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THE NATURE OF CORPUSCULAR RADIATION IN THE UPPER ATMOSPHERE (USSR)

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Summary

On the basis of an analysis of the space distribution of "earth corona" belts, it is possible to draw a number of conclusions concerning the mechanism of generation and "leakage (or dissipation)" of hard particles (corpuscles). It was shown that the concentration of particles in the solar corpuscular stream is sufficiently high to effect a renewal of particles in the external belt during a period of approximately several hours. The energy distribution of protons and the velocity of generation of hard particles in the internal belt were calculated on the basis of the decay mechanism of neutrons formed in stars, taking into account the moderation of these neutrons during their diffusion through the atmosphere. It was shown that the recording of hard charged corpuscular components of nuclear explosions clearly distorts, for a certain period of time, measurements of the intensity of corpuscular radiation in the "earth corona", particularly in the high energy region.

Research conducted with the aid of Soviet and American artificial earth satellites resulted in the discovery of a region of intensive corpuscular radiation, starting at an altitude of 400-600 km (1-4). On the basis of recent results, obtained with the aid of cosmic rockets, it was possible to obtain a picture of the space distribution of the intensity of the hard corpuscular radiation surrounding the earth (5,6). At the same time, it was discovered that two "belts" of corpuscular radiation are present. The first, or internal, belt is an equatorial ring limited (approximately) by the geomagnetic latitudes $\pm 40^{\circ}$ (according to [6], the width of this belt is somewhat smaller), with a maximum concentration at an altitude of approximately 3,000 km (above the geomagnetic equator). The second, or external, belt extends to a distance of up to 6-8 earth radii, and the maximum concentration of particles in this belt is located at a distance of 3.5-4 earth radii R_E. It is interesting to note the presence of characteristic "tongues" in the space distribution of particles in the external belt, which stretch out towards the area of maximum occurrence of Northern lights (aurora polaris). An important factor is that the hardness of particles in the internal belt is greater than in the external belt (1,4).

In order to provide an explanation for the cloud of fast charged particles surrounding the earth (this phenomenon will be further designated by us under the name of "earth corona"), a number of authors have advanced an hypothesis involving a decay of albedo neutrons, followed by a capture of the protons and electrons formed in this manner by the magnetic trap of the earth (7-9). However, in our opinion, the analysis of the space distribution of particles in both belts of the earth corona makes it impossible to explain the formation of the external belt as being due to the decay of albedo neutrons. Indeed, the presence of an equatorial belt means that the particles forming this belt "avoid" moderate and high geomagnetic latitudes. Apparently, this results from the fact that geomagnetic disturbances and Northern lights occurring at higher latitudes appear to "shake out" particles from the internal belt, thereby preventing the accumulation of particles in this belt. This means, however, that the equatorial belt is replenished with particles coming only from below, from the lower layers of the earth's atmosphere.

On the contrary, the space distribution of particles in the external belt clearly indicates that these particles are replenished from an extraterrestrial source. The particles produced by this source are apparently unable to reach relatively low altitudes. On the other hand, particles in the external belt, located in the magnetic trap at a distance of 3.5-4 R_E, will accumulate in this trap during a longer period of time than at a distance of 5-6 R_E, since the frequency and amplitude of geomagnetic disturbances at 50-60° latitudes (reached by lines of force bisecting the plane of the equator at a distance of 3.5-4 R_E) are many times lower than in areas of maximum occurrence of Northern lights. This fact precisely explains the observed position of the maximum particle concentration in the external belt. The different origin of particles in both belts is also expressed in their different hardness. Thus, on the basis of an analysis of the space distribution of particles in the earth corona, it is possible to draw the conclusion that geomagnetic disturbances and Northern lights connected with these disturbances constitute the principal reason for the "leakage" of particles in the external (and also apparently in the internal) zone. Naturally, in case of the internal belt, we can only be concerned with Northern lights occurring at low altitudes, which are rather rare.

