COSMIC RAY IONIZATION OF LOWER VENUS ATMOSPHERE

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Abstract. Cosmic ray particles passing through dense lower atmosphere of Venus decay giving rise to various charged and neutral particles. The flux and degradation of dominant cascade particles namely neutrinos and pions are computed and ionization contributions at lower altitudes are estimated. Using the height profile of pion flux, the muon flux is computed and used to estimate ionization at lower altitudes. It is shown that cosmic ray produced ionization descends to much lower altitudes intercepting the thickness of Venus cloud deck. The dynamical features of Venus cloud deck are used to allow the likely charging and charge separation processes resulting into cloud-to-cloud lightning discharges.

1. Introduction

The solar extreme ultra-violet radiations are one of the most dominant sources of ionization of stratified planetary atmospheres. Detailed study of terrestrial atmosphere has been carried out and the change in the electron density with changing phases of solar radiation are fully understood. The terrestrial studies often times work as a guide for the study of photoionization of planetary atmospheres. The ionization of terrestrial and planetary atmospheres can not be fully accounted for in terms of EUV-ionization. The ionization extending to lower altitudes have been attributed to cosmic ray ionization which has two dominant constituents: the solar cosmic ray and the galactic cosmic ray.

These two sources have different spectral features, one is easily distinguished from the other and thus their ionizing effects can be easily separated and studied. The Venus has a relatively denser atmosphere as compared to Earth's. However, the effect of cosmic ray on the ionization of lower atmosphere is quite different due to absence of magnetic field in the Venus' and Mars' atmospheres. In the absence of shielding effects similar to that arising due to geomagnetic field, the cosmic ray particles penetrate deeper into the atmosphere and transfer their energy comparatively more freely. The cosmic ray flux plays an important role in the ionization of non-magnetic (weakly magnetic) planets. It is quite likely that the cosmic ray plays comparatively more dominant role in the charging of clouds and building up of electrical discharges. In this paper we have evaluated ion-pair production rate due to cascading processes of cosmic ray degradation. There is substantial production rate at much lower height and obtains structure like behaviour in the ion production rate. This is similar to C, D, and E regions of the Earth's atmosphere.

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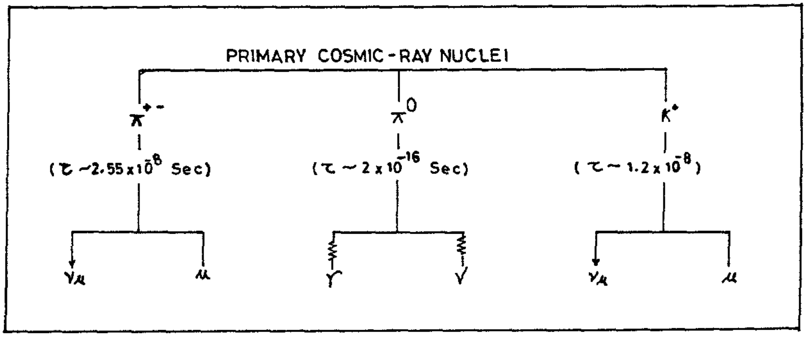

Fig. 1. Schematic outline of principal cosmic-ray phenomena in the Venus atmosphere.

2. Cosmic Ray Attenuation, Cascading Processes and Production of Ion Pairs

The cosmic rays incident on the atmosphere interact with the atmospheric gas atoms and molecules. The effective steps are shown in Figure 1. The by-product of these reactions are nuclear fragmented mesons and neutrino. The energy of these particles are very high and they can penetrate through the atmospheric gases. In the Earth's atmosphere, these particles penetrate through and come down to the Earth's surface and penetrate into the Earth's surface. The Venus lower atmosphere is about 90 times denser than that of Earth's atmosphere. Hence, high energy particles penetrating deeper into the Venus atmosphere interact with the atoms and molecules and produce ionisation. Further, due to a very small magnetic field there is no cut-off energy of cosmic rays as is observed in the case of the Earth's atmosphere.

The incident radiation is composed mainly of atomic nuclei consisting of $\sim$90% protons, $\sim$10% He nuclei, and about 1% heavier nuclei. These particles arrive isotropically carrying kinetic energy from few Mev to 10^{14} Mev.

