A Model for the Cosmic Ray Produced Ionization in the Middle Atmosphere

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Ion production by cosmic rays is an important aspect of studies related to middle atmospheric electrodynamics and global electrical circuits. Since observations on ion production rates by cosmic rays, are few and particularly scarce over low latitude stations and theoretical computations incomplete and not matched to observational data, the available information on experimental data is synthesized. New computations for ion production rates due to primary cosmic ray spectra are carried out using Bethe-Bloch formula applicable above 30 km and due to secondary cosmic γ-ray spectrum using simple Chapman’s theory below 30 km. The experimental data and computed values are compared and model ion production rates over a few latitudes are presented. The range of variations in the model values of ion production rate and ion densities under different geophysical conditions including the effect of background aerosols are also discussed.

1 Introduction

One of the important aspects of the middle atmospheric electrodynamic phenomena is the ion production by galactic cosmic rays. The ion production rate and its variations need to be measured and studied in order to understand the possible mechanisms of the global electrical circuit and of the sun-weather relationships1-3. Also the nuclear interaction of galactic cosmic rays in the denser regions of the lower atmosphere is an interesting problem of cosmic ray physics.

Only a few experiments have been carried out for detailed measurements of ion production rates in the middle atmosphere over different latitudes. Ion production rates up to middle stratospheric heights have been measured by Gish4, Neher5-7, Anderson8, Morita and Ishikawa9, Morita et al.10,11, Rosen and Hofmann12,13, using balloon borne ionization chambers. Except for a few balloon flights, most of these measurements of ion production rates have been carried out over high latitude stations.

Apart from direct measurements, ion production rates can be derived from (i) the measurements of ion conductivity and mobility, and (ii) from measured ion densities and accurate values of effective recombination coefficients in the middle atmosphere. Several balloon borne measurements of ion density and ion conductivity have been reported by Kroening14, Paltridge15, Morita et al.16-18 and Rosen and Hofmann19 which can be used to get the ion production rate values with appropriately selected values of recombination coefficients.

Models of ion production rates have been suggested by Heaps20 and Nicolet21 using certain parameterized expressions. These expressions are mainly based on the set of measurements by Neher. Velinov22 calculated the ion production rates above 50 km using Bethe-Bloch formula, mainly to determine the contribution of galactic cosmic rays to D-region ionization. Such theoretical computations have not been carried out to assess the ion production rates in the troposphere and stratosphere.

In the present study we (i) extend the theoretical computation of ion production rate down to about 25 km using primary cosmic ray fluxes and its electromagnetic interaction; (ii) demonstrate a method of calculating ion production rates below 20 km, where the effect of secondary cosmic rays becomes dominant (iii) propose a model of ion production rates for low latitudes based on the experimental data available up to 30 km from ground and computed values above 25 km using Bethe-Bloch formula; and (iv) study the variations in model ionization rates in the middle atmosphere due to atmospheric density/solar activity and presence of aerosols.

2 Experimental Data on Ion Production Rate and Ion Density

A list of experiments conducted for measuring ion production rates (q) is given in Table 1. All these experiments used balloon borne ionization chambers. The height range and geomagnetic latitude covered so far for collection of data are given in the last two columns of Table 1. It can be noted that there are very
few observations over the low latitude stations. Since
the data collected by Neher5 -7 covers a wide range of
latitudes and sunspot activity, we have compiled these
ion production rates in Table 2. The data for 0° and 11°
geomagnetic latitudes are obtained by extrapolating
the reported variation of \( q \) with respect to geomagnetic
latitudes at different atmospheric depths. The increase
of \( q \) with latitude and its anti-correlation with solar
activity are clearly seen from Neher’s observations5 -7.
The ion production rates as obtained from Neher’s
experimental observation are shown in Fig. 1. It can be
noticed that for geomagnetic latitudes of 0° and 11°,
there is no effect of solar activity on \( q \) but there is a
significant variation of about 26% in \( q \) between solar
maximum and minimum periods for geomagnetic
latitudes at and above 30°. The ion production rates at
Madras (3°N), a low latitude station, have been
measured by Gish4. The observed values are found to
be on an average 17% higher than Neher’s values at the
equator for lower altitudes and about 7% higher for
higher altitudes. In another comparison related to high
latitude measurements by Gish4,' the observed values
were about 7-8% higher compared to those measured
by Neher5 -7. Rosen and Hofmann12,13 and Morit11
have also measured ion production rates over a high
geomagnetic latitude station (Wyoming, \( \lambda = 50° \)).

