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GEOMAGNETICALLY TRAPPED RADIATION: HALF A CENTURY OF RESEARCH

The study of charged particles trapped in the geomagnetic field was stimulated by an attempt to understand the physical mechanism of magnetic storms. Following the first observations of a radiation belt, the cosmic-ray neutron-albedo theory successfully explained the energy spectrum and spatial distribution of trapped high-energy (>100 MeV) protons of the inner belt. Since these early achievements much of the research effort has been devoted to account for the acceleration of lower-energy electrons, relationship to solar activity, etc., and to the practical problems of protecting equipment and astronauts from the damaging ionizing effects of trapped particles[1].

1. THE EARLY STEPS

The study of the motion of a charged particle in a magnetic dipole field was initiated in attempts to explain the polar aurora in laboratory experiments by Birkeland and analyses by Poincaré. A major advance came from Carl Störmer in 1903, who developed the theory of particle motion in a dipole field. One constant of motion is the particle's kinetic energy. Since the Hamiltonian is independent of the azimuthal angle, the angular momentum of a charge in the cylindrically symmetric dipole is another constant of motion, referred to as Störmer's constant. A third constant of motion cannot be found and Störmer had to resort to numerical integrations. He derived a general result as follows: a particle coming from infinity cannot be trapped; it will either strike the earth or be reflected and return to infinity. He demonstrated the existence of allowed and forbidden zones around the earth dipole. He showed that there exists an inner allowed region within the normally forbidden region, but inaccessible for particles coming from infinity. Störmer and others therefore assumed that the allowed regions would be empty. Some suggestions of particles in inaccessible regions of an (assumed) solar dipole field came from Hannes Alfvén and was followed up by John Wheeler and his students [around 1949].

An important advance also came from experiments in Alfvén's institute by Malmfors and by Brunberg and Dattner, and from similar studies by Bennett at the US Naval Research Laboratory.

1 The historical introduction is a condensation of a review article by S.F. Singer and A.M. Lenchek, forming chapter 3 in Progress in Elementary Particle and Cosmic Ray Physics. (Edited by J.G. Wilson and S.A. Wouthuysen) North Holland Publishing Company, Amsterdam, 1962.

2. FIRST IDEAS ABOUT THE RING CURRENT

The impetus for studying particle motion in the geomagnetic field came from efforts to evaluate the contribution of cosmic ray secondaries ('albedo') to rocket experiments of the primary cosmic ray flux [75]. Griem and Singer [27] investigated the motion of albedo particles that were completely trapped in the Earth's magnetic field before being removed by collision loss.

An independent approach came from efforts to explain the origin and character of the Ring Current, thought to be responsible for the main phase of geomagnetic storms, the large decrease in magnetic field intensity lasting one or two days. Early work was carried out Chapman and Ferraro [9] and criticized by Alfven [1]. This ongoing debate [see here a discussion by S. Akasofu in *Eos* 84, 22 July, 2003] prompted Singer [63] to look for another mechanism, based on the hypothesis that solar particles might be completely trapped in the earth's magnetic field. He argued that even though a single particle could not enter the trapped region, the collective action by a number of particles might perturb the dipole field sufficiently to permit entry.

Using the perturbation theory developed by Alfvén, Singer then described the motion of these trapped particles in the Earth's dipole field and calculated the azimuthal drift velocity, protons drifting towards the west and electrons towards the east. This drift produces a current which he identified with the Ring Current postulated to account for the main phase of magnetic storms. He further suggested that a small number of these particles might be accelerated through collisions with magneto-hydrodynamic waves, perhaps connected with the observed micro-pulsations of the geomagnetic field, and be accelerated to auroral energies.