Nuclear collisions at high energy are generally inelastic in as much as a significant of the collision energy is used up in the production of new particles most of which are unstable. The newly created charged and neutral particles which are used in our program are shown schematically in Figure 1. The differential flux of particles of type j at the depth x is given by Cowsic *et al.* (1966) and Yas pal (1967).

$$F_j(x, E) = \langle B_j \rangle \frac{x}{\lambda} e^{-x/\Lambda} \frac{S_0}{E^{\gamma+1}(1 + u_j)}, \tag{1}$$

where $S_0/E^{\gamma+1}$ is the cosmic ray nucleon spectrum at the top of the atmosphere; λ, the interaction mean free path of nucleon; Λ, the attenuation mean free path of nucleon; U_j, $Hm_j/cE\tau_j$, m_j and τ_j being the mass and proper lifetime of particle j, and H is the scale height of the atmosphere in the direction in which the flux is measured; $\langle B_j \rangle = \int_0^1 n_j(r_j) r_j^\gamma \, \mathrm{d}r_j$, where $n_j(r_j)$ is the number of particles of type j, which receive a fraction r_j of the incident nucleon energy in an interaction (here $j = \pi^0, \pi^\pm, K^\pm$).

The production rate of neutrinos and muons by pions and kaons is given by

$$P_i^j(x,E) = \frac{m_j}{C\tau_j \rho(x)} b_{ij} \int_{-1}^{1} F_j[x, E/r_{ij}(\varphi)] \, \mathrm{d}\cos\varphi / 2E \tag{2}$$

For neutrinos there is no attenuation after production and the differential flux for neutrinos at the depth x is given by

$$F_\nu^j(x,E) = \int_0^x P_\nu^j(y,E) \, \mathrm{d}y \tag{3}$$

However, the differential flux for muons is given by

$$F_\mu^j(x,E) = \int_0^x \mathrm{d}z \, w(z, E + b(x-z), x) P_\mu^j[z, E + b(x-z)]. \tag{4}$$

where $w(z, E + b(x-z), x)$ is the survival probability, defined as the possibility that a muon of energy E survives decay in traversing from a depth z to x and b is the energy loss in traversing unit thickness.

The basic formula for the energy loss per cm path into the material media by a particle travelling with the velocity $v = c\beta$ and undergoing inelastic collisions is written as (Heitler, 1954)

$$\left(\frac{\mathrm{d}E}{\mathrm{d}h}\right)_{\text{coll}} = -NZ\phi_0\mu \frac{3}{4}\frac{z^2}{\beta^2}\left[\log\frac{2\mu\beta^2 W_m}{I^2 Z^2 (1-\beta^2)} - 2\beta^2\right], \tag{5}$$

where N = number of atoms per cm^3; $\phi_0 = (8\pi/3)\, r_0^2$ unit cross section; μ = rest energy of electron; z = charge of primary particle in terms of electronic charge; Z = atomic number; I = average ionization energy 11.5 ev; W_m = maximum energy that can be transferred to a free electron by the primary particle.

The following important limiting cases have been used in the present computational study:

(i) Heavy particles, non-relativistic energies,

$$E - MC^2 = T \ll MC^2$$

$$\left(\frac{\mathrm{d}E}{\mathrm{d}h}\right)_{\text{coll}} = -NZ\phi_0\mu z^2 \frac{3MC^2}{4T} \log\frac{4Tm}{IZm} \tag{6}$$

(ii) Heavy particles, extreme relativistic energies,

$E \gg MC^2$, but $E \ll MC^2$ (M/m) :

$$\left(\frac{\mathrm{d}E}{\mathrm{d}h}\right)_{\mathrm{coll}} = -NZ\phi_0\mu\frac{3}{2}z^2\left[\log\frac{2E^2m}{IZM^2C^2} - 1\right]. \tag{7}$$

The integrated electron ion pair production rate arising from above processes of energy losses q (cm^{-3} sec^{-1}) at the height h (km) for ambient neutral particles of type i is written as (Velinov, 1968)

$$q_i(h) = \frac{2\pi}{Q}\int_E^{\infty}(\mathrm{d}E/\mathrm{d}h)_i n_i(h, E)\,\mathrm{d}E, \tag{8}$$

Q = 35 eV is the energy required for the formation of an electron-ion pair: ($\mathrm{d}E/\mathrm{d}h$) is the ionization losses of particles, $n_i(h, E)$ is the differential flux of particles being expressed in particle cm^{-2} sec^{-1} ster^{-1} GeV^{-1} at the height h (km). There is no geomagnetic cut off energy as is used in the case of magnetic planets.

3. Results and Discussions

The primary cosmic ray spectrum at the top of the Venus atmosphere (300 km) has been chosen. The decay scheme as shown in Figure 1 has been followed. First of all we have computed the energy spectrum of muons, as we do not have any in situ measurements on Venus. So we have compared this flux with that of the Earth's atmosphere. The flux is a little bit higher for energy >8 GeV and decreases sharply below this energy. Computed muons flux versus energy has been shown in Figure 2 . Using above formulation and atmospheric parameters from VIRA model (Kliore *et al.*, 1985), we have computed the electron-ion pair production rate which is shown in Figure 3. If we consider the contribution of primary cosmic rays only then the maximum value of production is of the order of 10^3 cm^{-3} sec^{-1} around 64 km and decreases very sharply on either side. After considering the ionization by muons, the second peak comes at the height of about 25 km and decreases relatively slowly. We have also shown the electron-ion pair production by photo ionization. This is shown for the sake of comparison. This figure in totality gives an impression of presence of structure in the Venus ionosphere. Further, the extension of the presence of cosmic ray ionization may play an important source of ionic and electronic charges for charge separation arising from dynamical processes in the Venus cloud altitudes and likely generation of Venus lightning.

