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GREENBELT, MARYLAND

Rapporteur Paper presented at the 9th IUPAP International Conference on Cosmic Rays, London, England, September 6-17, 1965.

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by Juan G. Roederer*
Goddard Space Flight Center, Greenbelt, Maryland

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MAGNETOSPHERIC PHENOMENA

Juan G. Roederer

I. INTRODUCTION AND WARNING

This is supposed to be a Rapporteur Paper, reviewing the contributions on Physics of the Magnetosphere presented at the 9th IUPAP International Conference on Cosmic Rays, and placing them in the light of present knowledge in this field.

This, however, is a very difficult task to accomplish properly. First of all, the study of magnetospheric phenomena is only indirectly related to what one now has adopted de facto as "Cosmic Ray Physics." This explains the comparatively small number of papers presented at this meeting on the subject, and the quite unbalanced "national distribution" of authors (some countries, very active in this field, deliberately did not submit contributed papers on this subject). Second, the field itself is so wide, that it never could have been covered properly in the frame of only a subsection of a conference. Finally, this field has progressed so much in the last few years, that a rapporteur paper, if given in the traditional way before a cosmic ray audience, would require a long introduction just to explain some of the new basic concepts on which recent research is centered.

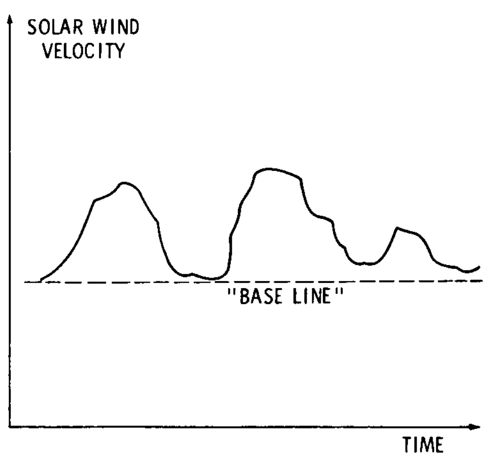
All these considerations constitute a reasonable excuse for departing from tradition in the presentation of this rapporteur paper: (a) contributed papers presented at this conference will not be mentioned explicitly, neither by title nor by author; (b) no specific references will be given at all; (c) only a qualitative discussion will be presented, describing the physical processes involved, rather than listing quantitative experimental and theoretical results; (d) no fancy figures will be reproduced; only qualitative sketches will be given, whenever necessary. For all these reasons, this paper should never be quoted for reference.

Two excellent review papers have been given at this Conference by N. F. Ness[1] and S. N. Vernov.[2] In addition, several chapters in two recent books, edited by H. Odishaw[3] and W. N. Hess,[4] respectively, deal in a detailed and quite up to date way with this subject, containing abundant literature references. For a quite complete collection of references, consult.[5] Many of the following discussions are based on the lectures given at the NATO Advanced Study Institute on Radiation Trapped in the Geomagnetic Field, held in Bergen, Norway (August 1965).[6]

In the qualitative description which follows, we shall start out in the solar wind, penetrate the stationary shock wave into the transition region, cross the magnetopause, work our way through the distorted field in the outer magnetosphere, diffuse into the trapping region and to lower altitudes, to finally end up precipitating into the upper atmosphere.

II. SHAPE AND STRUCTURE OF THE MAGNETOSPHERE

Let us start out in the solar wind. We now know that there is an uninterrupted flow of plasma radially outwards from the sun, representing the continuous expansion of the corona caused by a steady dissipation of energy into heat at its base. Recent satellite measurements have established quite convincingly that the solar wind velocity never decreases below a certain "base line" of about 320 Km / sec, not even during very quiet periods at solar minimum. Transient increases of the velocity occur in correlation with active regions on the sun; after their passage, the plasma flow falls down to its base line very readily. Ion fluxes are of the order of 3×10^8 $cm^{-2} sec^{-1}$, with kinetic temperatures of the order of 10^5 °K at 1 a.u. Ion composition is mainly hydrogen; helium ions have been recently identified.



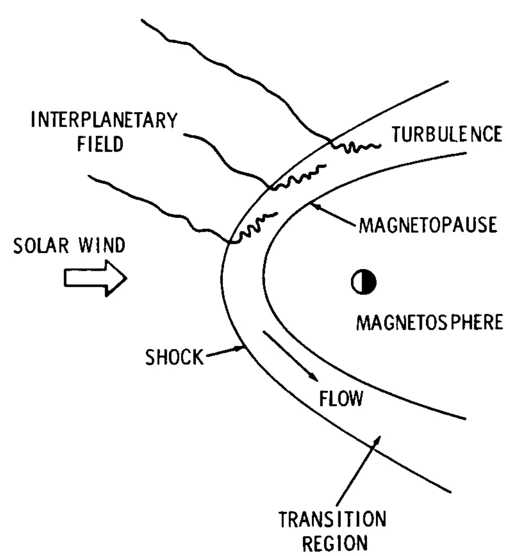
Embedded in this plasma, there is the familiar spiralled radial magnetic field, frozen in and carried outwards by the infinitely conducting medium. During quiet conditions, the field intensity is about 5 gammas. In correlation with the passage of active regions on the solar disk, this intensity may increase to 100 gammas. The average time lag of 4.5 days between the central passage of the active region and the field increase at 1 a.u. is in good agreement with the direct measurements of plasma velocity, and definitely proves the solar origin of the interplanetary field.

Under these conditions of density, temperature, field and bulk velocity, the solar wind represents a collisionless plasma flowing at supersonic speed with Alfvén Mach number 6-7 during quiet periods. To this flow, the earth's magnetic field is interposed as an obstacle.

The first "warning" given to a solar wind particle, that an obstacle is being approached, comes in form of a stationary shock wave. In ordinary gas flows at supersonic speed, the information about an obstacle is transmitted to incoming fluid particles by collisions with fellow particles in a very thin shock layer, where non-adiabatic compression and heating, and a general slowing down to subsonic velocities take place. This region is typically a few collision mean free paths thick. In a collisionless plasma, information can only be transmitted by the magnetic field, which here replaces the collision process in its key role of tying particles together. In a collisionless shock, a similar compression and non-adiabatic heating is likely to occur, in a region about one ion cyclotron radius thick. This would be, for typical solar wind parameters, of only 1000 Km.

The existence of this shock or bow wave is now perfectly established experimentally, and its position and shape in the "front" side of the magnetosphere (and up to about ± 120° of the earth-sun line) are quite well determined near the equatorial plane. The geocentric distance to the subsolar point of the shock is about 13 earth radii during quiet conditions. The experimental study of this shock is of considerable value for plasma physics, since it provides essential information for the yet unsolved theoretical problem of collisionless shocks.