During geomagnetic disturbances, the regular nature of the field at high altitudes becomes disturbed, and particles imprisoned up to that time in the trap can escape both into interplanetary space and downwards into desner layers of the earth's atmosphere, thus causing the phenomenon known as Northern lights. The escape of particles from the trap into lower layers is connected with a derangement of the conditions governing the applicability of the adiabatic invariant. The main reason for this derangement, in our opinion, is the following one. If, at the time the solar particles penetrate into the earth's atmosphere, the energy density of the particles in the upper atmospheric layers will become approximately equal to the energy density of the magnetic field of the earth, the actual concept of the movement of a charged particle in a given external magnetic field (leading to the adiabatic invariant) loses all its meaning. A similar situation arises in case of a rapid "vibration" of magnetic lines of force. In this case, the magnetic moment of certain particles at high altitudes can undergo a substantial increase. Such particles will then be able to penetrate into regions of relatively greater magnetic intensity. Since each particle vibrates along the lines of force with a sufficiently high frequency, there will be a considerable probability for such a favorable reorientation of its velocity vector into upper atmospheric regions, where the terrestrial magnetic field is strongly deformed by solar corpuscular streams.

Another fact must also be considered, namely that the "stockpile" of particles held in the trap of the external belt is small in comparison with the number of solar particles which, during the period of geomagnetic disturbances, travel through an area equal in size to the effective cross section area of the terrestrial magnetic field. It is doubtful that the maximum concentration of particles in the external belt exceeds $\sim 10\ cm^{-3}$, if we assume that the average energy of each particle $\bar{\varepsilon} \sim 10^4$ ev. If this were not the case, the energy density of particles in the earth corona would be greater than the energy density of the terrestrial magnetic field at corresponding distances. In case the average energy of particles is greater than 10^4ev, the maximum permissible concentration of such particles would be even smaller. In view of the fact that the field of the earth, in case $R \lesssim (4-6)R_E$, retains its dipole nature in the first approximation (which is apparent already from the fact that an external belt is present and from the nature of the relative distribution of particles in this belt), the upper limit of the particle concentration must be even smaller. The effective volume of the external belt, according to data published in (5,6), can be estimated as being equal to $\sim 10^{29}$ cu.cm. Consequently, we can assume that the maximum number of particles in this belt is equal to $N \sim 3.10^{29}$. If $\bar{\varepsilon} \sim 10^3$ev (which is quite probable), then $N \sim 3.10^{30}$.

On the other hand, even in case of a weak disturbance, the stream of solar particles near the earth is equal to $\sim 10^7$ $cm^{-2} \cdot sec^{-1}$, which corresponds to a concentration of solar particles near the earth of (0.1-1) cm^{-3}. Assuming that the effective cross section area of the terrestrial field is equal to $\sim 10^{20}$ cm^2, we find that the external belt can be filled with solar particles in approximately 1 hour even during a weak disturbance. Therefore, it is clear that the dynamic equilibrium of the external belt is determined by the interaction of solar corpuscular streams, apparently carrying along with them a frozen-in magnetic field, with the magnetic field of the earth. At the same time, the solar particles undergo a complex process involving a redistribution of energy between their proton and electron components. Simultaneously, a certain portion of these particles is accelerated, so that their energy becomes considerably greater than the mean energy of particles present in the original solar stream. At the same time, the original energy level of the bulk of these particles is apparently somewhat reduced. A portion of the particles is reflected back into interplanetary space, and another portion is caught in the trap of the terrestrial magnetic field, where it remains until the next more or less strong magnetic disturbance.

It becomes evident that the bulk of the particles present in the external belt must possess relatively low energies lying within a range of 1-10 kev. It is necessary to conduct an experimental study of particles lying within this energy range and present in the external belt region. At the same time, the problem concerning the proton component of the external belt also assumes a great significance. It can be assumed that the number of protons with an energy ranging from several hundred to several thousand electron-volts(ev) present in the external belt must be at least equal to the number of electrons present in this belt.

