ENERGY DEPOSITION OF CORPUSCULAR RADIATION IN THE MIDDLE ATMOSPHERE

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INTRODUCTION

Main components of corpuscular radiation contributing to energy deposition (ED in eV $cm^{-3}s^{-1}$) in the atmosphere (10-100 km) are cosmic ray nuclei (CR - galactic and solar) and high energy electrons (HEE), mainly of magnetospheric origin.

COSMIC RAY INTERACTION IN ATMOSPHERE

Two types of interactions with nuclei of air constituents are important: inelastic nuclear interactions and Coulomb collisions. Figure 1 shows the energy losses dE/dx, range h (in height scale) and probability of inelastic nuclear interaction for proton in air (nuclear data from JANNI, 1982).

Nuclear interactions lead to the decrease of initial CR flux due to fragmentation of nuclei and to the creation of "new" corpuscular particles and electromagnetic radiation. Above 50 km ($\sim$ 1 g cm^{-2}) less than 0.2 % protons, 5 % He and 20% of Fe nuclei had their first nuclear interaction. This fraction increases with decrease of h, and below $\sim$50 km nuclear interactions must be included for ED calculations.

Relations between the parent CR nuclei and their secondary products, which again undergo nuclear interactions, coulomb collisions and decay, are complicated. In DATTA et al. (1987) it is recognized that gamma rays constitute the resultant component from different decay channels. From the knowledge of γ-ray profile and absorption coefficient of γ-rays in atmosphere, the ion production rate (PR = ED/35(eV)) was predicted which for middle latitude gave good agreement with direct PR measurement below 20 km. Figure 2 illustrates profile of PR down to 10 km. For low latitudes the main sources of PR variability are atmospheric density variations (e.g. seasonal).

The coulomb collisions of CR nuclei in atmosphere lead to direct ionization. The mean relative ionization energy loss, dE/dx, is given by Bethe-Bloch formula (BBF). VELINOV et al. (1974) used BBF for PR computations of CR above 50 km where coulomb collisions are dominant. Figure 3 shows profiles of PR. Due to Z^2 dependence in dE/dx, heavy CR nuclei contribute significantly to the total PR by ionization: CR protons being 86% of CR population give 30% of PR while nuclei Z $\geq$26 (only 1.15% of CR) give 51.5% of total production. For estimation of PR by CR Figure 1 may be used.

Three main factors control the ED of CR (not assuming meteorological variations): geomagnetic filter, modulation effects of CR in heliosphere and solar CR impact.

First of them leads to the latitudinal (λ_m) variations of ED profiles. In real magnetic field, according to trajectory calculation, the approximation $R = 16.237\ L^{-2.0359}$, L being McIlwan's parameter and R_c - rigidity of particle (R = p/Ze), gives realistic estimate of vertical effective cut-off rigidity (SHEA et al., 1987). This approach does not include fine structure of forbidden and allowed trajectories around R_c and non-vertical directions. R_c is changing during geomagnetic storms. The approach to this problem is in (FLUCKIGER et al., 1986). The simplified estimates for D_{st} = 200 nT give for λ_m = 55° variation in PR $\delta q/q \cong 50\%$ and for λ_m = 40° $\delta q/q$ = 20-25 %.

Modulation of CR in solar cycle is the cause of ED variations by CR at higher latitudes. Charge state of anomalous CR oxygen (up to 30 MeV/n) is now established to be O^{+1} (McDONALD et al., 1988); BISWAS et al., 1988), thus its rigidity is rather high. At $\lambda_m \cong 44°$ the PR at h ≥ 50 km may be affected by this CR component being strongly dependent on solar-cycle phase. These ions can be stripped by residual atmosphere and become stably trapped (BLAKE, 1988).

Variety of solar flare particle energy spectra, composition, angular distribution and temporal profile near the Earth may lead to changes in ED of CR at higher latitudes, which could be significant for 40-90 km.

