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COSMIC RAYS AND THE GEOMAGNETIC FIELD - THEORY AND PRACTICE

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When I received an invitation to take part in this tribute to Professor Sandoval Vallarta I was, of course, honoured to be offered the opportunity to participarte in so distinguished an occasion, but in accepting, I was conscious of the fact that my first hand acquaintance with cosmic ray physics dates only from the Renaissance Period following the Second World War and that my knowledge of what may be termed the Classical Period of the thirties is distinctly second hand.

When I started out on cosmic ray research at Manchester in 1946 I elected to work on the geophysical and astrophysical side of things although nuclear physics had the glamour at that time and in starting me off my supervisor, P.M.S. Blackett, offered two pieces of advice. The first was in the form of the general proposition that "if I was going to be any good at cosmic rays I should be able to think of an experiment which would take me to a nice Pacific island". I worked hard at that for several years but I am afraid that when I eventually came up with a cast iron case for spending two years on Tahiti he was amused but insufficiently impressed to provide the necessary funds. The second piece of advice was more specific and perhaps more useful.

if less exotic. "You must make yourself thoroughly familiar with the theory of the geomagnetic effects of cosmic rays -you will need to understand the work that has been done by Stormer and by Lemaître and Vallarta". Those were the halcyon days when young people took account of what they were told to do by their elders and I set about it.

Much of it was already incorporated in the text books on cosmic rays at that time. The basic Stormer theory of particle motion in a dipole field had been inspired by Birkeland's experiments on the motion of cathode rays in magnetic fields, particularly those of a dipole and of a single pole which had led Birkeland to the belief that the aurora borealis was caused by cathode rays emitted by the sun. Influenced by this view, Stormer proceeded to calculate the trayectories of such particles mathematically. His first results were published in 1904 and thereafter he and his students devoted much time and energy to the numerical integration of the equation of motion of charged particles in a dipole field which was used as a first approximation to the magnetic field of the earth. Although they were in the first instance concerned with the points of arrival and direction of arrival at the earth of particles starting out from the sun, they also established some general characteristics of the motion which in the sequel were to prove to be of great importance to the cosmic ray problem, although they were largely irrelevant so far as the aurora was concerned.

The problem of cosmic ray motion in the geomagnetic field had its birth in the world survey of cosmic ray intensity carried out by Compton and his associates which, for the first time, established beyond doubt that the intensity was controlled by the geomagnetic field, and substantiated the view already expressed by Clay that the primaries were charged particles rather than photons. Meanwhile, Georges Lemaître had returned to Cambridge, Massachusetts from Cambridge, England, where he had developed his cosmological theory of the disintegration of the primeval atom which, in the more barbaric terminology of today has become known as the "big bang". One of the consequences of Lemaître's theory was the existence of a universal population of high energy charged particles which could perhaps be identified with Compton's primary cosmic rays. Vallarta and he then joined forces in putting Compton's experimental data on a firm theoretical basis, an aim which was in line with a piece of philosophy expressed many years later in a paper on gravitation theory by Vallarta, Barajas, Birkhof and Graef (1944) which I would like to quote. They wrote:

> ......"We would like to point out that for the physicist all mathematics is fundamentally a form of abstract model building of more or less general aspects of nature and that no experiments which the physicist may perform in his laboratory can advance very far without free access

to a variety of abstract models which are not to be thought of as final."

In January 1933 Lemaître and Vallarta published together in the Physical Review their paper which was to become a classic. It was an extension of earlier work that had been done by Stormer but it included a vital new step which related the intensity of cosmic rays, an easily measurable quantity, to direction and position in the geomagnetic field. This vital step consisted in the realization that Liouville's theorem was applicable to the problem and in this context leads to the conclusion that:

"For a cosmic ray flux that is isotropic and homogeneous at infinity the intensity in allowed directions at the earth is the same as that at infinity and is zero in all other directions."

On this basis computation of the intensity then reduced to the problem of computing the allowed and forbidden directions. At much the same time and independently, Rossi and Fermi had arrived at the same conclusion.

In their calculations, Lemaître and Vallarta, like Stormer, approximated the earth's field to that of a dipole but they wisely pointed out in a footnote that the real field should properly be represented in terms of spherical harmonics of which the dipole is of course only the first order term - something which nevertheless seemed to be forgotten later in the day by others.