The fact that the internal equatorial belt is clearly separated in space from the external belt constitutes a serious argument in favor of the assumption that both belts of the earth corona have a different origin. The process involving the decay of albedo neutrons may play a significant role in the formation of the external belt. At present, an unambiguous identification of particles recorded in the internal belt cannot be made on the basis of available experimental data(6). These particles may either consist of protons with an energy of several score megaelectron-volts (mev), or electrons with an energy of several mev, or finally, electrons with an energy of several hundred kilo-electron-volts (kev), which, upon hitting the body of a rocket or a satellite, give rise to X-ray radiation, which could have been recorded by the counters used in these particular measurements. If the presence of protons with an energy of several score mev and a very highly slanted energy spectrum is established in the internal belt, it will be difficult to explain their origin as being due to any other type of mechanism, except the one involving a decay of albedo neutrons. On the other hand, electrons with $E > 782$ kev (limit of the beta-spectrum) should be practically absent in this case; and this fact can also be used in checking the hypothesis concerning the decay of albedo neutrons. In calculating the generation of charged particles occurring during the decay of albedo neutrons, some authors(7-9) gave an extremely rough picture of the process involving the exit of neutrons from the atmosphere. No analysis whatsoever is made in studies (7) and (9) concerning the moderation of neutrons in the atmosphere during their diffusion upwards. In study (8), this analysis was conducted in an unsatisfactory manner, since the diffusion occurring along the average absorption distance L was calculated for an area, the depth of which $t \ll L$, and the moderation of neutrons formed in stars was not taken into account. We will show that it is impossible to obtain reliable quantitative estimates of this mechanism in the low energy region without performing an analysis of the moderation occurring during diffusion.

We shall assume that neutrons arise in stars, the atmospheric distribution of which, in proportion to an increase in the depth t (calculated from top to bottom in g/sq.cm.), remains approximately constant up to $\sim$ 100 g/sq.cm. and is equal to $N_0 \simeq 10^{-2}$ stars/sec.g, and then drops according to the law $N_0 \exp(-\frac{t}{80 \text{ g/sq.cm.}})$ [10,p.316.]
The $n(E_0)$ energy distribution of neutrons "evaporated" in the star is an approximately Maxwellian distribution, with a maximum near 2-6 mev (10,p.40), (11), while the directional distribution is approximately isotropic. On the average, the number of evaporated neutrons per star is equal to 3.5. The effective cross section of inelastic collisions of neutrons, having an energy $E > 2.3$ mev, with nitrogen nuclei, is not high, and such collisions can usually be disregarded (12,p.547), (13, p.5.). When $E < 2.3$ mev, only elastic collisions will take place. Let us calculate the mean quadratic distance $\langle x^2(E_0,E)\rangle^{\frac{1}{2}}_{mean}$ along one coordinate from a flat source with an initial energy E_0 to a neutron moderated to an energy E. According to (12,13):

$$\langle x^2(E_0, E)\rangle_{mean} = 5.2 \int_{E_0}^{E} l^2(E) \frac{dE}{E}$$

where l is the length of the free path in air, determined on the basis of the effective cross section values published in (14). Calculations were performed for a number of values of E_0 = 0.5; 2; 4;6;8;10; and 15 mev. A rate of contribution of neutrons with a given initial energy was taken into account, which corresponded to a form of Maxwell distribution. For each initial energy E_0, it is possible to find such a depth t_0, from which, during the process of diffusion of the neutron upwards through the bulk of the atmosphere, the energy of the neutron drops below $\sim$ 0.3 ev, which corresponds to $\sim$8 km/sec (first cosmic velocity). As was shown in article (15), the true absorption of neutrons can be disregarded until the energy reaches this value. Neutrons with a smaller energy will be unable to rise to a sufficiently great altitude in the atmosphere. We shall assume that all neutrons which have evaporated above the depth t_0 with a velocity directed upwards are leaving the atmosphere. Let us assume that the number of such neutrons is equal to 0.1 of the total number of neutrons evaporated in the star; actually, this fraction may differ 2-3 times from the assumed figure. We shall assume that the number of stars N_0 neutrons/g.sec. formed per second is independent of the depth, which, in case of the depths $t \leqslant 150$ g/sq.cm. of interest to us, will not result in noticeable errors. At the same time, the number of albedo neutrons formed over a surface of 1 sq. cm will be equal to:

$$N_0 \cdot 3.5 \cdot 0.1 \cdot n(E_0)dE_0 \simeq 3 \cdot 10^{-3} n(E_0)dE_0 \text{ neutrons g/sec.}$$