3. THE DISCOVERY OF THE RADIATION BELTS

In order to verify the hypothesis of the existence of trapped particles, Singer [64] suggested a specific experiment, to be carried out in the *Farside* vehicle, a four-stage rocket launched at the equator from a high-altitude balloon, and designed to reach an altitude of 4,000 miles. Unfortunately, the single successful flight in November, 1957 did not carry the Geiger counter intended for it, which would have detected trapped radiation one year earlier.

The discovery of geomagnetically trapped radiation was made by Geiger counters in artificial Earth satellites. *Sputnik-2* (November 1957) showed a fairly sharp counting-rate increase starting at 400 km; at 700 km the rate was ~40 percent above the 500 km intensity [81].

For *Explorer-1*, the maximum altitude was high enough to give an unmistakable increase in counting rate (by more than 100 times), which actually blocked the Geiger counter. The correct interpretation of this radiation in terms of trapped particles was given by Van Allen in May, 1958 [78]. In initial papers, the trapped radiation was interpreted as of solar origin and held to be responsible for magnetic storms and aurorae [79]. Differing views concerning the source of energy were put forth by Dessler [14], who assumed local acceleration, and by Gold [25], who assumed that fast particles could be 'conveyed' from the Sun.

4. THE NEUTRON-ALBEDO HYPOTHESIS

However, it seemed difficult to explain the existence of trapped solar radiation so very close to the Earth near the equator [65]. Hence Singer fell back on cosmic rays as a possible injection mechanism, and suggested fast cosmic-ray albedo-neutrons as a likely source for the observed radiation, which he assumed to consist of energetic protons. (The popular acronym given to this source of trapped particle in the magnetosphere is *CRAND*, standing for *Cosmic Ray Albedo Neutron Decay*).

Singer showed that this injection mechanism would give intensities that were in reasonable agreement with the observations. Assuming that the atmospheric density determines the lifetime of trapping, he calculated the expected intensity vs. altitude distribution and also the energy spectrum of the trapped high-energy protons [see Appendix], which result from the decay of the high-energy neutrons [66]. Kellogg investigated the possibility that decay electrons from thermal cosmic-ray albedo neutrons form a portion of the radiation belt [34, 35]. Independently, Vernov et al. [82] suggested cosmic-ray neutrons as a source for the geomagnetically trapped radiation and pointed out also that magnetic scattering would provide a limit on the lifetime at high altitudes. Also independently, N. Christofilos may have made a similar suggestion [unpublished; C. McIlwain, private communication].

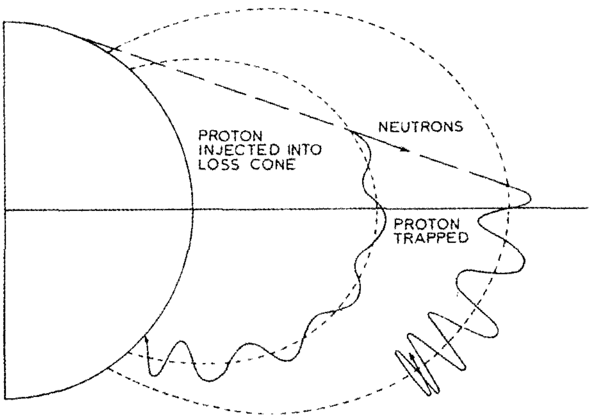

fig. 1. Schematic diagram to illustrate the neutron-albedo theory. The primary cosmic radiation, incident on the earth's upper atmosphere, produces nuclear disintegrations, which emit both energetic protons and neutrons. The energy spectrum of the protons has been measured (e.g. in photographic emulsions carried in balloons). The neutrons are assumed to have a similar energy spectrum. A tiny fraction of neutrons will decay in flight while traversing the Earth's magnetosphere (typical decay rate is 10...13 cm^{-3} sec^{-1}) and release a decay proton of the same kinetic energy. If the released proton is injected into a loss cone it will be immediately lost and not contribute to the trapped radiation flux. Magnetically trapped protons will eventually disappear by energy loss in the Earth's exosphere (typical lifetime is 10^{13} sec).