Figure 1 taken from that paper shows the important result they derived which provides a quantitative basis for the variation of intensity with latitude and, incidentally, provides in principle the means of using the geomagnetic field to determine the momentum spectrum of the cosmic rays in the latitude sensitive region.

A further consequence of the theory concerned the sign of the charge on the particles. According to the Stormer - Lemaître - Vallarta theory the cone of *forbidden* directions extends to maximum energy in the easterly direction for positive particles and to the west for negative particles so that if the primary cosmic rays are positive we should expect greatest intensity from westerly directions and vice versa. This effect extends to the highest energies at the equator and for this reason can only be detected at ground level in the equatorial zone. In the equatorial zone the measurable effect increases with increasing altitude.

In these circumstances there could hardly have been a more appropriate locality for making the observations that would determine the sign of the charge on the primaries than the Valley of Mexico where we now are. At the prompting of Vallarta, Alvarez was despatched to Mexico City to make the requisite measurements and a similar expedition to the same location was made by T.H. Johnson and Serge Korff.

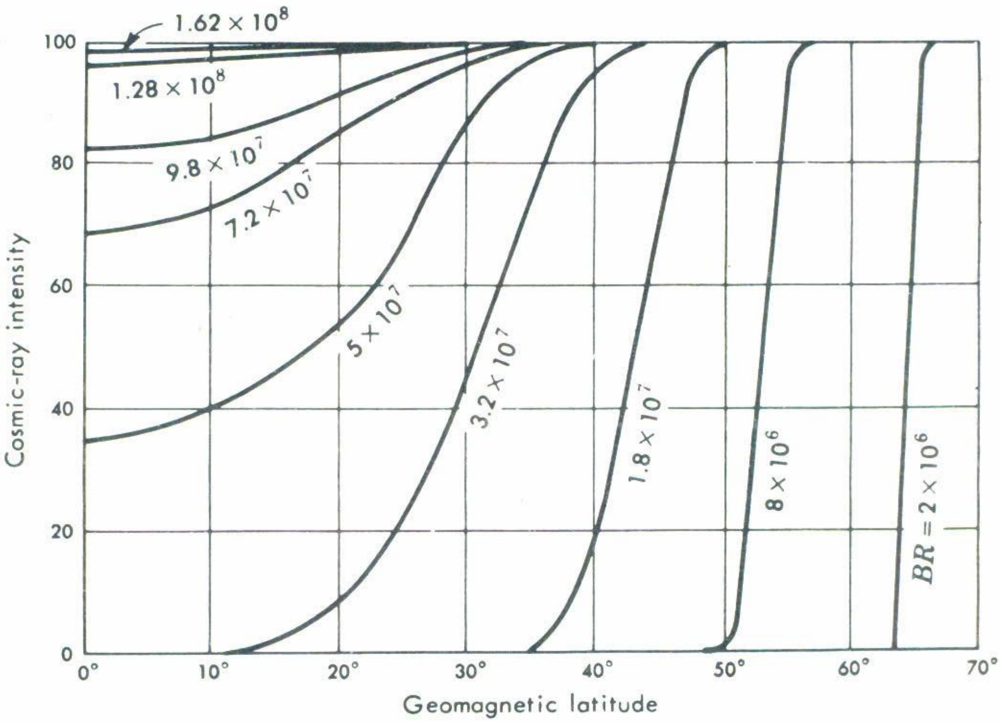

Fig. 1. The intensity of cosmic rays of magnetic rigidity indicated plotted as a function of geomagnetic latitude. (From Lemaitre and Vallarta, The Physical Review 43 (1933) 87.

The sudden incursion into Mexico of these now famous men intent upon performing these critical observations calls to my mind some lines written by the English poet John Keats. Perhaps I may be allowed to quote them:

"Then felt I like some watcher of the skies
When a new planet swims into his ken
Or like stout Cortez when with eagle eyes
he star'd at the Pacific and all his men
Look'd at each other with a wild surmise
Silent, upon a peak in Darien".

In order to avoid the necessity of a footnote by the Editor of these Proceedings and in defence of my fellow countryman I should add that, although

Keats confused Cortez with Nuñez de Balboa, he ought perhaps to be excused on the grounds that Moctezuma after all confused him with Quetzalcoatl!