During the diffusion of neutrons, formed at a certain depth t, through the atmosphere, their spectrum will vary, whereby the fraction of energy-carrying neutrons which have left the atmosphere n(E)EdE is proportional in the interval EdE to:

$$EdE \int_{0.3 \text{ mev}}^{15 \text{ mev}} \frac{d \langle x^2(E_0, E) \rangle_{mean}^{\frac{1}{2}}}{d \ln E} n(E_0)dE_0$$

The fraction of neutrons with an energy $E > 2$ mev may be somewhat exaggerated (i.e. higher than it should be) in view of the fact that inelastic collisions were disregarded.

Results of the calculation of the distribution (spectrum) of neutrons leaving the atmosphere are shown in the following table (column 3).

Table

Energy Range, ev	k	Albedo Neutron Flux, sq.cm.sec^{-1}	Number of Decays in Belt Over a Unit Area, cm^{-2}.sec^{-1}
0.3 - 1	0.36	$2.3 . 10^{-3}$	$0.83 . 10^{-3}$
1 - 10	0.24	4.6	1.10
$10^1 - 10^2$	0.11	5.1	0.56
$10^2 - 10^3$	0.035	7.4	0.26
$10^3 - 10^4$	0.012	12.8	0.15
$10^4 - 10^5$	$3.5 . 10^{-3}$	53.0	0.18
$10^5 - 10^6$	$1.2 . 10^{-3}$	137	0.16
$10^6 - 10^7$	$3.5 . 10^{-4}$	143	0.05
$10^7 - 10^8$	$1.2 . 10^{-4}$	20	0.02
Total		$3.8 . 10^{-1}$	$3.3 . 10^{-3}$

The fraction of neutrons with a velocity v, undergoing decay in the internal belt, the upper limit of which in the equator plane will be assumed by us as being equal to $1R_E$, will be proportional to:

$$K = \exp\left(-\frac{1R_E}{tv}\right)\frac{1R_E}{tv}$$

where t=770 sec.

The internal belt can also be replenished as a result of the decay of neutrons formed in the course of other interaction processes, of cosmic rays with the atmosphere, besides interaction with stars, and also as a result of the decay of unstable neutral particles, for example mesons. A certain fraction may also be contributed by neutrons with a higher energy level(8).

Thus, as a result of the decay of albedo neutrons "retarded" in the earth's atmosphere, the internal belt is supplied with a total of approximately 2.10^{16} electrons per second, having an energy of the order of several hundred kev. In addition to such electrons, this belt will also be supplied with protons having approximately the same energy as the corresponding albedo neutrons; however, the time during which these protons will be accumulating in the belt will be relatively short. The number of such protons with an energy $E > 30$ mev, arising each second in the internal belt, and which could have been recorded with the aid of the counters used in studying the internal belt, is approximately equal-to $1.5.10^{14}$, i.e. is equal to less than 1% of the number of electrons with an energy of several hundred kev. However, the probability that the Geiger counters used in this particular case could record a proton with such an energy is close to unity. At the same time, electrons with the above energy were absorbed by a jacket of $\sim$ 1 g/sq.cm, and only the arising X-ray bremsstrahlung was recorded by the Geiger counter. In view of the fact, however, that the probability of the appearance of a retarding X-ray quantum is approximately equal to 1%, the counting efficiences of protons and electrons achieved by means of the counters used in study (7) are apparently comparable.