With the demonstration that cosmic-ray albedo-neutrons could furnish a reasonable radiation belt, Singer [67, 69] in November 1958 explicitly predicted the existence of two separate radiation belts, an inner belt (at 1...2 Earth radii) of cosmic-ray origin and containing penetrating protons, and an outer one mainly of solar origin containing 'soft' particles. Both the *Pioneer-3* rocket and *Lunik-1* observed two distinct belts with maxima at 1.5 and at about 3.4 Earth radii, with a rather pronounced minimum in between [76, 83].

5. THE SPATIAL AND SPECTRAL DISTRIBUTIONS OF TRAPPED RB PARTICLES

The existence of a minimum ('slot') does not by itself indicate separate origins for the two belts. Dessler [15] made the important point that large anomalies of the Earth's field could affect the trapped particle intensity, and Gold [26] held that both belts could be of solar origin with particles drifting inward, and with the slot caused by an instability of the geomagnetic field near a distance of 2 Earth radii. However, an important conclusion concerning the separate origin of the two belts was drawn by Christofilos [10] from the observed fact that electrons, artificially injected by atomic bomb explosions, produced shells whose position did not change with time. He argued that a radial drift of trapped particles is very unlikely, and that therefore the two observed belts are of separate origin.

On the other hand, the decrease in intensity of the inner belt beyond the first maximum may be due to a breakdown of adiabatic invariance of the magnetic moment of trapped high-energy protons; as a further consequence the maximum energy of the trapped protons should decrease with increasing altitude [17, 68, 88].

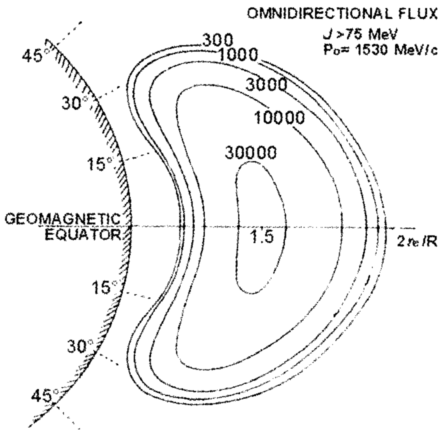

fig. 2. The omni-directional proton flux with energies >75 MeV, as computed from first principles. The figures on the iso-intensity contours are in units of protons-cm^{-2} sec^{-1}. The upper limit to the spectrum is set by the breakdown of adiabatic invariance of the magnetic moment [68]. The atmospheric density model assumes T=1,500 K at 530 km. The shape of these contours seems to depend markedly on the atmospheric model chosen; thus the radiation belt data may be used to give information on exospheric structure. The energy spectrum of the trapped protons can be derived from the energy spectrum of the albedo neutrons (see Appendix).

Intensity contours, approximately kidney-shaped, have been determined for the inner belt by *Explorer IV* [76], and show very clearly the control exercised by the actual geomagnetic field (approximately represented as an eccentric dipole). Intensity contours, more crescent-shaped, have been determined for the outer belt by *Pioneer* and *Lunik* probes [76, 77, 81, 83]. The neutron albedo theory accounts quite well for the spatial distribution of protons in the inner belt [70].

The nature of the trapped particles has been measured with various degrees of refinement. Krassovsky et al. [39, 40], in *Sputnik-3*, identified the bulk of the outer belt particles as low energy (10...50 keV) electrons. Vernov et al. [83] have given their energy spectra as $E^{-5}...E^{-3}$ from measurements in *Lunik-1*. (The pioneering contributions of Acad. Sergey Vernov in space sciences and specially in cosmic-ray physics have been recalled by Panasyuk [58]).

For the inner belt, the most detailed knowledge of the trapped protons comes from photographic emulsion measurements [22]. With more detailed theoretical analyses by Lenchek and Singer [45] one finds good agreement with the spectrum predicted by the neutron albedo theory (see Appendix).