The results of these experiments, which were confirmed a little later by Rossi and de Benedetti in Eritrea, established that the primary cosmic rays were predominantly positively charged. In discussing these results in a later paper in 1933 Vallarta made further predictions about the way in which the azimuthal intensity variation would depend on latitude.

Meanwhile, all was not completely plain sailing. The next year 1934 Stormer published a paper in Physical Review disputing the validity of the application of Liouville's Theorem to the problem, although Swann had in the meantime discussed this point in some detail and had concluded that Lemaître and Vallarta were fully justified in its use.

What followed has been described by Vallarta at the Hobart Cosmic Ray Conference in 1971. At that meeting he explained how matters came to a head at a meeting in Oslo in 1936. I will quote Vallarta's account which is recorded in the Proceedings of the Hobart Conference and is written with an economy of words that would have done credit to a Hemingway and an appreciation of the structure of the English sentence that would do no discredit to Winston Churchill.

> "At the time Lemaître and I were able to convince Stormer that we were right. He demurred for a little while, but then at a big party given aboardship on the Oslofjord, Stormer, who was president of the congress, suddenly got up and asked my wife to dance the first waltz of the evening and told her while dancing that on the next day he would make a statement to the congress about the Liouville theorem which he did. Thus on a happy note the controversy came to an end."

That is the authorized version but perhaps I may be permitted at this long range to enquire whether Señora Vallarta has been accorded full credit for her part in the proceedings. Is there not some possibility of confusion of cause and effect -of overemphasis on the power of logic perhaps? Might it not be that when exposed to the warm sun of Mexico in the form of María Luisa the Scandinavian ice simply melted?

In the intervening years between 1933 and the satisfactory resolution of question of the Liouville Theorem, Lemaître and Vallarta had taken a further significant step in their solution of the cosmic ray problem by making use of the Bush Differential Analyser at MIT for solving the equation of motion of cosmic ray particles in the geomagnetic field. By so using the Analyser they were able to trace out trajectories in the field -a process which had hitherto been carried out by laborious numerial integration.

By following through a systematic investigation of the trajectories they were able to show that the sky is divided into four regions:

(1) The Stormer cone within which no directions are allowed.

(2) The "main cone" within which all directions are allowed.

(3) The "penumbra" which lies between the main cone and the Stormer cone and is crossed by alternate bands of allowed and forbidden directions giving the effect of partial illumination.

(4) The "shadow cone" which lies close to the horizon adjacent to the nearest pole and within which lie only orbits which have passed one or more times through the earth prior to arrival at the point of observation.

The properties of the main cone, penumbra and shadow cone were defined with ever increasing precision by Vallarta and his students during subsequent years and the results incorporated in the accepted body of knowledge of cosmic rays as set out in the standard text books on the subject.

In addition to this work, the progress of which is recorded in a long succession of publications, there were other problems to be looked at and one of these related to the solar magnetic field. Following the pioneering work of Hale on photospheric magnetic fields there was a widely held view that the sun had a dipole magnetic field with a polar strength of some 50 gauss. A field of that magnitude if it extended out into interplanetary space was capable of producing very marked cosmic ray effects including the so-called latitude cutoff where there appears to be no further increase in cosmic ray intensity in going from latitude 50° to the pole, indicating a total absence of low energy particles in the primary beam.

Vallarta and Godart showed that a solar dipole of the magnitude required to explain the latitude cutoff would be capable of producing a 27-day variation in cosmic ray intensity, together with a diurnal variation due to the rotation of the earth relative to the solar forbidden cone. The predicted effects provided in principle the means of establishing whether or not such a solar dipole field existed in interplanetary space. In practice, it proved quite difficult to decide this point because of the ingenuity of such authorities as Hannes Alfvén and James Wheeler in explaining why the measured effects would be much smaller than the simple theory of Vallarta and Godart and Janossy and Lockett would predict. We now know well enough of course that the solar field extends out into space but not as a dipole.

This is but one of the many problems that attracted Vallarta's attention during this period and although I don't have time to mention them all I can assure you that many of them are still of interest today, as for example, the calculations with Graef and Kusaka of the extent to which the geomagnetic field would reduce the magnitude of the sidereal anisotropy due to Galactic rotation as calculated by Compton and Getting; the question of whether the dipole moment of the sun is variable in time; the similarity of the energy spectrum of *CR* nuclei with $Z > 1$ to that of the protons which he deduced from the early measurements by Bradt and Peters and the escape of solar flare particles from sunspot magnetic fields.

