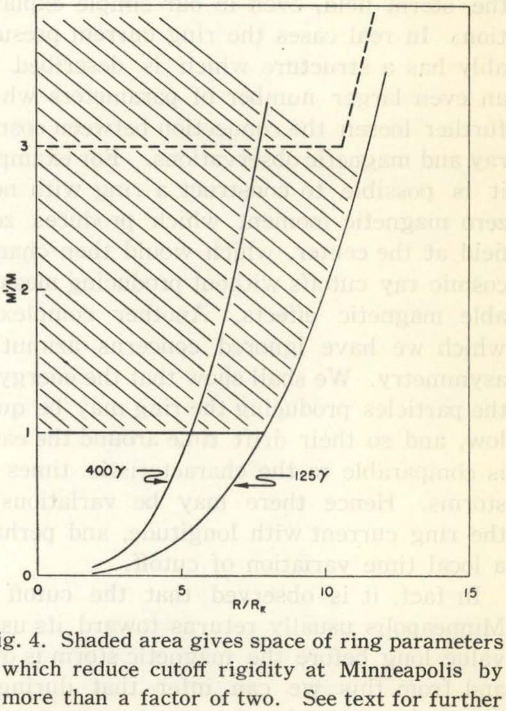

Fig. 4. Shaded area gives space of ring parameters which reduce cutoff rigidity at Minneapolis by more than a factor of two. See text for further explanation.

radius must be larger than 8 R_E and its magnetic moment larger than M.

In calculating more accurately the parameters of the storm time ring, we are somewhat hindered because we do not know accurately what the geomagnetic cutoff at Minneapolis should be in the absence of a ring. Let us assume that it is about 530 Mev corresponding to the Quenby-Webber cutoff of 1.16 BV[4] for Minneapolis and that this value is reduced to 250 Mev by a quiet ring (see below). During magnetic storms the cutoff at Minneapolis is reduced to below 75 Mev and therefore the magnetic moment of the ring must increase to more than 1.9 M. However, there is evidence from neutron and gamma-ray production[2] by protons in the atmosphere that the cutoff is reduced to at least 40 Mev at Minneapolis which would require the ring to have a magnetic moment equal to 3 M. For this latter case the parameters of the ring must fall within the dotted boundary in Fig. 4.

As has been mentioned, the cutoff at Minneapolis depends only on the magnetic moment of the ring whereas the storm field at the equator depends on M'/R^3. Therefore we should not expect to find perfect correlation between the cutoff at Minneapolis and the storm field, even in our simple explanation. In real cases the ring current presumably has a structure which is described by an even larger number of parameters which further loosen the connection between cosmic ray and magnetic observations. For example, it is possible to construct a ring with non-zero magnetic moment which produces zero field at the center, which would then change cosmic ray cutoffs without producing measurable magnetic effects. Another complexity which we have ignored concerns azimuthal asymmetry. We shall show that the energy of the particles producing the ring may be quite low, and so their drift time around the earth is comparable to the characteristic times of storms. Hence there may be variations in the ring current with longitude, and perhaps a local time variation of cutoff.

In fact, it is observed that the cutoff at Minneapolis usually returns toward its usual value long before the magnetic storm is over and from this we can infer that during a magnetic storm the ring current must move inward. Suppose, for example, that the magnetic storm field remains constant while the cutoff at Minneapolis returns toward its normal value. Then the ring parameters must move along a curve line like the 125 γ curve in Fig. 4 and must move toward the origin and out of the region which represents a significantly lowered cutoff. The ring therefore shrinks in such a way that M'/R^3 is constant but M' decreases, returning the cutoff at Minneapolis to normal. An example of this is shown in Fig. 2. During the storm of July 14 the magnetic field at the equator was reduced by about 125 γ for several hours, and then at about 1700 dropped further to about 400 γ negative. The earth's field recovered slowly from the large decrease, and at 0300 on July 16, a DST analysis communicated to us by Chapman and Akasofu shows that H at the equator is depressed by 200 γ. At this time, solar protons were no longer arriving at Minneapolis, although measurements at Murmansk[3] showed that there was still a strong beam in space. In Fig. 4 we have drawn a curve for a ring current producing a field of 400 γ (twice that observed, and corresponding to the maximum of the ring). It may be seen that even for such a large field, shrinkage of the ring to 4 earth radii would reduce its effect on cutoffs to small values.