Another source capable of supplying particles to the internal belt, which is considerably more powerful than the decay of albedo neutrons, might be mentioned. A recent communication stated that, during the nuclear explosion conducted on 1 August 1958 over the Johnston atoll at an altitude of about 160 km, an aurora polaris was observed at Apia (on Samoa Island) at a distance of about 3,500 km from the explosion site (16,17). The fact that both the explosion and observation points are located approximately on the same magnetic meridian indicates that the charged particles formed in the explosion (specifically, beta-decay electrons), which gave rise to the artificial aurora polaris, were moving along lines of force running above the magnetic equator at altitudes of 500-1,000 km. For example, the minimum number of electrons which were formed and left the explosion area can be estimated in the following manner. From the description of the observations (16), it follows that the effective surface of the area covered by the aurora polaris was equal to $\sim 10^{15}$ sq.cm. Let us assume that the artificial aurora polaris had an intensity mark(rate) of 4. Actually, it was apparently brighter, since the purple light of the glow could be clearly detected under bright moonlight(a glow rate of 1 can be hardly discerned against the bright background of the night sky). In case of a glow rate of 4, the energy flux is of the order of 10 erg/sq.cm.sec. Assuming that the average energy of the particles which gave rise to the aurora polaris is approximately equal to 1 mev, we find that the flux of such particles is approximately equal to 10^7 $cm^{-2}.sec^{-1}$. At the same time, during the time that the aurora polaris was in effect, a total of 4.10^{24} particles travelled through the entire area of glow. In view of the fact that the artificial aurora polaris lasted for 6-7 minutes, and that a weaker glow was then observed for another 10-15 minutes (16), it follows that the beta-decay of particles formed during the explosion also took place when these particles reached a high altitude. At the same time, a certain number of beta-electrons might have been endowed with initial velocities in a direction which was almost perpendicular to the direction of the lines of force. Such electrons landed in the magnetic trap, thereby replenishing the internal belt. Since during the process of expansion and diffusion of radioactive explosion products, these electrons were able to rise to a considerable altitude above the center of the explosion, a portion of the beta-electrons formed was able to travel at a higher altitude than 500-1,000 km(above the magnetic equator). At such high altitudes, the beta-electrons located in the trap are capable of remaining there for a considerably longer time than at lower altitudes. It can be estimated that during the explosion of 1 August 1958 at least 10^{23} electrons were captured in the magnetic trap, of which about 10% were located at altitudes of 2,000-3,000 km. In case the explosion occurred at a higher altitude and at higher latitudes, the percentage of beta-electrons captured by the magnetic trap of the internal belt was somewhat higher.

A vertical gradient of the magnetic field will cause a drift of electrons in an eastern direction having a velocity of:

$$W_D = \frac{1}{w_c R} \left(\tfrac{1}{2}W_{\perp}^2 + W^2\right)$$

where w_c is the Larmor frequency, R is the curvature radius of a line of force (18). In case of electrons with an energy of about 1 mev, W_D is equal to approximately 10^6 cm/sec; for this reason, after a period of time of about 1-10 hours (depending upon the latitude and altitude), the electrons captured in the magnetic trap "will flow out" along magnetic parallels, thereby forming an equatorial belt.

Thus, one high-altitude nuclear explosion can place in the equatorial belt as many hard particles as are released by the decay of albedo neutrons taking place over a period of about 10^6-10^7 seconds. Several explosions of this type can fill up the equatorial belt with the observed number of hard particles. It should be noted that the presence of a small number of positrons, formed in the course of specific beta-decays, can be expected among the hard particles present in the equatorial belt.

Another source supplying hard particles to the earth corona might also be mentioned. During normal (i.e. non high-altitude) nuclear explosions, fission products emit so-called "delayed" neutrons. According to estimates made in (19,20), 6.10^{-4} 56-second and $1.5.10^{-2}$ 22-second delayed neutrons are formed during each fission of U-238. During a period of time of about 1 minute, the cloud formed after an explosion "rises" to an altitude of about 10 km. Since the range of delayed neutrons in the atmosphere (under normal conditions) is approximately equal to 250 m, a certain fraction of these neutrons will leave the atmosphere. During the decay of these neutrons, electrons with an energy of about 0.5 mev will be formed in the magnetic field of the earth, whereby a portion of these electrons will land in the trap.