All in all, for a period of some thirty years there were few volumes of the Physical Review that did not have one or more contributions bearing the name Vallarta. Those that I have already mentioned were related directly or indirectly to the geomagnetic field work and I have said nothing about the many contributions on wave mechanics, gravitational theory, relativity, x rays and the organisation of scientific research.

Meanwhile, interest in the geomagnetic effects on cosmic rays was developing in the years following the Second World War. Vallarta himself pointed out in 1948 that a better approximation for the geomagnetic field is afforded by the eccentric dipole and he gave suitable corrections to be applied to the centred dipole calculations. The neutron monitor with its high sensitivity to primary cosmic rays in the energy range $10^9 - 10^{10}$ eV and the availability of high flying aircraft made possible surveys of the distribution of cosmic rays over the earth's surface with a greater precision than had been possible in the past. As is so often the case these new developments in technology produced new puzzles to be solved and one of these surfaced in a very striking fashion here in Mexico at the Guanajuato meeting in 1955.

Figure 2 shows the results of such an airborne survey carried out by John Simpson and reported at that meeting. The points represent the positions of minimum cosmic ray intensity which should correspond to the geomagnetic equator for a dipole field. The full line shows this equator and you can see that there is a big discrepancy.

There was much speculation at the time as to whether this discrepancy arose from the distortion of the outer geomagnetic field due to rotation of the earth in the electrically conducting interplanetary plasma. In the event it turned cut that the disparity arose from the neglect of the higher order terms in the spherical harmonic expansion of the field, as suggested at the Guanajuato meeting by P.M.S. Blackett and experimentally verified by Pamela Rothwell and John Quenby. As I mentioned earlier Lemaître and Vallarta in their very first paper in 1933 pointed out in a footnote that whilst they were using the dipole approximation for the geomagnetic field a proper representation required the higher order terms. Furthermore, T.H. Johnson in 1937 had observed a discrepancy in a sea level cosmic ray intensity survey which he ascribed to the deviations of the real field from that of a dipole.

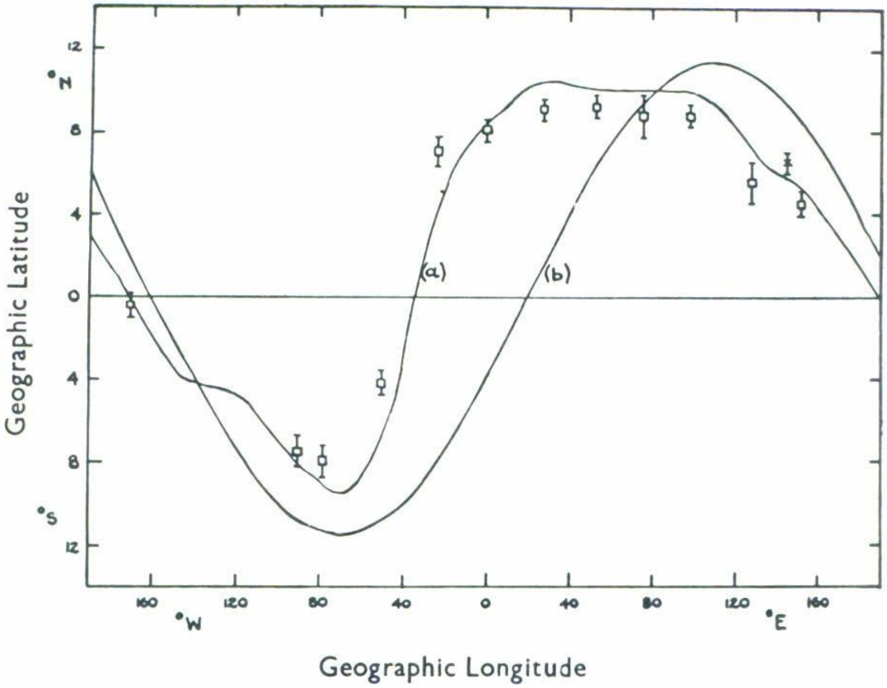

Fig. 2. The cosmic ray equator and the geomagnetic equator. (From Quenby and Webber, Philosophical Magazine, 4 (1959) 90.