HIGH ENERGY ELECTRON DEPOSITION

For electrons both angular scattering and energy losses should be included in calculation of ED in atmosphere (WALT, 1968). Scattering on orbital electrons is small in comparison with that on the nucleus, however interactions with orbital electrons are important for energy losses. The angular diffusion leads to large straggling of penetration depth reached by individual electrons. Calculation of electron ED is possible only by numerical methods. For estimation Figure 4 show dependence of stopping-power (both collision - ionization S_{col}, and radiative S_{rad}) and range for electrons h (taken from BERGER and SELTZER, 1983). The concept of range for electron is different from that of protons and it can be used only for rough estimates. The relative fraction of radiative losses increases with energy (bremsstrahlung - BS). BS photons deposite the energy by photoeffect and Compton scattering. For spectra $\alpha^{-1}\exp(-E/\alpha)$, the altitude profile of ED in atmosphere is on Figure 5 (taken from BERGER et al.,1974). ED by monoenergetic electrons was examined in (REES, 1963) giving estimate that only E_e > 30 keV are important below 100 km.

BS of electrons, treated theoretically in (WALT et al., 1979; SELTZER and BERGER, 1974), is used for remote sensing of electron precipitation from satellites (IMHOF, 1981, IMHOF et al., 1982a, IMHOF et al, 1982b), local measurements of balloons (MATTHAEUS et al., 1988) and rockets (SHELDON et al., 1988).

VAMPOLA and GORNEY (1983) used spectra of locally precipitating electrons 36-317 keV to calculate ED profiles. Power-law approximation in spectra yields in two maxima: the main at 70-90 km, where ED is comparable with ED by solar Hα on day side while on night side the ionization by electrons is dominating, and secondary peak ∼40 km due to BS. During meagnetospheric substorms the electron precipitation pattern is drastically changing both temporally and in local time (e.g. GOTSELYUK et al., 1986; GOTSELYUK et al., 1988). Global distribution of electrons E > 30 keV at low altitudes revealed connection of additional precipitation zones with man-made activity (GRIGORYAN et al., 1981). Detailed global distribution of HEE was studied on OHZORA satellite (NAGATA et al., 1987).

Measurements with good energy resolution showed the "finer structure" of electron precipitation. Preferentially on the night side, electrons with hard spectra (α = 500 keV) precipitate in narrow range of L near plasmapause contributing thus significantly to ED at 70-90 km (IMHOF et al.,1986). Electron spectra in inner belt (L = 1.2 - 2.0) exhibit strong peaks at 50-500 keV (DATLOWE et al., 1985). Thus profile of ED in middle atmosphere, especially in south atlantic anomaly (SAA), could have complicated form.

Narrow peaks in precipitating electron spectra 68-1120 keV within drift-loss cone produced by VLF transmitters in inner zone are reported in (IMHOF, 1981b). Similar conclusion in 36-317 keV at outer edge of inner zone is in (VAMPOLA, 1983). Later study (VAMPOLA and ADAMS, 1988) revealed importance of VLF transmitters for HEE precipitation in inner zone, in the slot and outer zone. Theoretical approach assuming gyroresonant pitch-angle scattering of electrons with waves both near equator as well as at low altitudes is well developed now (INAN, 1987; NEUBERT et al., 1987). An attempt to measure stimulated precipitation of HEE by powerful LF wave emitted from satellite is one of the objectives for Aktivny satellite-subsatellite experiment (SCHEVCHENKO, 1988; TŘÍSKA et al, 1988). Resonance conditions of measured electrons (20-600 keV) give for f = 10 kHz the possible precipitation at L < 3 within the drift loss cone near the bounce loss cone boundary (KUDELA, 1989).

Trapped electrons at geostationary orbit up to E > 10 MeV are present and their intensity is associated with solar cycle activity (BAKER et al., 1986). While auroral electron precipitation is located in narrow interval (around λ_m = 70°) and may cause ED increase above 100 km, very HEE can deposite energy at lower heights and in broad latitude range. BAKER et al. (1987) found significant enhancement of PR at 40-80 km, well above both CR and extreme UV ED. This electron population could be important in coupling SW-magnetosphere variability to the middle atmosphere. Compilation of PR in middle atmosphere by different measurements is presented on Figure 6.