The Possibility of a Quiet Ring.

The storm time ring current discussed above appears quite reasonable in the light of the important evidence for a quiet time ring obtained by Smith *et al*[20]. They found that at a distance of 10 R_E, the earth's field differs radically from the field produced in the earth's interior, and that the difference could be ascribed to a toroidal ring current having a major radius of 10 R_E and a magnetic moment $1/2 \cdot M_E$. Their analysis used a ring current model and neglected the intrinsic magnetic moment contribution, so that their interpretation is not valid to high accuracy. Their results were obtained at magnetically quiet times and so indicate that a ring is a permanent feature of the earth's environment, which is intensified during storms.

There is also cosmic ray evidence which may be interpreted as indicating the presence

Table II. Comparison of Cosmic Ray Cutoff Rigidities.

Location	Reference	Cutoff	Cutoff Q and W	Q and W Lat
32. 1°N 95.5°W	11	5.00±0.5BV	4.4BV	42.4°N
32. 3°N 97 °W	7	4.6 ±0.2	4.4	42.6
38. 6°N 95.5°W	13	2.25±0.15	2.35	50.6
45.75°N 96.5°W	13	0.8 ±0.1	1.24	58.2
42. 6°N 88.1°W	12	1.41±0.08	1.31	56.0
44. 6°N 92.7°W	12	1.20±0.04	1.30	57.7
45. 5°N 8 °W	5	4.7 ±0.15	4.0	44.3
51. 5°N 2.6°W	22	2.6 ±0.1	2.12	52.1
43. 8°N 91.5°W	6	<1.14	1.31	57.0
46. 1°N 88.4°W	*	0.6 ±0.1	0.95	60.0

* Ney (Private Communication)

of a permanent ring current. Table II presents a number of measurements of cosmic ray cutoff rigidities together with the values calculated according to the theory of Quenby and Webber by L. I. Cogger[4]. Fig. 5 displays the ratio of the measured cutoff rigidity to the calculated values as a function of the effective latitude of Quenby and Webber's theory. There is considerable scatter but it

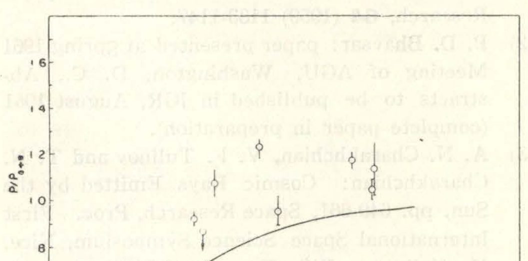

Fig. 5. Measured values of cutoff rigidity and calculated cutoff for a ring with $M'=\frac{1}{2}M$, $R=8R_E$.

will be seen that at northern latitudes the measured value lies well below the calculated value. The curve gives the cosmic ray cutoff to be expected in the presence of a ring current with a magnetic moment equal to 1/2 of the earth's and a radius of 8 R_E. Thus the cosmic ray cutoff at quiet time seems to indicate a ring current.

At present the whole question of cosmic ray cutoffs at high latitudes is a vexed one, however, and the experimental situation is consistent with a permanent ring current, but does not require it. The measured cutoffs never appear to be sharp (E. P. Ney and P. S. Freier, private communication), and the reason for this is not clear, but may be due to penumbra effects, to time variations of the field, or to energy loss in complex orbits. On the theoretical side, the calculation of the cutoff in the absence of a ring is also uncertain. The Quenby and Webber value for Minneapolis is 1.16 BV, the Rothwell value is 0.88 BV, but machine calculations by one of us (PJK) indicate a value greater than 1.35 BV.

Trapped Radiation Intensity and Ring Currents.