### Table 1—Summary of the Balloon Experiments Conducted for Measuring Ion Production Rates Using Ionization
Chambers

<table>
<thead>
<tr>
<th>Reference</th>
<th>Period of observation</th>
<th>Place of observation</th>
<th>Geomag. lat. covered by the experiment</th>
<th>Height range covered km</th>
<th>Geomag. lat. covered for the data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neher5</td>
<td>June-July 1958</td>
<td>Base station at North Dakota and mobile stations</td>
<td>38°N-87°N</td>
<td>5.5-36</td>
<td>36°N-87°N</td>
</tr>
<tr>
<td>Neher6</td>
<td>Oct. 1958</td>
<td>While going towards south pole on ship</td>
<td>13°N-79°S</td>
<td>10-36</td>
<td>13°N-79°S</td>
</tr>
<tr>
<td>Neher6</td>
<td>July-Aug. 1965</td>
<td>15 flights from ship going north from Peru to Thule and 14 simultaneous flights from Bismarck, North Dakota</td>
<td>13°S-88°N</td>
<td>9.75-36</td>
<td>13°S-88°N</td>
</tr>
<tr>
<td>Gish4</td>
<td>1939</td>
<td>Madras, India</td>
<td>3°N</td>
<td>0-26</td>
<td>3°N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Omaha, Nebraska, USA</td>
<td>51°N</td>
<td>3-30</td>
<td>51°N</td>
</tr>
<tr>
<td>Rosen and Hofmann12</td>
<td>Aug. 1978</td>
<td>Wyoming, USA</td>
<td>50°N</td>
<td>5-35</td>
<td>50°N</td>
</tr>
<tr>
<td>Rosen and Hofmann13</td>
<td>May 1979</td>
<td>Wyoming, USA</td>
<td>50°N</td>
<td>2-30</td>
<td>50°N</td>
</tr>
<tr>
<td>Morita11</td>
<td>Aug. 1979</td>
<td>Wyoming, USA</td>
<td>50°N</td>
<td>4-30</td>
<td>50°N</td>
</tr>
<tr>
<td>Morita11</td>
<td>Dec. 1979</td>
<td>Wyoming, USA</td>
<td>50°N</td>
<td>4-35</td>
<td>50°N</td>
</tr>
<tr>
<td>Morita11</td>
<td>June 1980</td>
<td>Wyoming, USA</td>
<td>50°N</td>
<td>4-25</td>
<td>50°N</td>
</tr>
</tbody>
</table>

### Table 2—Ion Production Rates at Different Latitudes during Solar Maximum (1958) and Minimum Year (1965) Measured
by Neher5.6 Using Two Series of Balloon Flights

<table>
<thead>
<tr>
<th>Altitude/km</th>
<th>Geomag. lat.</th>
<th>Solar maximum year (1958)</th>
<th>Solar minimum year (1965)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>11°</td>
<td>30°</td>
</tr>
<tr>
<td>10</td>
<td>14.5</td>
<td>16.5</td>
<td>23.5</td>
</tr>
<tr>
<td>12</td>
<td>17.2</td>
<td>18.0</td>
<td>24.0</td>
</tr>
<tr>
<td>14</td>
<td>14.5</td>
<td>15.5</td>
<td>21.5</td>
</tr>
<tr>
<td>16</td>
<td>11.5</td>
<td>12.2</td>
<td>13.7</td>
</tr>
<tr>
<td>18</td>
<td>7.4</td>
<td>8.4</td>
<td>10.0</td>
</tr>
<tr>
<td>20</td>
<td>5.0</td>
<td>5.5</td>
<td>6.9</td>
</tr>
<tr>
<td>22</td>
<td>3.25</td>
<td>3.6</td>
<td>4.05</td>
</tr>
<tr>
<td>24</td>
<td>2.0</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>26</td>
<td>1.3</td>
<td>1.4</td>
<td>1.75</td>
</tr>
<tr>
<td>28</td>
<td>—</td>
<td>1.05</td>
<td>1.15</td>
</tr>
<tr>
<td>30</td>
<td>—</td>
<td>0.85</td>
<td>0.75</td>
</tr>
<tr>
<td>32</td>
<td>—</td>
<td>0.68</td>
<td>—</td>
</tr>
<tr>
<td>34</td>
<td>—</td>
<td>0.55</td>
<td>—</td>
</tr>
<tr>
<td>36</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

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These values when normalized for solar activity variation compare well with Neher's measurements as shown in Table 3.