Finally, the inner belt also contains a large flux of low-energy electrons [85]. Only a tiny fraction of them arise from the decay of thermal cosmic-ray albedo neutrons [29]. Quantitative calculations of the energy spectrum and intensity produced by this mechanism [36, 46, 86] do not give good agreement with the observations. Since their magnetic moments are smaller than those of the inner belt protons, these electrons will remain adiabatically trapped to higher radial distances and extend beyond the proton belt. They contribute to the trapped radiation beyond 2 Earth radii. They may even form all of the outer radiation belt, as suggested by Dessler and Karplus [16], who argue this view as against a solar origin for most of the outer-belt electrons.

Cosmic rays from solar flares can also contribute to the trapped radiation through the intermediary of albedo neutrons from the polar cap [3]. This phenomenon has been analyzed by Lenchek and Singer [45], who investigated in particular the peculiar spatial distribution and dynamics of the energy spectrum.

After the early successes of Radiation Belt (RB) and Ring Current (RC) experimental and theoretical studies in the 60s, the interest of the space community shifted toward particles of smaller kinetic energy and magnetospheric plasmas of lower temperatures. It was only in the 90s that the community became again concerned with modeling the RB environment.

6. THE MARCH 24, 1991 EVENT

A revival of interest for the Radiation Belts can be observed in 1988, when McCormack [52] noticed that the NASA models badly failed to predict the energetic particle fluxes which were measured at low altitudes in the late 80s.

The renewal of interest for RB studies has also been prompted by an exceptionally large enhancement of relativistic electron flux, and of energetic proton flux, measured by the *CRRES* satellite deep inside the magnetosphere. These extreme flux enhancements occurred simultaneously following the Sudden Storm Commencement (SSC) of March 24, 1991. By chance, *CRRES* was then in the slot region, when the unexpected injection and acceleration of charged particles suddenly took place.

Electrons were accelerated up to 10 MeV, and protons reached energies larger than 50 MeV. *CRRES* recorded with unprecedented detail the abrupt initial flux enhancement in all energy channels, as well as subsequent drift-echo flux enhancements. The latter correspond to successive revolutions of bunches of energized electrons and protons, drifting in opposite directions around the Earth. The relativistic electrons observed at $L = 2.5$ had been injected at large equatorial distance ($>10R_E$) over a limited range of local times. They were accelerated while surfing deeper into the geomagnetic field, and drifting around the Earth with a period of 3 minutes [5, 80].

The counting rates of these electrons for different energy thresholds are shown in the top panel of fig. 3a. The dawn-dusk component (E_Y) of the electric field, and the northward component (B_z) of the magnetic field perturbation measured by *CRRES*, are shown in the lower panels of fig. 3a.

Such powerful injections of bunched RB particles had never been noticed before. However, in a retrospective search, it was found that similar events had occurred earlier, with smaller magnitudes. Subsequently, similar injections of relativistic electrons at $L<3$ have been recorded following violent storms of February 21, 1994. September 7, 2002; October 29, 2003, but all of them had lower intensities [50, 74].