Right behind the shock, satellites and space probes indeed have identified a transition region of subsonic plasma flow, heated up to temperatures of a few million degrees. An important expected effect of the shock is that it will compress, i.e. amplify in an extremely short time any small irregularity of the interplanetary field flowing transversally into it; these irregularities may then contribute to a general breakup into turbulence right behind the shock, in the transition region. This turbulence is badly needed as the



randomizing process which can account for the entropy increase during the non-adiabatic compression of the collisionless gas.

Experimental evidence for turbulence in the transition region was found in magnetic field measurements, which show chaotic changes in field direction and intensity. On the other hand, plasma measurements reveal a sudden change from a directional, steady flow into a considerably isotropized, irregular flow, whenever the shock is traversed from interplanetary space into the transition region.

The turbulence in the transition region may be responsible for statistical (Fermi-type) acceleration of electrons and protons. On the other hand, the sudden compression of field irregularities in the shock may provide a betatron mechanism for particle acceleration. Evidence for sporadic occurrence of intense fluxes of >40 kev electrons was found in the transition region. On the other hand, there is evidence for a non-Maxwellian high energy tail in the proton distribution. These effects are stronger at the dawn side of the transition region.

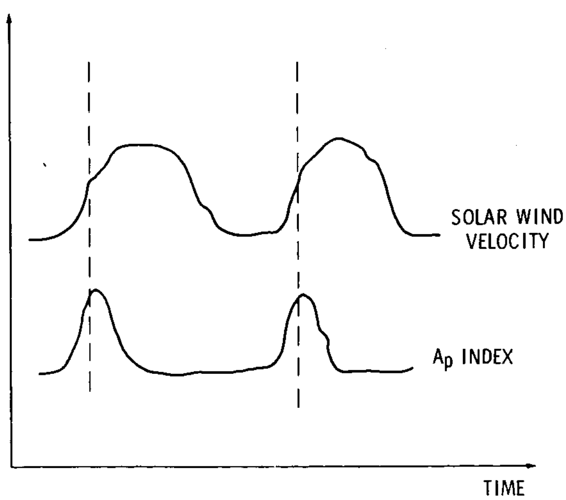
The transition region acts like an elastic medium transmitting the kinetic pressure of the solar wind right onto the geomagnetic field: the infinitely conducting plasma in the transition region will push and compress this field right up to a point where balance is achieved between the kinetic pressure and the geomagnetic field pressure. Again, the thickness of the boundary layer will be given by a typical ion cyclotron radius in the compressed geomagnetic field. Impinging particles from the thermalized solar wind in the transition region will tend to drift for some time along the boundary, originating electric currents. These are precisely the currents necessary to confine the earth's field in a finite volume. The sudden termination of the geomagnetic field is called the magnetopause.

There is now ample experimental information about the magnetopause, its thickness, position and shape near the equatorial plane, in the front side of the magnetosphere. Field measurements suggest values as low as 100 Km for the boundary thickness; a typical position of the subsolar point of the magnetopause is 10 earth radii, during quiet times. So far, there is good agreement between these measurements and recent theoretical models for the boundary, at least near the equatorial plane. These models try to determine the shape and position of a surface such that the (known) kinetic pressure of the plasma outside equals to the magnetic pressure inside, given by the (known) earth's internal field, plus the field caused by the currents flowing in the surface, which must be placed there in such a way as to cancel exactly the total field outside. Once the position of the magnetopause is known, one can compute the position of the shock wave, and herewith test the various assumptions made in the theoretical treatment of the collisionless shock.

So far there is no experimental information about the magnetopause at high latitudes, in the noon meridian plane. This, however, is a very interesting region, since it is there, where neutral points in the magnetic field are to be expected. These neutral points are of considerable importance for the mechanisms of particle transfer from the solar wind to the magnetosphere.

The magnetopause extends into the anti-sun direction encircling the tail of the magnetosphere; measurements were made up to about 30 earth radii. The plasma motion in the transition region far away from the stagnation point seems to be again highly directional, flowing along the magnetopause. There is good evidence for a 5° tilt of the whole tail with respect to the earth-sun line, probably related to the interplanetary magnetic field, which, due to its twist, increases the total pressure on the magnetosphere at the dawn side.

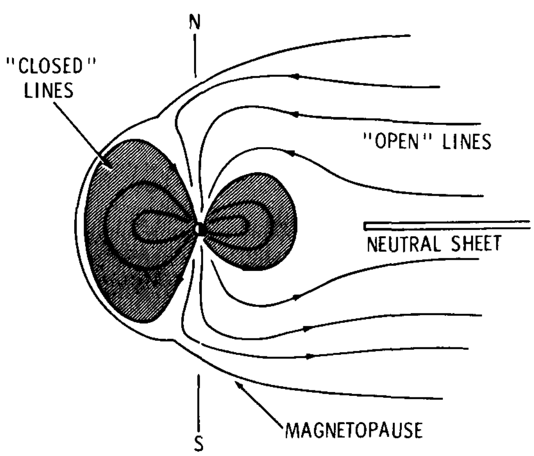
An extremely important question is that of the stability of the magnetopause. It is now believed that instabilities at the boundary are the origin of the geomagnetic activity, i.e. the K_p index. They probably cause h.m. waves to propagate down to the earth, showing up as fluctuations in the surface field. Essentially three different situations have to be analyzed: quiet conditions (stationary boundary), increase of solar wind (compression), and decrease of solar wind (expansion to the normal state). During absolutely quiet conditions in interplanetary space, the turbulence behind the shock may be a persisting cause for instabilities, giving rise to the quiet time remanent geomagnetic activity, especially in the polar caps. Stability conditions during compression could be entirely different from those holding during expansion. In effect, recent solar wind measurements seem to show a correlation of A_p index increases with the increasing phase of the solar wind flow, and not with the absolute value of the solar wind velocity.



Instabilities in the magnetopause must play a crucial role in two important processes: energetic particle transfer across the boundary, and viscous-type momentum transfer from the solar wind to the magnetosphere.

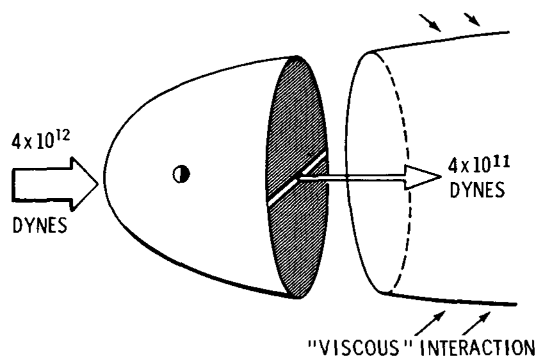
We now come to the field structure inside the geomagnetic cavity. The sources of this field are: the magnetization of the earth's interior, the currents flowing on the surface of the magnetopause, the currents in the neutral sheet in the tail of the magnetosphere (see below), and, eventually, diamagnetic ring currents originating in trapped particle density gradients at 2-4 earth radii, in the equatorial plane. During quiet conditions, the latter may be of very small effect. At geocentric distances less than, say, 5 earth radii, only the internal geomagnetic field dominates; beyond 5 R_e, the currents in the magnetopause (and in the neutral sheet) perturb the dipole-type internal field, and introduce a strong noon-midnight asymmetry.