In SAA electrons even with higher energies (E > 100 MeV), apparently not connected with above population, have significant flux (GUSEV et al., 1983) and can conttribute to PR below 40 km. Radiative losses are important for them, too. Penetration of electrons from interplanetary space to high latitudes was studied by McDIARMID et al., (1975) and such HEE were used as a sounding tool for magnetospheric boundary changes and their connection with IMF and SW parameters (KUZNETSOV et al, 1987; KUZNETSOV et al, 1988). Their latitudinal extent is in some cases down to λ_m = 62° and their flux (10^5 $cm^{-2}s^{-1}ster^{-1}$ for E $\gtrsim$ 30 keV) could contribute to enhanced PR at 90 km.

SUMMARY

Galactic CR depending on solar-cycle phase and latitude are dominant source of ED by corpuscular radiation below 50-60 km. Below 20 km secondaries must be assumed. More accurate treatment need assuming of individual HE solar flare particles, cut-off rigidities in geomagnetic field and their changes during magnetospheric disturbances.

Electrons E > 30 keV of magnetospheric origin penetrating to atmosphere contribute to PR below 100 km especially on night side. High temporal variability, local-time dependence and complicated energy spectra lead to complicated structure of electron ED rate. Electrons of MeV energy found at geostationary orbit, pronouncing relation to solar and geomagnetic activity, cause maximum ED at 40-60 km.

Monitoring the global distribution of ED by corpuscular radiation in middle atmosphere need continuing low altitude satellite measurements of both HEE and X-ray BS from atmosphere as well as measurements of energy spectra and charge composition of HE solar flare particles.

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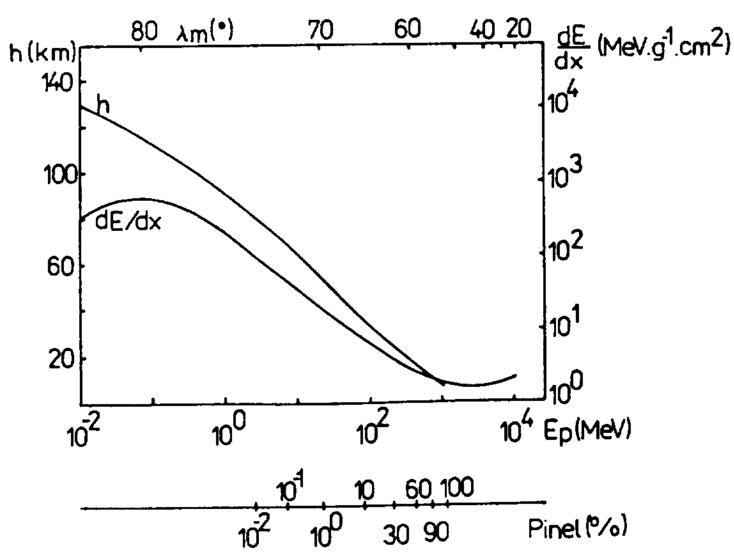

Fig. 1 Energy losses of protons.

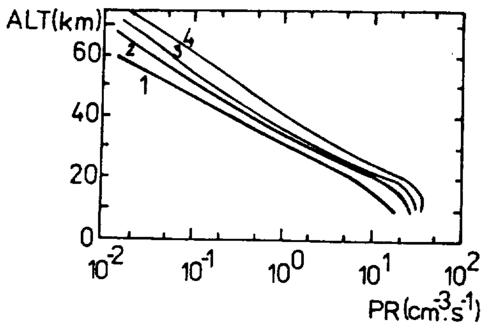

Fig. 2 1, 2 - seasonal variation at 30°; 3, 4 - sol-max, sol-min for 55° (compiled from DATTA et al., 1987).

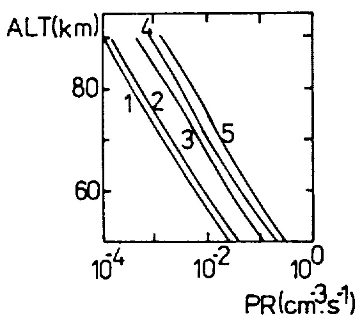

Fig. 3 1, 2 - 0° (sol-max, summer and sol-min winter); 3, 4, 5 - 55° (max summer, max winter, min winter) (from VELINOV et al., 1974).