Under equilibrium conditions and in absence of atmospheric transport and aerosols, the ion production rates and ion densities are related by the following simple relation

$$q = a_{\text{eff}} n^2$$  

where $a_{\text{eff}}$ is the effective ion-ion recombination coefficient, $q$ and $n$ are ambient ion pair production rate and ion density, respectively.

Rosen and Hoffmann\(^{12,13}\) have measured simultaneously the ion production rate and ion density and computed the value of $a_{\text{eff}}$ which has been compared with the theoretical two and three body recombination coefficients. The uncertainty in the calculated values of $a_{\text{eff}}$ is found to be about 15\% above 32 km and below 9 km. Whereas the difference above 32 km was attributed to measurement error in the ion densities, the difference below 9 km was explained as possibly due to the aerosol attachment process.

A number of authors\(^{23-27}\) have studied the recombination coefficient both theoretically and by conducting laboratory experiments. It has been suggested by Bates\(^{27}\) that the total recombination coefficient can be expressed as

$$a_{\text{eff}} = a_2 + a_3$$  

where $a_3$ is the termolecular recombination coefficient and $a_2$ is regarded as the binary recombination channel.

Using $q$ values measured by Rosen and Hofmann\(^{12,13}\) and the theoretical 2 and 3 body recombination coefficients, Bates\(^{27}\) has calculated the ion densities and compared with the observed data. The comparison shows that the agreement between the computed and observed ion densities is good except at 5 km level.

Ion production rates can also be estimated from the electric conductivity and ion mobility using the following expression.

$$\mu = \sigma/n e$$  

where

- $\mu$ Average mobility of the ions
- $\sigma$ Electric conductivity
- $n$ Ion density
- $e$ Charge on the ion

Ion mobility spectrum has been obtained from experimental observations by Conley\(^{28}\), Rose and Widdel\(^{29}\), and Takagi et al.\(^{30}\).

Morita et al.\(^{16}\) measured positive ion density and positive polar conductivity in the altitude range 0-19 km. The measured ion density when compared with another direct experiment by Kawano et al.\(^{31}\) showed discrepancies below 10 km and this was attributed to the possible variation in the concentration of the atmospheric aerosols over a few days.

<table>
<thead>
<tr>
<th>Altitude km</th>
<th>Ion Production Rate (cm(^{-3}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rosen and Hofmann(^{12,13,19}) 1977-1979</td>
</tr>
<tr>
<td></td>
<td>Calculated from $n$ (expt) and $a_{\text{eff}}$ (Bates)</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>32.4</td>
</tr>
<tr>
<td>15</td>
<td>33.6</td>
</tr>
<tr>
<td>20</td>
<td>16.8</td>
</tr>
<tr>
<td>25</td>
<td>6.0</td>
</tr>
<tr>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>35</td>
<td>1.7</td>
</tr>
</tbody>
</table>
An alternative method of computing ion densities from the ion production rates is to use a suitable ion scheme which incorporates a large number of possible ion-chemical reactions including aerosol reactions. A number of such schemes are available for different heights of the middle atmosphere. The accuracy of the computations depend largely on the values of the reaction rate coefficients determined by using laboratory techniques. Mitra’s 13-ion scheme\(^2\) considers a number of ions including the effects due to aerosol attachment and recombination. This scheme is quite adequate to determine the total ion concentration from the initial value of ion production rates.

### 3 Theoretical Computation of Ion Production Rates

The ionization produced by cosmic ray primaries was calculated by Nicolet\(^2\) using the following empirical expression.

\[
q_{CR} = 1.5 \times 10^{-18} \left[ 1 - 3 \times 10^{-3} (F_{10.7} - 70) \right] \times 
\cos^{-4} \lambda \left[ 1 \right] \quad (4)
\]

where \(F_{10.7}\) is 10.7 cm solar flux, \(\lambda\) is the geomagnetic latitude and \(M\) is the atmospheric density.