Most remarkable is the recently established radial character of the field in the tail of the magnetosphere, and the existence of a thin layer or "neutral sheet", which separates the two regions of mutually opposite field directions. The orientation of the neutral sheet is controlled by both, the solar wind and the earth's dipole axis: it wobbles about the sun-earth line, keeping its normal in the sun-earth-dipole-axis plane.

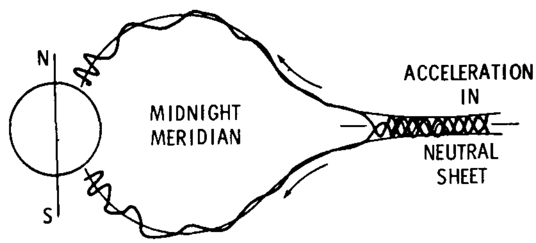


The lines of force stretching out into the tail, come from the polar regions of the earth. Consequently, there are two quite distinct families of field lines emerging out of the earth's surface: those which return back to earth, and those which are "lost" into the tail. No particles can ever be trapped on the latter. Both families are separated by a surface which intersects the earth's surface at geomagnetic latitudes not yet determined experimentally, but which according to the magnetospheric models should be about 78-80° in the noon meridian, and 65-70° at midnight, during quiet conditions. This limiting surface between "closed" and "open" lines is expected to change considerably during geomagnetic disturbances.

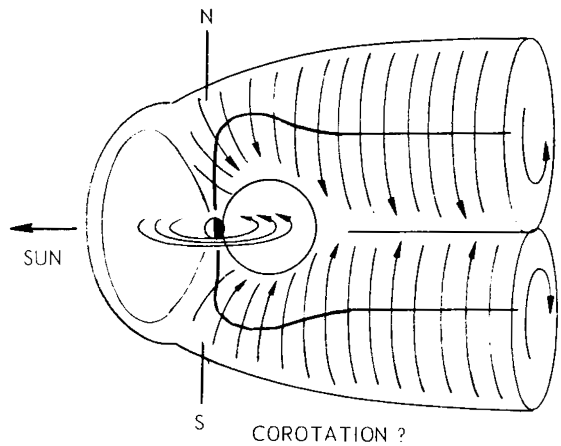
There is no convincing experimental information about the extension of the geomagnetic tail; at about 30 R_e there is no indication in the data for a closing-in of the magnetopause. Theories differ widely about the lower and upper limits for the length of the tail. At about 20 R_e, the tail has a diameter of roughly 40 R_e. Taking into account the measured values of the magnetic field intensity, and assuming circular shape of the cross section, one obtains a total force of about 4×10^{11} dynes with which the tail pulls on the rest of the magnetosphere through magnetic stress. This is a very considerable fraction of the 4×10^{12} dynes with which the solar wind presses against the entire front side of the magnetosphere. In other words, a very efficient "friction" mechanism must be effective at the boundary of the tail. This mechanism - very likely provided by instabilities - may also be responsible for convective plasma motions in the tail, necessary to explain the stretching out of the geomagnetic field lines.



The existence of a geomagnetic tail has opened up new viewpoints about mechanisms for the conveyance of low energy solar protons from interplanetary space down to the earth's atmosphere, particularly into the polar regions. The neutral sheet, on the other hand, is a very attractive region for the study of particle acceleration, and may well play a crucial role in the production of night side, rapid onset, auroras. Recent calculations have shown that particles, accelerated in the neutral sheet, would emerge along a very thin layer of field lines, with extremely small initial pitch angles, being therefore able to reach regions of high magnetic intensity and to precipitate into the dense layers of the nightside atmosphere.



An important, but experimentally unsolved, question is that of the motion of the magnetospheric plasma. Or, which is equivalent in view of the almost infinite conductivity, the question of the motion of the geomagnetic field lines. These field lines are "solidly rooted" in the ionosphere. If the ionosphere co-rotates with the earth (which may not



be true at all for high geomagnetic latitudes), the field lines must co-rotate, and with them, the whole magnetospheric plasma. The driving force for this motion, of course, must be provided by electric fields which cause charge-independent drifts, i.e. bulk motions, normal to the field lines. The electric fields are extremely important for the motion of moderately energetic particles, such as, for instance, auroral particles.

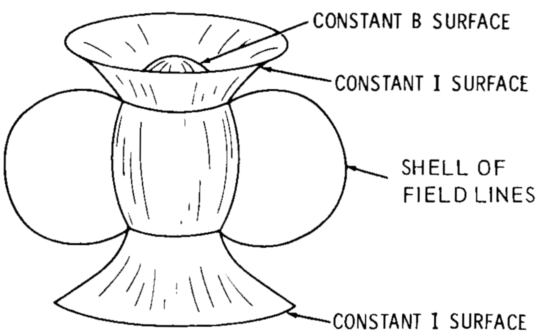
III. MOTION OF CHARGED PARTICLES IN THE MAGNETOSPHERE

A general study of the adiabatic motion of energetic particles in the earth's magnetic field is necessary for a better understanding of trapped particle phenomena. Let us consider a time-independent magnetic field, in absence of electric fields. In this case, only two of the three adiabatic invariants are needed, in order to describe the longitudinal drift of a particle: the conservation of the magnetic moment, M, and that of the "longitudinal invariant," J:

$$M = \frac{p_\perp^2}{2mB} = \frac{K.E.}{B_m} = \text{const} \ldots (1) \qquad J = \oint p_{/\!/}\, ds = \text{const} \ldots (2)$$

p is the momentum, B_m the field intensity at the mirror point. The integral (2) is taken along a field line, for a complete bounce motion. In absence of electric fields, the particle's energy is also conserved. In this case, the two invariants (1) and (2) can be replaced by two other invariants, which now depend on the field geometry only:

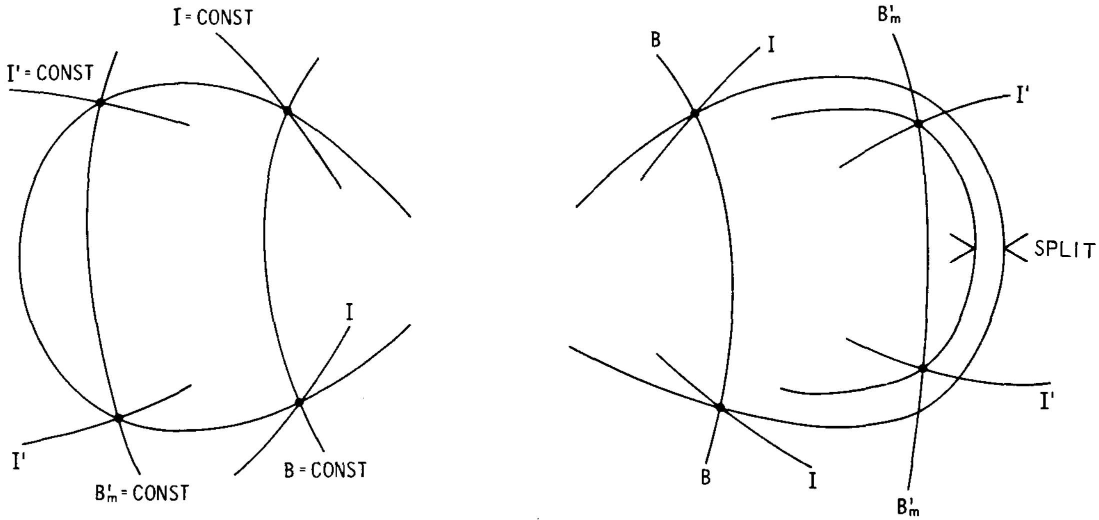
$$B_m = \text{const} \ldots (3) \qquad I = \int_m^{m'} \sqrt{1 - \frac{B(s)}{B_m}}\, ds = \text{const} \ldots (4)$$