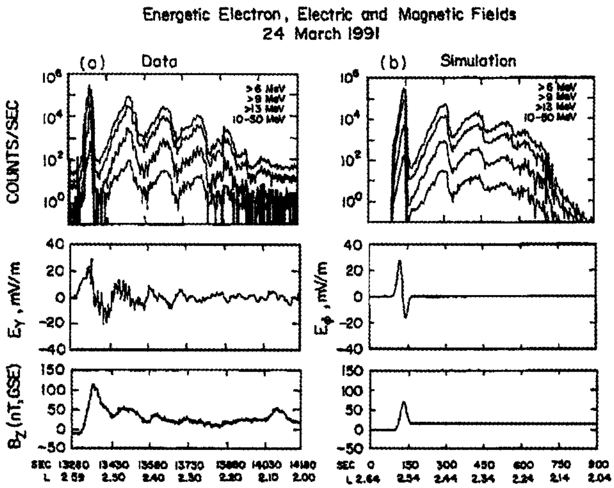

fig. 3. (a) Data from the CRRES satellite at the time of the March 24, 1991, Sudden Storm Commencement. Top panel shows count rates as a function of time from four energetic electron channels [5]. Middle and bottom panels show the measured electric field E_Y in a co-rotating frame of reference, and the B_z magnetic field component with a model magnetic field subtracted, in GSE coordinates over the same time interval [89]. (b) Simulated results in the same format as (a) determined at the same location corresponding to the trajectory of the CRRES satellite, including the *Aerospace* detector responses in the top panels. Time is measured from start of the numerical simulation by Li et al. [47].

The remarkable March, 1991 event definitely lent new momentum to studies of the Radiation Belts and raised the question: what is the mysterious mechanism by which RB particles are accelerated to such high energies?

7. WHAT PHYSICAL MECHANISM ACCELERATES PARTICLES DURING STRONG STORMS?

Detailed analysis of the unique *CRRES* observations, combined with kinetic particle simulations indicated that the acceleration of ambient trapped particles (or untrapped solar flare particles) can be explained by the electric field of a collisionless shock passing through the magnetosphere.

A solar Coronal Mass Ejection (CME) hit the front of the magnetosphere, compressed it, and produced the Sudden Storm Commencement observed on the ground, as well as an enhancement of B_z observed at *CRRES* (see bottom panel of fig. 3a). Solar flare particles were also present at the time of the CME impact.

Starting with an ensemble of 1 to 9 MeV equatorially mirroring electrons, distributed between 3 and 9 R_E, and using an adjusted time-dependent electric field model, Li et al. [47] simulated the motion of over 300,000 test particles in the magnetosphere. The 'adjusted' analytic model of the shock-induced electric pulse is displayed in the mid-panel of fig. 3b, for the position of *CRRES*. The electrons that were in the dayside magnetosphere at the time of the interplanetary shock passage experienced the accelerating electric force during an appreciable portion of their eastward drift path about the Earth. The simulated fluxes of electrons at the positions of *CRRES* are shown in the top panel of fig. 3b for the same energies as in fig. 3a. It can be seen that the flux values obtained with Li et al. [47] kinetic model match very well the experimental results.

Using an almost similar model for the induction electric field pulse, Hudson et al. [31] simulated the rise in the flux of protons drifting westward and inwards onto deeper drift shells. The simulated proton flux increases abruptly by several orders of magnitude on a drift time scale. This was followed by quasi-periodic echo enhancements fitting very well the proton fluxes measured at the positions of CRRES, during the March, 1991 event (not shown).

Equally good results have been obtained by Hudson et al. [32] with MHD test particle simulations, where B-field and E-field pulses are used from MHD models of the magnetosphere induced by the solar wind variations, instead of the 'adjusted' analytic E-field model adopted by Li et al. Other Global-MHD test particle simulations for another geomagnetic storm event have been performed by Kress et al. [41]. They obtain again the formation of a new belt of >10 MeV electrons deep in the magnetosphere. Furthermore, they showed that the pitch angle distribution of the accelerated electrons is first significantly peaked at 90°: i.e. predominantly equatorially mirroring electrons. This initial pancake pitch-angle distribution eventually diffuses as a result of pitch angle scattering due to VLF wave-particle interactions. Kress et al. [41] found a diffusion timescale in agreement with the delay in appearance of peak fluxes of relativistic electrons at the positions of *SAMPEX*, in low Earth orbit.

Using the Li et al. analytic E-field model, Gannon et al. [24] performed a parametric study for the peak location (the L-parameter where the flux is maximum in the new belt) as a function of parameters characterizing the SSC electric-field pulse model. Their parametric study shows that a pulse propagation speed >1,200 km/s is required in the equatorial plane to achieve the flux levels in a new belt, which are comparable to those observed by *CRRES* during the March 1991 storm. Furthermore, they conclude that a pulse peak amplitude >120 mV/m is required to form new electron belts inside $L=3$.