We now estimate the flux of charged particles which is required to give a ring current of moment 1/2 M. Since the magnetic moment of the ring depends on the total energy of trapped particles we need to know the average energy in order to calculate their flux. The radiation counters carried in Explorers IV, VI and VII do not indicate much radiation in the region we are considering, so the average energy must be below their detectability threshold of about 20 kev. Rockets fired into aurorae in the auroral zone have detected large fluxes of electrons of energy 5 kev[14], the energy in each case being not much above the threshold of detectability. Lines of force from the auroral zone go through the trapping region we are considering, and so it seems reasonable to believe that the auroral electrons are samples of the particles trapped in the ring current. This argument is somewhat strengthened by the observation that electrons which appear in the aurora over Minneapolis have energies comparable to those trapped along the same line of force, but it remains a weak argument nevertheless, and we must admit that we do not even know the kind of particle which produces the ring current. We take the average energy to be 5 kev, therefore, but this may only represent an upper limit. If the center of gravity of the ring is at 8 R_E, and we take the average contribution to the magnetic moment per particle to be 2 W/B, then the total number of 5 kev particles required to give 1/2 of the earth's moment is 2.5×10^{30}. If we take the ring to be a torus of minor radius 3 R_E, major radius 8 R_E, then the electrons flux must be 2×10^{9} electrons/sterad$\cdot$cm^2 sec. This is comparable to the flux of higher energy electrons in the outer Van Allen zone. Thus we have evidence that low energy particles are trapped out to distances far beyond what is normally called the peak of the outer Van Allen zone. If the trapped particles were protons of the same energy, their flux would be lower by a factor of $\sqrt{m/M}\approx40$. The trapped particles could also be protons of higher energy, corresponding to a still lower flux.

Recently, results from ion traps carried on Soviet space probes have become available. They find a flux of 2×10^{8} particles/cm^2 sec of electrons of energy $200-10^4$ ev. Their measurements were made on September 12–13, 1959, two of the ten quiet days for that month. This flux seems lower than that required to give a significant quiet ring, but the volume of the ring and the energy spectrum of the particles are as yet too uncertain for a definite conclusion. In fact, Gringauz[9,10] concludes that the flux he measured is consistent with Smith's[20] results. We note also that the Soviet ion traps could not have measured a flux of the order of that calculated here as their instrument was nearly saturated at the level they did observe.

Changes in geomagnetic cutoffs have also been discussed by Obayashi[15] and by Rothwell[17]. In their theories, the earth's magnetic field is affected at large distances by a magnetic field carried by plasma clouds from the sun. These theories differ in end results from the one presented here in that the cutoff at sufficiently far northern latitudes is reduced to zero, rather than to a finite fraction of the Störmer value.

Obayashi also discusses the effect of the compression of the earth's field by a plasma cloud which would be the effect expected on Chapman's and Ferraro's model for the initial phase of a magnetic storm. The effect of such a compression is to increase the cutoff rigidity. Decreases in solar proton intensity corresponding to such increases in cutoff rigidity at the time of sudden commencement have been observed and these confirm the Chapman-Ferraro theory of the initial phase as the lowering of cutoff confirms the ring current theory of the main phase.

Acknowledgments

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Discussion

Elliot, H.: A ring current changes the field in its immediate vicinity by a relatively large amount. Can a ring of the moment you propose be supported in the earth's field?

The Quenby-Webber threshold rigidities have now been revised using a better approximation and this has resulted in a higher value of threshold at Minnesota.

Kellogg, P.J.: Yes, it is sufficiently diffuse. The sharp ring I have used would reverse the earth's field but this is not to be taken literally, and the ring is undoubtedly very diffuse.

Sarabhai, V.A.: What would be the effect of a diamagnetic ring?

Kellogg: The effect of a diamagnetic ring has been worked out by a perturbation theory and is being published. Its effect is not greatly different from that of the ring used here.

Kane, R.P.: 1) What exactly you imply by saying that the actual cut-off when the ring would be absent is not known?

2) Would you say that the existence of particles in the range 300 Mev to 700 Mev at Minneapolis a direct evidence for the presence of a permanent ring current?

Kellogg: 1) Perhaps the ring is always present, even at quiet times. So the cut-off without a ring can not be measured. Calculations by machine are difficult for.

Minneapolis best indicate a cut-off of 1.35 Bv or higher (much higher than the value given by Quenby and Webber). So far these give, however, the most reliable figure for the cut-off without a ring.

2) I would be inclined to say so but the experimental situation is confused. A sharp cut-off is never observed, but rather the observed lower spectrums is rounded, with the peak intensity coming at as much as twice the energy of the lowest particles.

This is not understood and so we have to be cautiuos in saying what the measured cut-off is.

McDonald, F.B.: Bending of cosmic ray energy spectra below theoretical cut-off appear to be a well established experimental fact and not related to instrumental effects.

Kellogg: Yes, our lack of understanding is in the interpretation, not in experiment.