(4) is extended along the field line between the two conjugate mirror points. For any trapping field geometry, we can assign to each point in space a pair of values I, B_m, such that a particle mirroring there, has the value I for the integral (4), B_m being simply the field intensity

at that point. As the particle drifts to other field lines, it must keep these values constant, i.e., it will cover a shell of field lines which pass through the intersections of two given constant I and constant B_m surfaces.

Let us consider the geomagnetic field. Take a particle which starts at a given longitude, sitting on a given field line and mirroring at a value B_m. The integral (4) computed along the field line between the two mirror points, has a value I. This means that when drifting through any other longitude, say 180^o away, this particle will be bouncing along a field line which passes through the intersection of the corresponding I = const and B_m = const surfaces. Now take a particle which starts on the <u>same</u> initial field line, but which mirrors at a lower value $B'_m < B_m$. Its in-

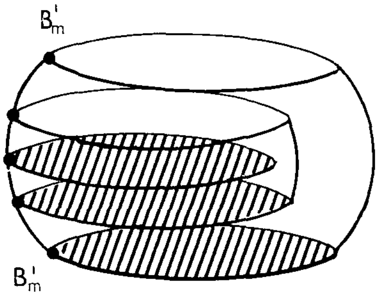


INITIAL FIELD LINE AT ϕ

SPLITTED SHELLS AT ϕ + 180°

tegral (4) will also be lower, I' < I. After an 180^o longitudinal drift, this second particle will be traveling along a field line which passes through the intersection of the surface I' = const and B'_m = const. <u>Only</u> in case of perfect azimuthal symmetry (as in the pure dipole), will these surfaces intersect exactly on the <u>same</u> line as that of the first particle. In the general case, particles starting on the same field line at a given longitude will populate different shells, according to their initial mirror point fields, or, what is equivalent, according to their initial equatorial pitch angles $\alpha_e = \arcsin(B_e/B_m)$ (of course, all these different shells are tangent to each other at the initial field line).

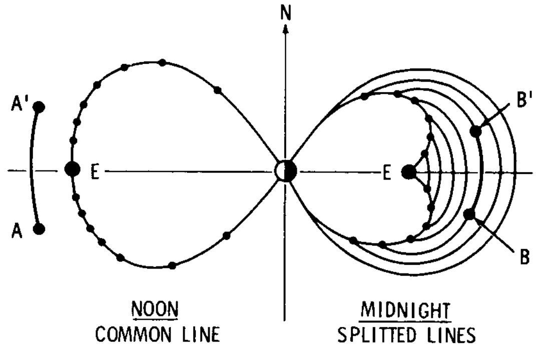
For the case of the real geomagnetic field (in absence of external



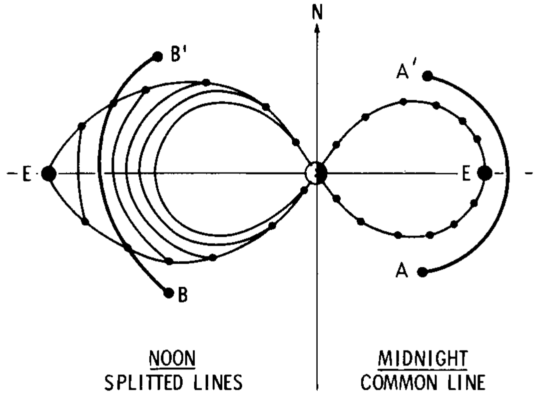
perturbations), it can be shown that the distance between splitted shells is only very small, a fraction of 1% of the distance of the equatorial point of a field line to the center of the earth. In other words, with a very good approximation, one can say that all particles initially on the same field line, will mirror on a common field line at any other longitude. This has a formidable consequence: it enables a two-dimensional description of the three-dimensional radiation belts, at least up to distances of about 5 R_e. Indeed, if particles do populate the same shell irrespective of their initial mirror points, the omnidirectional flux of these particles will be the same on all points of the shell having the same B value (provided of course, no appreciable injections or losses occur during the drift). In order to describe omnidirectional particle fluxes in the inner magnetosphere, we therefore need only two "space" parameters: the value of the magnetic field intensity at the point of measurement and a parameter which characterizes the (unique) shell which goes through that point. This is the famous L-parameter. L is a particular relation between I and B_m which remains constant (within $<$ 1%) on a given field line, and, therefore, on the whole shell generated by particles starting on that field line. Numerically, L gives the average distance of the equatorial points of a shell to the center of the dipole.

But what happens in the outer magnetosphere, where the azimuthal symmetry is brutally removed? Particles starting on the same field line, say in the noon meridional plane, will now populate different shells, depending on their initial mirror points or equatorial pitch angles. For instance, they will cross the midnight meridian on different lines.

Let us start with a particle mirroring at or near the equator, on a line in the noon meridian, close to the boundary. For this particle, $I \simeq 0$; it will drift around the earth on the equator following a constant-B path. This constant-B path comes considerably closer to the earth at the night side, because the field is weaker there (less compression), and we must go to lower altitudes in order to find a given B value. On the other hand, a particle which starts on the same field line on the noon meridian, but which is mirroring at high latitudes, will have a high I value. Under these circumstances, it can be shown that the value of I is not much different from the length of the field line between mirror points. On the midnight meridian, the particle will therefore be found on a line which has nearly the same length than the initial one, i.e. stretching out to roughly the same equatorial distance. In summary, all particles initially on the same noon-line, will cross the midnight plane on line portions shown in the figure. Furthermore, it is easy to realize that particles mirroring inside that area (BB'), will cross the noon meridian outside (AA') the initial line.



If this noon-line is on the boundary, no stably trapped particle could be found mirroring inside the hatched area in the midnight meridional plane. Any particle doing this would not be able to complete a drift around the earth: it would leave the magnetosphere before reaching the noon meridian. We may call this a "pseudo-trapped" particle (only transiently trapped). Notice finally that a sharp trapping boundary in the noon side does not result in a sharp boundary in the back side.