We close this historical review by noting, with Walt [84], that the rather remarkable fit of all these different kinds of simulations leads us to conclude that: 'a most important lesson from the March, 1991 event, is the realization that, even after decades of experimental and theoretical efforts, all important physical processes producing energetic Van Allen belt particles had not yet been described, let alone understood'.

There is still an open question: how the bulk of the ambient electrons can coherently acquire much larger post-storm fluxes and energies, than before recovery phases of geomagnetic storms — and this solely by resonant wave-particle interactions with a wide spectrum of VLF or ULF waves — in spite of the unavoidable presence of random-phase non-resonant wave-particles which tend to increase the entropy of the system, instead of decreasing it.

8. FUTURE PERSPECTIVES

What other surprises and discoveries can we now expect for the coming years? Are we not overlooking other key physical mechanisms: e.g. possible direct entry of Solar Energetic Electrons (SEE) into the geomagnetic field — for instance as the result of lowering of the magnetic barrier separating the inner and outer allowed zones of Störmer's theory, when the IMF turns southward, as shown by Lemaire [43, 44]. Who knows what are the additional physical mechanisms relevant to inject and accelerate RB particles within magnetospheres — that will be examined in the years to come by our descendants?

APPENDIX

Dimensional analysis of the energy spectrum of trapped protons[2].

The equation of continuity describing the particle distribution is

$$\partial n/\partial t = 0 = q(E) - d/dE[n\, dE/dt] - \sigma(E)\, \rho_a\, n\, \beta\, c \qquad (1)$$

where n is the number of protons [cm^{-3} MeV^{-1}] having directions within a unit solid angle, q(E) is the number of protons produced [cm^{-3} MeV^{-1} $ster^{-1}$ sec^{-1}], $\sigma(E)$ is the catastrophic absorption cross section, ρ_a is the averaged density (cm^{-3}) of atmospheric nuclei with the above cross section, βc is the proton velocity. Note that n refers to a particular line of force, labeled by the geocentric distance r_e, and to a particular equatorial pitch angle; we omit the symbols r_e, and μ (=cos α_e), which are implied. The dependence on r_e, and μ is contained in the source term,

2 From Singer and Lenchek, 1962

$$q(E) = j_n^{eff}(r_e, \mu, E)\, \Lambda_n/\gamma\beta c, \qquad (2)$$

Lambda is the decay rate $MeV^{-1}\, cm^{-3}\, ster^{-1}\, sec^{-1}$. [$\Lambda_n$ is inverse of the neutron lifetime]

We have found that the equilibrium energy spectrum of differential intensity is given by a certain integral over the source function. In general, the result is not expressible as a simple power law nor indeed can a closed analytical expression be given. Nevertheless, considerable insight into the understanding of the shape of the spectrum can be gained by a simple dimensional analysis. The analysis proceeds by approximating all functions of energy in the continuity equation (1) by power laws, reducing the equation to an identity and thereby determining approximately, the logarithmic slope of the spectrum. Since the power law approximations for β(E), dE/dx vs. E, etc., are good only over small intervals of energy, the result is valid only over a small interval. However, since in the exact calculation, the source function, q, is a rapidly varying (monotonically decreasing) function of E, most of the contribution to the intensity at E (the lower limit of the integral) comes from q evaluated near E. It is found that the exact result is, in fact, fairly closely approximated by the power-law technique now to be described.

We set all constants equal to unity and write
$j(E) = E^{-v}$, $j_n(E) = E^{-\alpha}$, $\beta = E^b$, $\gamma = (1-\beta^2)^{-1/2} = E^g$, and $\eta = E^{-v}$.