As was reported in (21), during the course of 1958 (i.e. at a time when observations of the hard corpuscular radiation belt were performed), the US conducted a series of experimental nuclear explosions surpassing in intensity the series of tests conducted previously. Thus, for example, during the period of 28 April to 26 July, the US exploded 32 bombs in the Pacific Ocean region alone, many of which were high-power bombs. As a result of these explosions, the level of hard corpuscular radiation in the internal belt, and also probably in the external belt, was no doubt considerably increased. Thus, it is quite possible that, during powerful nuclear blasts, a contamination of the hard portion of the energy spectrum of particles takes place in the internal belt, which is due to the decay of delayed neutrons and radioactive products rising above the site of the blast. This fact makes it difficult to study the intensity of particles formed by cosmic rays.

The relative role played by albedo neutrons and products resulting from nuclear blasts during the formation of an equatorial belt depends to a considerable extent on the time of accumulation of the particles supplied to the trap. If this time is sufficiently long, then albedo neutrons, as a constantly operating factor, play a major role. If one assumes, on the other hand, that geomagnetic disturbances act as the trap-destroying mechanism, then the time during which the equatorial belt is replenished must be considerably shorter than 1 year, and is most likely equal to about 1 month. For example, in 1958, several aurora polaris were recorded at low latitudes, several of which had a very high intensity (for example, on 10-11 February 1958).

Thus, there are two main sources capable of replenishing the equatorial belt with particles, namely a constant source and a variable source. The first source is the decay of albedo neutrons, and primarily of neutrons with a relatively low energy. During a time of approximately 10^6-10^7 seconds (the probable time of replenishment of the belt), this mechanism can supply about 2.10^{22}-2.10^{23} electrons with an energy of up to 780 kev and 10^{20}-10^{21} protons with an energy of over 30 mev. These figures may be compared with the number of hard particles observed in the equatorial belt. According to (6), the maximum intensity of particles recorded by counters is equal to $J \approx 2.10^3$ $cm^{-2}.sec^{-1}str^{-1}$ (Translator's Note: The abbreviation "str." above is not clear; it could stand for "strelka", meaning the pointer, indicator or hand of a counter device; or for "strochka", meaning line). In case of an isotropic field of corpuscular radiation, the concentration of these particles will be equal to:

$$n = 4\pi J/v$$

where v is the particle velocity. If we assume that X-ray quanta were recorded, having an energy of the order of several hundred kev and arising during the bombardment of a rocket body with electrons having the same energy, and if we further assume that the efficiency of such a process is approximately equal to 1%, then we find that $n_{e\,max} \simeq 10^{-4}$ cm^{-3}, while the total number of such quanta in the internal belt is approximately equal to 10^{23}. If one assumes that counters were able to record protons with an energy greater than 30 mev, then the maximum concentration of these protons in the internal belt will be equal to $\simeq 3.10^{-6}$ cm^{-3}, and their total number will be equal to $\simeq 3.10^{21}$. Thus, even the decay of albedo neutrons may be able to supply the observed recorded number of hard particles, if the time of their accumulation is of the order of 5.10^{6} seconds.

In addition, there is a variable source of hard particles, namely the products resulting from nuclear blasts, which at times may significantly increase the intensity of hard corpuscular radiation in the equatorial belt. The lithium resonance line λ 6708 Å, which was recently discovered in the twilight spectrum (22,23), constitutes an indirect indicator of the contamination of the upper atmosphere with nuclear blast products. The intensity of this line is subject to considerable variations. In addition to nuclear blasts, cosmic rays could act as a source of lithium in the earth's atmosphere. A similar problem, concerning the presence of the light helium isotope He-3 in the atmosphere, formed the subject of frequent discussions in the literature. However, even without a quantitative calculation, we might mention that a mechanism connected with cosmic rays can hardly be used as an explanation for the observed strong variations in the intensity of λ 6708 Å.

It would be very desirable to conduct further experiments, which would allow a more precise identification and determination of the energy distribution of particles in the equatorial belt, and which would also allow to determine the time of replenishment of this belt.

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