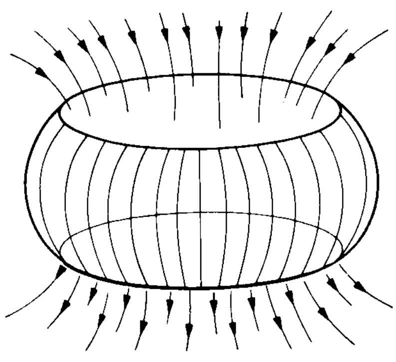
On the other hand, for a given field line in the midnight meridian, all particles mirroring anywhere on this line, will cross the noon meridian in an area like the one shown in the figure. All particles mirroring outside that area (BB'), will cross the midnight meridian outside (AA') the given line. If now there is an "obstacle" behind that line (like for instance the neutral sheet), no stably trapped particle could be found outside the hatched area in the noon meridian. Any particle injected there, would be lost into the "obstacle" before reaching the midnight meridian; in this high latitude noon region, only pseudo-trapped particles can exist.

From these considerations we deduce that the outer magnetosphere may be divided into the following zones: (1) a genuine trapping region; (2) a region in the back side, centered at the equator, which can be crossed by stably trapped particles, but in which they are not allowed to mirror; (3) a high latitude region in the front side where only pseudo-trapped particles can exist; (4) a region defined by the "open" field lines emerging from the polar caps, in which no trapping is possible at all, not even for one little bounce. The shape and simultaneous existence of regions (2) and (3) will depend on the position of the magnetopause and that of the neutral sheet, respectively.

These considerations are of crucial importance when data on spatial flux distributions of energetic particles in the outer magnetosphere are being analyzed, ordered, plotted and compared. Notice finally, that the L-value has no physical meaning beyond L = 5 or 6; the azimuthal asymmetry destroys any hope for a two-dimensional description of omnidirectional particle fluxes in the outer magnetosphere.

So far, we have not taken into account at all the energy of the particles. There are, however, quite distinct regions in energy space, regarding trapping conditions. For a given L-shell, there is an upper limit for the energy of a particle, beyond which no adiabatic motion, viz trapping, is possible. This limit is given by the energy at which the particle's gyroradius becomes of the order of a typical scale in the field geometry. There is no clear cut between the two regions; a proof for this is given by the good correlation found between the "non-adiabatic" quantity of local vertical geomagnetic cut-off rigidity for cosmic rays, and the adiabatic concept of local L-value.

On the other hand, there is a lower limit in energy, below which the effect of electric fields in the magnetosphere cannot be neglected. In this energy region, longitudinal drift velocities are comparable to the co-rotation velocities of the field lines. To obtain the total drift velocity, the electric drift must be added vectorially to the magnetic drift; anything may result. Furthermore, energy conservation is no longer true, and particles can be accelerated or decelerated in the electric field. Due to conservation of the magnetic moment (1), any increase in kinetic energy will be accompanied by an increase in mirror field intensity (lowering of mirror point altitude). And due to the conservation of J (2), this increase will also be accompanied by a decrease in L, i.e. a decrease of geomagnetic latitude of the end points of the corresponding field line. Auroral particles belong to this energy region.



$\Phi = \int B dS = CONST$

So far we have not mentioned at all the third adiabatic invariant, which expresses the constancy of the magnetic flux enclosed by a given particle shell. This invariant is important only for time-dependent magnetic fields.

Let us say a few words about the violation of the invariants. There is a characteristic period of time associated to each of the three invariants. For the magnetic moment, it is the cyclotron period; for the second invariant, it is the bounce period, and for the flux invariant, the longitudinal drift period. In the geomagnetic field, these periods are in general orders of magnitude apart (for inner belt electrons, typically, $\sim 10^{-6}$ sec, $\sim 10^{-1}$ sec and $\sim 10^{3}$ sec, respectively). Any time variation of the geomagnetic field with a time scale of the order of one of the characteristic periods, will lead to a violation, i.e. non-conservation, of the corresponding invariant. If, on the other hand, the time variation is much slower than a given characteristic period, it will leave the corresponding invariant untouched.

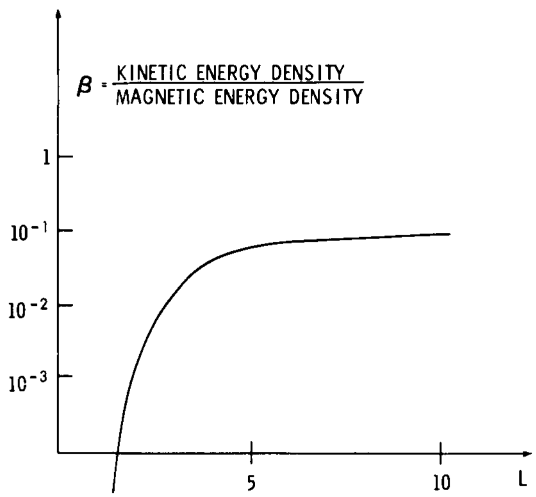
A fluctuation of the geomagnetic field with a typical time scale of, say, 15 minutes, will violate the conservation of the flux invariant for all particles having longitudinal drift periods longer than this; but it will not affect the conservation of M and J. If the field remains azimuthally symmetric during the perturbation, particles will always remain on common shells, even if they change position. The situation is quite different, when there is asymmetry. In this case, everything will depend on where (at what longitude) a given shell-particle was surprised by the violation. Once the field is back to the initial value, a given shell will be "smeared out" in the final state. This represents a very important shell diffusion mechanism. Any particle which during this process is brought to a lower shell will increase both its energy and its mirror point field intensity due to the conservation of M and J. It can be shown that this increase will also be accompanied by an increase of the equatorial pitch angle $\alpha_e = \arc\sin (B_e/B_m)^{1/2}$ (because B_e increases faster than B_m). This means that particles get more and more confined near the equator, as they diffuse inwards.

It is important to note that the ultimate physical cause for violation of the third invariant is given by induced electric fields, which are intense enough to make particles drift out of their "home shell". Energy changes are precisely betatron-type accelerations in these fields.