The electric fields in the Venus lower atmosphere have been measured at low frequencies using Electric Field Detectors aboard Pioneer Venus Orbiter. One of the difficulties has been the lack of knowledge of charging sources and their distribution in the Venus atmosphere. The presence of finite charges gives the possibility of charging of Venus clouds due to cosmic ray attenuation and degradation. The discharges between clouds to clouds give rise to electromagnetic

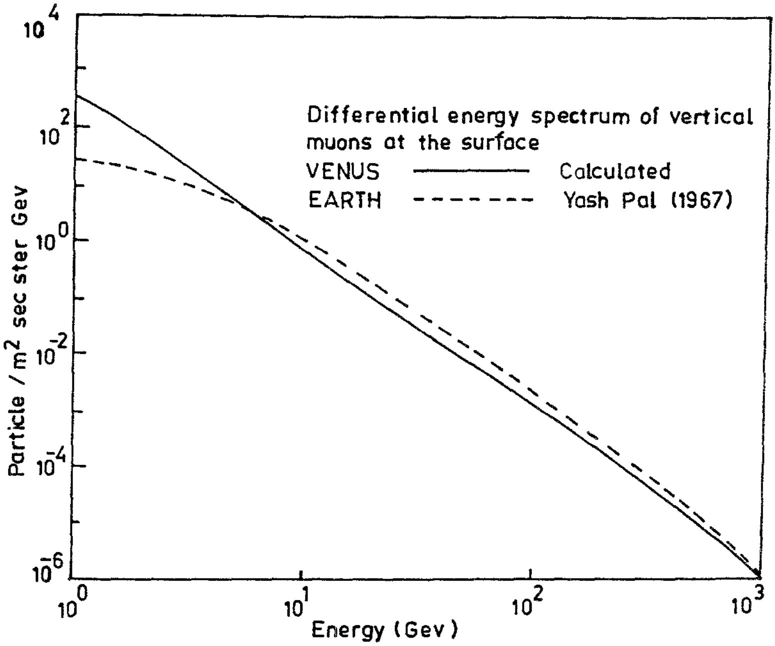

Fig. 2. Variation of muons flux with energy for vertical incidence.

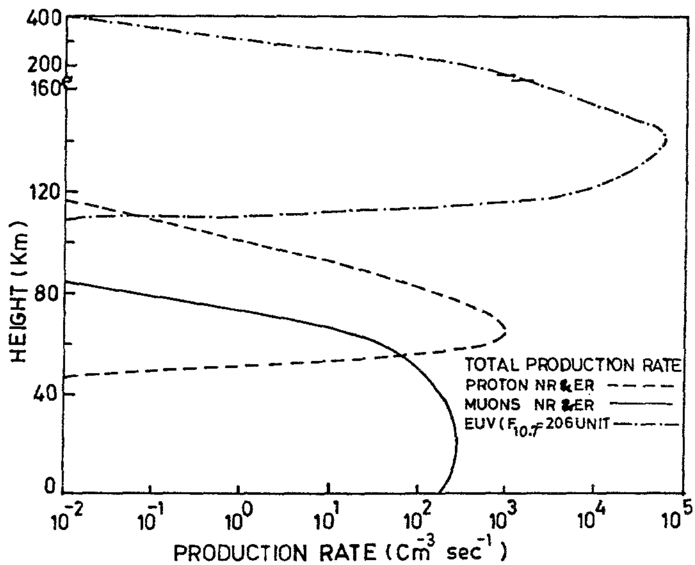

Fig. 3. Height variation of total production rate due to cosmic rays and EUV radiation for Venus atmosphere.

fields that is seen to concentrate during the nightside of Venus. The cloud-to-ground discharges are unlikely in the denser and warmer atmosphere of the Venus which has cloud tops at the height of 55–65 km.

4. Conclusion

The ion-pair production rate by photoionization, cosmic rays and muons are evaluated for the Venus lower atmosphere. The combined production rate clearly shows peaks at different heights leading to the structuring in the ionization density as is observed in the case of the Earth's atmosphere. The pressence of ionization at lower altitudes suggests the possibility of lightning discharge in the Venus atmosphere as has been observed by Galileo (Gurnett *et al.*, 1991).

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