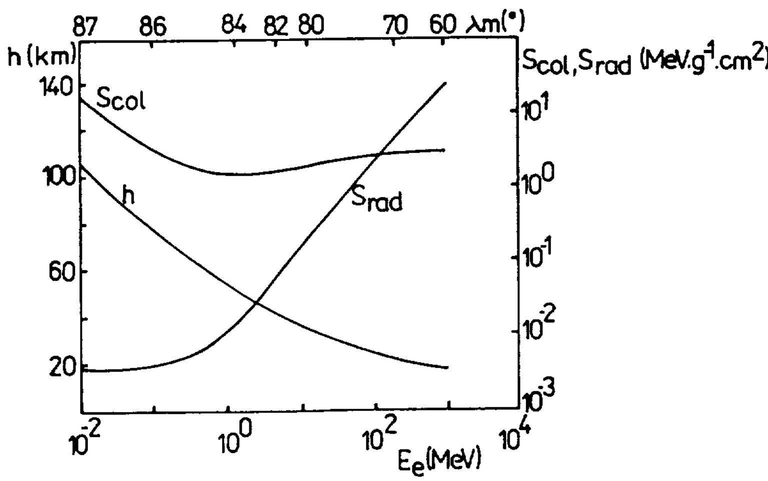

Fig. 4 Losses of energy of electron. Access to different latitudes is given at the top.

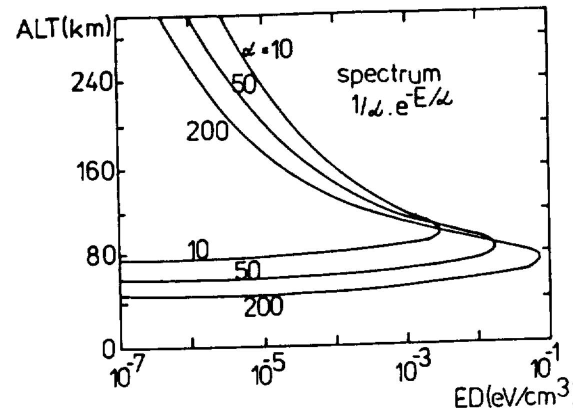

Fig. 5 ED for electron with initial isotropic distribution (for 1 electron/cm^2) (from BERGER et al., 1974).

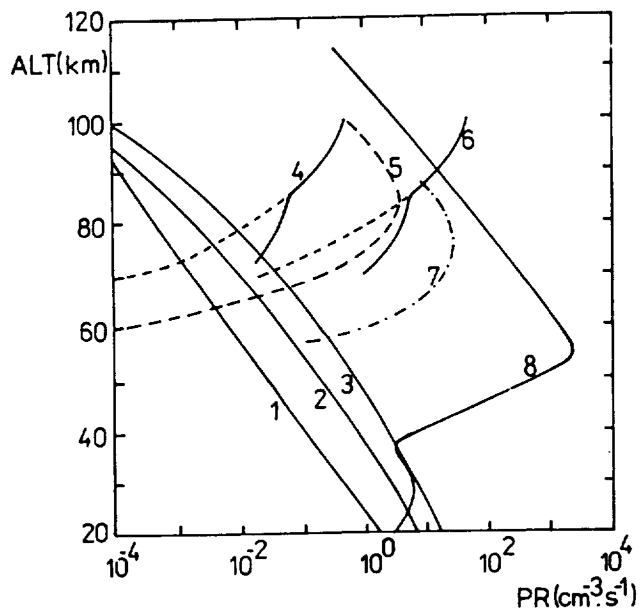

Fig. 6 Comparison of PR by corpuscular radiation. 1, 2, 3 - CR at 0°, 70° max and 70° min. 4, 6 - solar H_α scattered and direct. 5, 7 - due to electron precipitation at L = 4 (quiet and K_p = 6). 8 - due to very HEE. Compilation from SHELDON et al., (1988); BAKER et al., (1988) and VAMPOLA and GORNEY (1983).