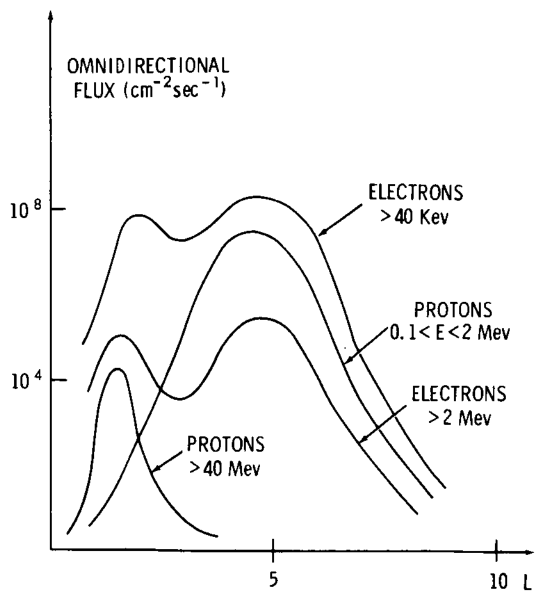
Let us finally consider an extremely short perturbation, like the elastic scattering of a trapped particle. In this case, the first and the second invariants will be violated and the particle will change its mirror point. In the case of symmetric field, the third invariant remains almost unchanged: the particle will remain on the same shell within the accuracy of one cyclotron radius. In an asymmetric field, however, we already have seen that a change in the mirror point of a particle leads to a change of the particle's shell. Particles diffusing in pitch angle will therefore diffuse across shells too, in an asymmetric field. This type of radial drift, however, will not be accompanied by any change in energy (this time, there is no electric field around to accomplish the acceleration).

IV. GEOMAGNETICALLY TRAPPED RADIATION

A great deal of information about the shape and the structure of the magnetosphere comes from the study of energetic particle distributions in space and time. We will discuss here only some very general features regarding radiation belts. First of all, if one estimates the ratio of particle kinetic energy density to magnetic field energy density (a quantity usually called β, indicative of the score in the game "particles vs. fields"), one obtains very high values, reaching 0.1 beyond $L \simeq 3$ (laboratory plasma experiments never achieved more than 10^{-3}). This indicates that the earth's radiation belts are probably loaded up with the maximum flux of particles compatible with plasma stability.



We first turn to the spatial distribution of energetic particle fluxes in the magnetosphere. It is quite well established that below $L \sim 6$, omnidirectional flux contours give a consistent picture in the two dimensional B - L space, indicating that shell splitting due to azimuthal asymmetry is negligible. An over-all qualitative picture of omnidirectional particle fluxes, near the equatorial plane, is shown in the sketch. The "inner" radiation belt with peak fluxes at about L = 1.6, is very stable, both during geomagnetic storms and throughout the solar cycle. The outer belt shows considerable time variations, mainly

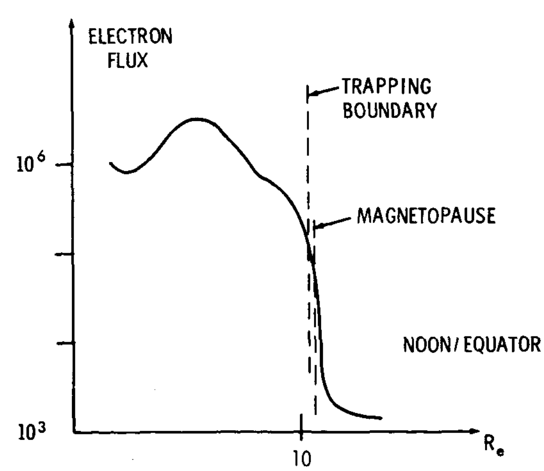


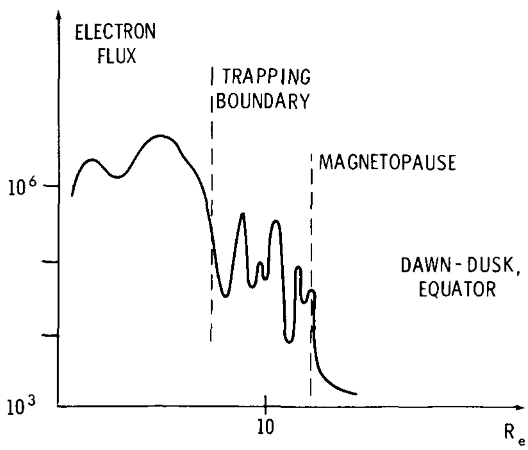
correlated with geomagnetic activity. Notice the characteristic "slot" in the electron fluxes around L = 2.5 - 3, more pronounced for higher energies. The flux of high energy protons decays very rapidly with L, likely due to the sharp decrease with increasing radial distance of the upper limit in energy for adiabatic trapping of protons.

Energy spectra of protons are now quite well known. In the inner belt, measurements extend to almost 1 Gev. In the outer zone, where high energy protons are absent, exponential spectra are found, with e-folding energies ranging from tens of Kev at high L values, to 400 Kev at L = 3. A very clear L - dependence of these spectra is thus established, indicating that protons drift in L, hardening their spectra towards lower L shells, as dictated by the conservation of M and J. Intense fluxes of 5 Kev protons have recently been found at low L values. They may play an important role for the ring current during geomagnetic storms. Energy spectra of natural electrons in the inner belt are not so well known; contamination by artificially injected electrons is still interfering the measurements. In the outer zone, spectra may tentatively be fitted by an exponential form with e-folding energies ranging from about 170 Kev at high L values to about 340 Kev at L = 4. Again, there is a trend for the spectrum to harden towards lower L values.

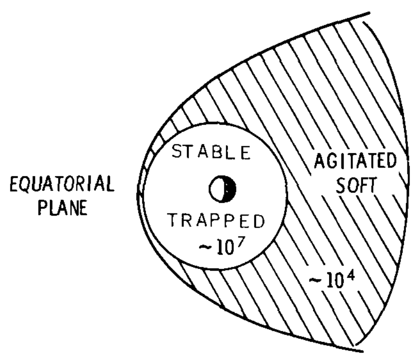
Beyond L = 6, the distortion of the magnetosphere calls for a three-dimensional description of the radiation belt. In the equatorial plane, isointensity contours consistently follow constant B rings, coming closer to the earth at the night side. Most of the information in this outer region comes from >40 Kev electron measurements. Typical fluxes here are of the order of 10^7 cm^{-2} sec^{-1}.

The "core" of trapped particles shows in general a well defined boundary. In the equatorial plane, and near the noon meridian, this trapping boundary is very close to, or coincident with the magnetopause; it shows up as a sharp drop in intensity by several orders of magnitude, over a rather short distance. As one goes towards the dawn or evening sides, the trapping boundary and the magnetopause get disconnected, leaving between them a region where strongly agitated fluxes are observed; typical intensities of >40