All the exponents, p, α, g, b, v, are functions of energy. For example, for sufficiently low energy b = ½ and g = 0. At energies >> Mc^2 we have b~0 and g~1.

At low energies (~<200 MeV) the effect of nuclear interactions is negligible and the steady-state continuity equation reduces to

$$q(E) = d/dE\, [n\, dE/dt] \qquad (3)$$

With the relations

$n = j/\beta = E^{-p-b}$, $q = \eta j_n/\beta\gamma = E^{-\alpha-b-g-v}$,

and

$dE/dt = k/\beta = E^{-b}$,

we have, upon substitution:

$E^{-\alpha-b-g-v} = E^{-p-2b-1}$

This implies

$p = \alpha + v + g - b - 1 = \alpha + v - 1.5$,

and hence, in the nonrelativistic regime,

$$j(E) \text{ is proportional to } E^{-(\alpha + v - 1.5)} \qquad (4)$$

Since the effective neutron albedo energy spectrum was $\eta(E)\, j_n(E)$ is proportional to $E^{-(\alpha + v)}$ we see that the effect of energy loss is to flatten the spectrum by a power of 1.5 ($\alpha + v > 1.5$).

Conversely, for low energies, we may deduce the albedo spectrum from the equilibrium spectrum; the albedo spectrum is steeper by $E^{-1.5}$.

This is in agreement with the earlier result [66] where an albedo spectrum $E^{-1.8}$ led to an equilibrium velocity spectrum proportional to $\beta^{0.4}$. Note that $\beta^{0.4}d\beta = E^{-0.3}dE$ non-relativistically.

An equilibrium spectrum between $\sim E^{-1.4}$ and $\sim E^{-1.8}$ has been observed between 20 and 100 MeV [3, 30, 57]. These observations imply an effective neutron-albedo spectrum between $\sim E^{-2.9}$ and $\sim E^{-3.3}$.

The values $\alpha = 1.8$, $\nu = 1.1$ used here satisfy this requirement. This emphasizes the importance of some form of modulation of the 'isotropic' neutron spectrum, as by the energy-dependent anisotropy effect contained in $\eta(E)$.

In the limit of 'very high' energy, pure absorption by nuclear interactions applies. The energy at which slowing down can be neglected relative to nuclear interactions is not well defined and depends on the ratio of oxygen to hydrogen in the atmosphere. The 'cross-over energy' may vary from ~300 MeV for a pure oxygen atmosphere to ~900 MeV for a pure hydrogen atmosphere. It is also slightly dependent on the degree of ionization.

If we assume pure absorption, with a cross section independent of energy, then neglecting energy loss, the continuity equation is simply

$$q = \sigma \rho_b j \qquad (5)$$

Therefore $E^{-\alpha-\nu-b-g} = E^{-p}$ or $p = \alpha + \nu + b + g$

For $E >> Mc^2$ we have $b \sim 0$ and $g \sim 1$. For $E \sim Mc^2$ we find $b + g \sim 0.5$.

Since $b + g$ is always positive, we see that the effect of nuclear interactions is to steepen the spectrum.

One outcome of such a dimensional analysis is the conclusion that, relative to the effective albedo spectrum, the equilibrium spectrum of the trapped protons is flatter by ~1.5 in the power law exponent at E ~<200 MeV and is steeper by ~0.5 in the exponent at E ~1 GeV; thus the equilibrium spectrum does not follow a single power over the entire range 10...1000 MeV. The observations show in fact a spectrum whose power steepens continuously at increasing energies [3, 22].

The effective neutron albedo spectrum $E^{-2.9}$ thus leads to an equilibrium spectrum asymptotic to $E^{-1.4}$ at E ~50MeV, and steepens continuously to $E^{-3.4}$ at ~1 GeV. The observed spectra have an exponent of 1.4 to 1.8 in the range 20 to 100 MeV and agree very well with the calculated slope at the higher energies.

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