Figure 3 shows Johnson's results which show a marked disparity between the position of minimum cosmic ray intensity and the dipole equator. If nothing else, this can be taken as a warning that footnotes like the fine print in business contracts cannot be left unread with impunity!

Following the realisation that the dipole approximation to the field was no longer adequate to match the increased accuracy of measurement the basic Lemaître-Vallarta treatment of the problem has now been elaborated by extensive use of fast modern digital computers to take into account the most up to date representation of the geomagnetic field incorporating both the higher order terms of the internal field and the external magnetospheric current systems in so far as they are at present known.

Accurate knowledge of the geomagnetic cutoff energies as a function of position and direction of arrival are of importance in determining the momentum spectrum of the cosmic ray primaries in the low energy regions, in evaluating specific yield functions which permit us to determine the energy dependence of the temporal variation of the cosmic ray intensity observed deep in the atmosphere, and in understanding the penetration of solar flare particles into the magnetosphere.

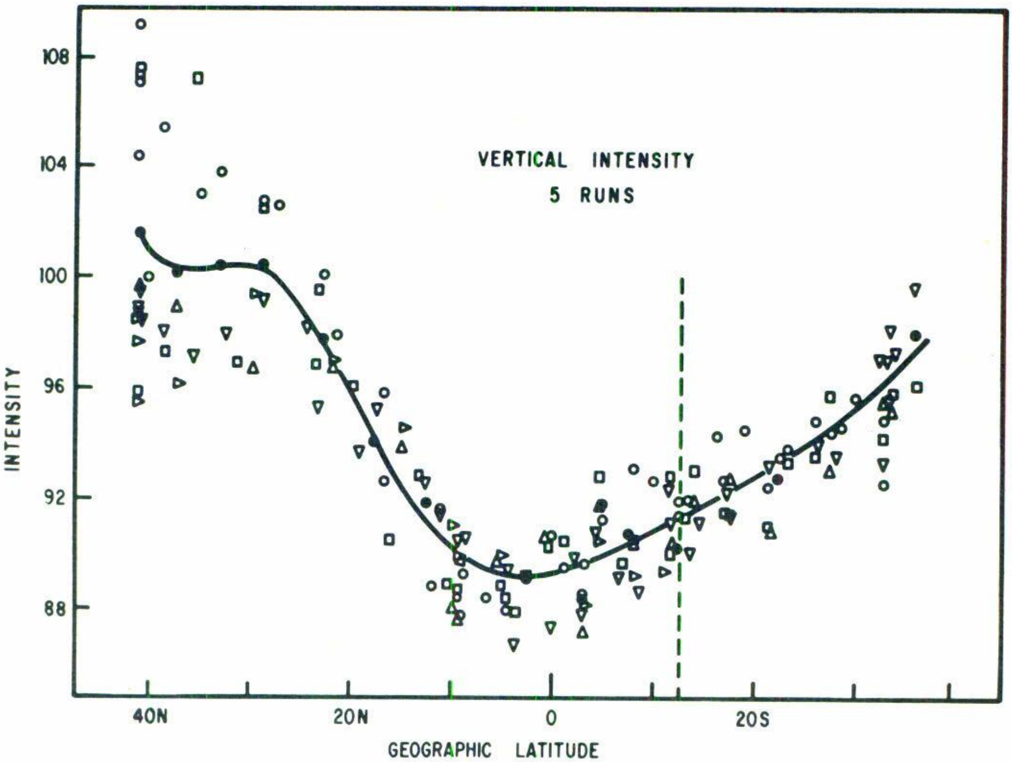

Fig. 3. The anomalous distribution of sea level cosmic ray intensity in relation to geomagnetic coordinates. (From Johnson and Read, The Physical Review 51 (1937) 557.

We still continue to build in this field on the firm foundations laid down long ago and it must be a source of considerable gratification to our friend and colleague Manuel Sandoval Vallarta to see now, more than forty years later, the healthy and vigorous tree that has sprung from the seed which he, together with Lemaître, planted in that historic paper in January of 1933.

Let me end by thanking the members of the organising committee, Drs. Flores, Gall, Moshinsky and Troncoso and their supporting organisations, for making it possible for me to be present at such an auspicious occasion, and at the same time, I would like to congratulate the committee on their choice of venue in this beautiful Museo Nacional de Antropología.