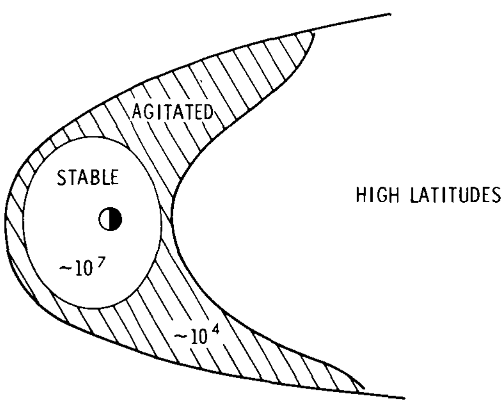




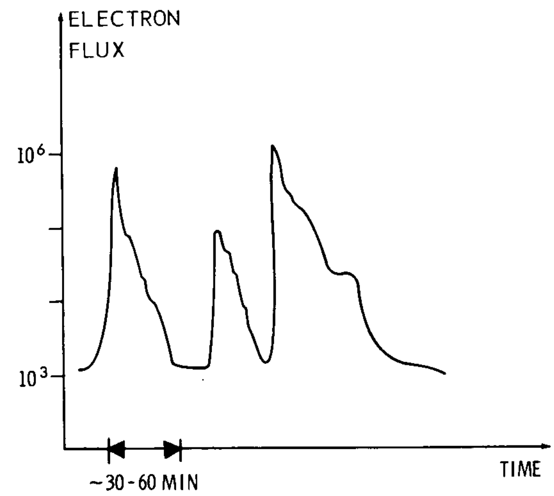
Kev electrons are here of the order of 10^4 cm^{-2} sec^{-1}. These electrons have much softer spectra than in the trapping region. They may be pseudo-trapped particles, injected or accelerated in the day side, bouncing along closed fields lines, but unable to complete a drift around the earth (page 11). In the night side, always on the equatorial plane, there is a much smoother and less marked transition from the high fluxes of stably trapped electrons into the unstable region, occuring in general at about 8 R_e (see discussion page 11). This region of strongly varying fluxes of soft electrons extends out to about 15 R_e into the tail, in the sun-earth direction.



The whole picture changes greatly at higher geomagnetic latitudes. The trapping boundary moves inwards, as expected in view of the magnetic field configuration. On the day side, the higher energy (>280 Kev) electron fluxes seem to terminate at lower latitudes than the >40 Kev flux. Going to the night side, the region of strongly varying soft electron fluxes stretches out like a "skirt" along the sides of the magnetosphere. Near the midnight meridian, at these higher latitudes, this region disappears completely: the stably trapped electron flux drops abruptly to the background. This clearly indicates that the "cusp" of soft electron fluxes stretching out into the tail, mentioned in the preceding paragraph, is strictly confined to low latitudes. It is probably related to the presence of the neutral sheet.



A very important fact is the appearance of electron "islands" in the back side of the magnetosphere. These are sharp increases of electron fluxes, up to $10^7\ cm^{-2}\ sec^{-1}$ for > 40 Kev, followed by an exponential decay. They are clearly time-dependent phenomena. Similar events were observed near the magnetopause and in the transition region. Their frequency of appearance is positively correlated with K_p.

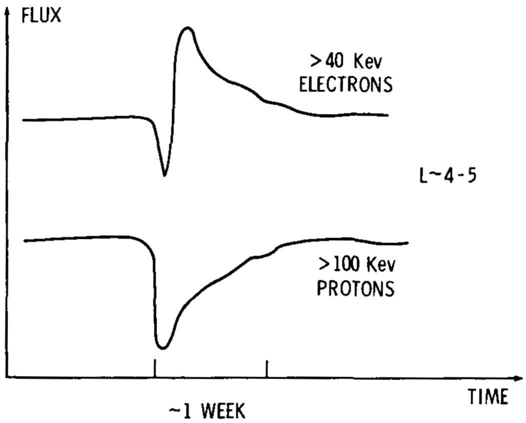


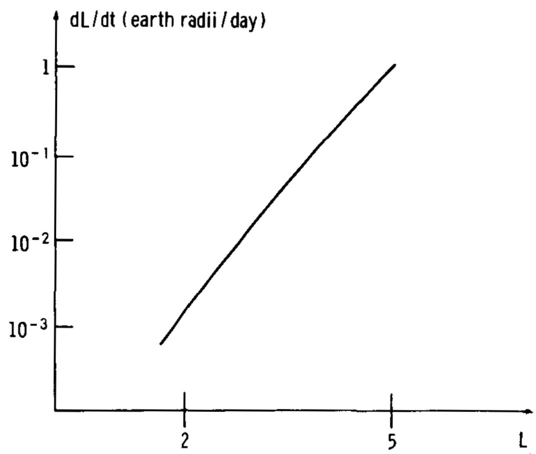
Recent measurements of very low energy electrons (0.1 - 10 Kev) show a distribution profile of high fluxes ($10^8 - 10^9\ cm^{-2}\ sec^{-1}\ Kev^{-1}$), strongly dependent on geomagnetic activity, which in general seems to extend from low latitudes in the back side towards high latitudes at the dawn and evening sides. Turning finally to extremely low energy electrons, in the range of 100 ev, no clear boundary is seen at all, until the shock is reached. This seems to indicate that the magnetopause is quite transparent to these particles.

The analysis of time variations of the radiation belts is a highly complicated business. We can only refer here to some of the salient features. Only the core of trapped particles will be considered. First of all, we may mention the following types of time variations: the 11 year variation; transient variations associated with storms or high-K_p; decays after artificial injections, and short term periodic variations. The study and the interpretation of these variations is complicated by the fact that it is very difficult to observe the flux and energy spectrum at a fixed point in the magnetosphere throughout a typical time scale of the variation; hence it often is very difficult to determine whether one is dealing with a variation in flux or in energy spectrum, whether one has just a shift of the whole spatial distribution of the belt, or whether several of these occur simultaneously.

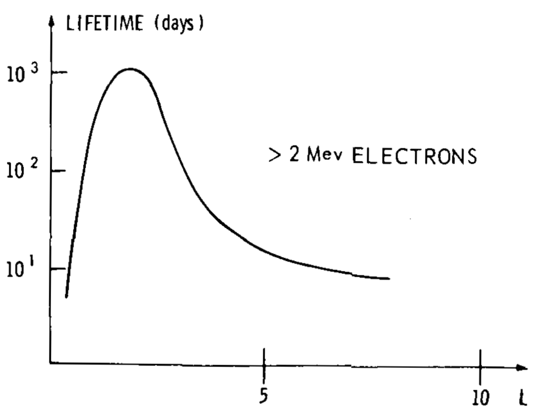
Regarding the 11 year variation, it seems an established fact that the inner belt is pretty constant throughout the solar cycle. The outer belt particles show so many and intense short term variations, that it is difficult to establish a "base line" which then could be followed throughout the solar cycle. In general, a gradual decay of intensity during declining solar activity was detected. In any case, it seems clear that what keeps the outer belt alive, is the solar wind, or more precisely, the solar wind fluctuations. Turning them off, very likely the outer radiation belt would disappear.

As to the short term variations associated with increases in the geomagnetic activity, one may say in summary that they are more intense at higher L values, that they are felt more by electrons than by protons, that variations of high energy particles are delayed in time up to several days with respect to the lower energy ones, and that certain common patterns in time seem to be followed by electrons and protons, respectively (see sketch). One common feature is a sudden change, followed by a gradual recovery. The relaxation times of these recoveries provide important information on particle lifetimes. Typical maximum increases for >40 Kev electron fluxes are given by factors of the order of 100. Another important information came from studies of inward motion of intensity profiles of outer belt electrons, after a big storm. Assuming that this represents a diffusion in L, one can derive values for the diffusion "velocity" dL/dt.





Artificial injections of electrons by means of nuclear explosions have provided important information about particle lifetimes. The commonly observed feature is a rather fast decay of the initially strongly antisotropic distribution of particles into the "normal mode" corresponding to each L shell; this normal mode decays roughly exponentially, with a characteristic lifetime which not only depends on L, but also depends on the mirror point field intensity (or equatorial pitch angle) of a given particle. Typical lifetimes for 2 Mev electrons are sketched in the figure, as a function of L.



A very important type of periodic time variations of energetic electron fluxes was found recently, occuring after a big storm, in association with synchronous variations of the magnetic field. Harmonic analysis of the flux variations revealed a strong predominance of a frequency, which roughly coincided with the mean longitudinal drift frequency of this group of electrons. This suggests the action of a resonant-type acceleration in a periodically varying field. Such a process, of course, is possible only if the induced electric field is azimuthally asymmetric, in order to give chance to a bunch of particles to consistently see a stronger field during the accelerating phase, every time they drift around the earth. This asymmetry may be provided by the natural distortion of the magnetosphere.

In regions of steep flux gradients, as at the lower edge of the inner radiation belt, this process may lead to considerable effects, even if there is only a very small energy increase of the resonant particles: as they get accelerated, they will drift inwards in L (conservation of M and J), i.e. to substantially lower flux regions, where they may stand out considerably over the background, as a monoenergetic group. This effect was observed recently in the form of sudden appearance and gradual decay of a 1.3 Mev electron peak, at an L shell of about 1.15. Equatorial magnetograms during the first hours showed marked recurrent variations, with a period in resonance with the 1.3 Mev electron drift around the earth.

The last part of our discussion will deal with radiation belt dynamics, i.e. with the sequence of processes injection → storage → loss. Let us consider a given class of particles. Under storage, we mean the history of the particle from the instant it becomes a trapped particle (injection), to the moment it disappears from the scene (loss). During this time, the particle is trapped in the geomagnetic field, subject to pitch angle scattering, L-shell diffusion and acceleration. Physical mechanisms governing these processes entirely determine all properties of the radiation belts.

Let us first start with the loss mechanisms. The ultimate sink, at least for lower L shells, is always the atmosphere. A particle, trapped on a given shell, may leave it without precipitating into the atmosphere. In that case, it just was transfered to another neighboring shell. But some day, somewhere, it will die in the upper atmosphere. In the inner belt, L-transfer processes seem to be very weak: it is more likely for a particle to get the "right" kick in pitch angle through a scattering process, ending up in the dense atmosphere. In the outer belt, during quiet conditions, L-diffusion (towards lower L shells) seems to be the dominating process; losses into the atmosphere are enhanced only during geomagnetic disturbances, which very likely make the pitch angle scattering mechanism temporarily overwhelm the L-transfer process. For low L-shells, most of the precipitation into the atmosphere occurs in the "South American" or "South Atlantic" Anomaly, where a given particle shell has its closest approach to the earth's surface (mainly because of the eccentricity of the geomagnetic dipole). Electrons, drifting from west to east, attain lowest mirror point altitudes in this Anomaly; those getting below, say, 100 km will be wiped out from the radiation belt by energy loss in the dense atmosphere. This leads to a region in B-L space with depleted electron fluxes, east of the Anomaly. However, this region is again replenished to some extend with electrons which diffuse into it by pitch angle scattering. These electrons will precipitate into the atmosphere the next time they drift over South America or the South Atlantic. A permanent flux of X-rays from electron Bremsstrahlung has indeed been detected at balloon altitudes in that area.

There are at least two types of pitch angle (or mirror point) diffusion mechanisms. One is elastic, multiple Coulomb scattering with air atoms. This process is only effective for electrons (for protons, slowing down by ionization loss and, eventually, charge exchange, are dominant). It describes very well all experimental observations for trapped electrons at very low altitudes ($L \lesssim 1.2$). For higher L values, its effects must become negligible, because of the extremely low atmospheric density. However, there is definite experimental evidence that a second efficient pitch angle scattering mechanism exists, and even increases with higher L values. The existence of the "slot" in the electron distribution at $L \sim 3$ is one indication in favor. The short lifetimes of electrons beyond $L = 3$ is another evidence. More support comes from experimental results about the efficient replenishment of electrons east of the South American Anomaly, in all B-L regions which plunge below sea level in the South Atlantic, i.e. which get depleted there. Calculations have shown that Coulomb scattering must refill these regions partially, a few degrees east of the center of the Anomaly; however, satellite measurements indicate that refilling continues at longitudes where Coulomb scattering is completely inefficient. A possible pitch angle scattering mechanism is given by resonant interactions of electrons with electromagnetic waves, such as whistlers. This is particularly attractive, for it predicts a maximum efficiency near $L = 3$, where the slot occurs. However, theoretical predictions so far show no agreement with experimental data on pitch angle distributions. Another possibility would be interaction with radiowave noise, or with hydromagnetic waves. Protons would not be affected by these mechanisms.

The other extremely important mechanism is that of L-diffusion. We already have mentioned, that the remarkable L-dependence of the shape of proton spectra is a strong indication that we are dealing with one and the same population of particles, which move inwards in radial distance. A mechanism which explains quantitatively this diffusion is provided by the violation of the third invariant (page 13) during periods of enhanced geomagnetic activity. This, together with shell splitting and conservation of M and J, leads to a gradual diffusion of protons towards lower shells, increasing their energy, and increasing their equatorial pitch angles. It is a rather slow process; it takes years for a proton to diffuse to low L values - this may explain the stability of the inner belt with respect to the 11 year cycle.

Electrons very likely undergo similar shell diffusion processes. In this case, however, the efficient action of pitch angle scattering mechanisms blurrs the picture considerably. As explained on page 14, any diffusion in pitch angle in a strongly asymmetric field will be accompanied by shell diffusion, even in the absence of geomagnetic perturbations. In this process, however, energy will be conserved. There is no theory yet, for the electron belts.

In addition to the betatron-type acceleration of a particle which moves across L-shells during third invariant violations, there must be other acceleration mechanisms. One already mentioned is the resonance-type mechanism acting during periodic variations of the earth's field. On the other hand, the characteristic time variations of the outer belt during K_p increases, may point to a third type of a locally acting acceleration mechanism.

As to injection mechanisms, most of the trapped particles ultimately may come from the solar wind. They may be brought into the magnetosphere at very low energies through neutral points, or instabilities at the magnetopause, being then energized as they drift towards lower shells. On the other hand, part of the belt population may be magnetospheric plasma, locally accelerated. Finally, cosmic ray albedo neutron decay certainly is a necessary, but not a sufficient, source. It may be sufficient for very high energy protons. It fails, however, to explain the observed fluxes and spectra, and solar cycle variations of intermediate and low energy particles. There is really only one well known source of geomagnetically trapped particles: the bomb.

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