Heaps\(^2\) derived a semi-empirical parameterization of experimental data of Neher\(^3-7\) on ion production rate. In the altitude range of 18-30 km the expression for \(q\) is

\[
q = (A + B \sin^4 \lambda) N_0 N^x \quad (5)
\]

and for altitudes above 30 km it is

\[
q = (A + B \sin^4 \lambda) N \quad (6)
\]

where \(A\) and \(B\) are constants, \(\lambda\) is the geomagnetic latitude, \(N\) is the total neutral number density, \(N_0\) denotes the reference number density at 31 km where Eqs (5) and (6) merge. The values of the exponents were given by

\[
n = 0.6 + 0.8 \cos \lambda; \quad \gamma = 1 - n
\]

Ion production rates above 50 km has been calculated by Velinov\(^2\) using the following Bethe-Bloch formula.

\[
\frac{dE}{dh} = 2 \pi n Z^2 i e^4 \left[ \ln \frac{2mc^2 W_{\text{max}}}{T^2 (1 - \beta^2)} - 2\beta^2 \right] \quad (7)
\]

where \(v\) and \(z_i\) are velocity and atomic number of penetrating charged particle, respectively, \(\beta = v/c\), \(W_{\text{max}} = 2 mc^2/(1 - \beta^2)\) and \(I\) is the average ionization energy of the atmospheric constituents.

The simplified form of Eq. (7) is used to derive the relation for ion production rate given below:

\[
q(h) = 1.8 \times 10^5 \rho(h) n_p > R_J \ln (R_c + 4.15) \quad (8)
\]

where

- \(\rho(h)\) The atmospheric density at height \(h\)
- \(n_p (> R_J)\) The integral spectrum of protons for rigidity greater than \(R_c = (Av) pc\)
- \(p\) Particle momentum
- \(z\) Charge of the particle

### 4 Present Computations

#### 4.1 Calculations of \(q\) Down to 20 km

Velinov\(^2\) had earlier carried out calculations of ion production rates for altitudes above 50 km in order to study the D-region ionization processes. This has now been extended down to 20 km altitude using the primary cosmic ray intensities. The nuclear interactions which are initiated around 25-30 km and which have dominating effects in producing ionization below 20 km are not taken into account in this simplified calculations. The simplified formula [Eq. (8)] is used for these computations. Input data needed for this calculation of \(q\) are atmospheric density and integrated proton spectrum with suitable cut-off rigidities for a particular latitude providing the lower limit of integration. The integrated proton spectrum for solar minimum and maximum years (1965 and 1958, respectively) have been taken from Hillas\(^3\). For geomagnetic latitudes 0° and 11° the integrated solar maximum cosmic ray flux is taken to be the same as the integrated solar minimum flux, as the cut-off rigidities at these latitudes are in the range above which there is no variation between solar maximum and solar minimum cosmic ray fluxes. But for higher latitudes the difference between solar minimum and maximum cosmic ray fluxes have been taken into account. The cosmic ray fluxes used are shown in Fig. 2.

The computed values of \(q\) using the above method have been compared with the values obtained from Heaps’\(^2\) and Nicolet’s\(^2\) parameterized model calculations. Nicolet’s model underestimates the experimental data of Neher\(^3-7\) and also shows a solar cycle effect even at the geomagnetic equator which is not observed experimentally. Heaps’ model\(^2\) provides a closer fitting to Neher’s experimental values but cannot be used for intermediate solar activity periods. Present calculations using the primary cosmic ray fluxes underestimates the ion production rate values as compared to Neher’s data. This discrepancy is believed to be due to the fact that below about 25-30 km, the secondary cosmic ray fluxes need to be taken into account. Notwithstanding this problem, the present method is preferable as \(q\) can be computed for any latitude during any solar activity period, if the primary cosmic ray fluxes are available.

In Figs 3 and 4, the present calculations of \(q\) and Neher’s experimental data are compared for different
The spectra of each component of secondary cosmic rays are required to realistically estimate the ion production rate below about 20-30 km. The intensities of the secondary radiation increases as it traverses down the atmosphere below 30 km. Table 4 shows the components of secondary radiations with their characteristic life times and decay modes. It can be seen that out of the secondary components, gamma rays constitute the resultant component of radiation from different decay modes of other particle radiations and hence must be potentially important for ion production in the atmosphere.

Making use of a simple formula we can write the ion production rate per unit volume at an altitude $h$ as follows.

$$q(h) = \sum_f q(h, E) = \sum_f \sigma(E) I(h, E) \rho(h)/Q$$

where

- $\sigma$ Mass absorption coefficient of air
- $I$ Intensity of gamma rays at height $h$
- $\rho$ Atmospheric density

The ion production rates due to primary cosmic rays have already been discussed. The main component of the primary cosmic rays is protons. On entering the denser regions of atmosphere, the primary cosmic radiation undergoes nuclear interactions with atmospheric molecules giving rise to secondary particles and secondary electromagnetic radiations. Each one of these components has a different energy spectrum at different levels of the atmosphere. The secondary particles also have their characteristic life times. Hence, in order to calculate the ion production rate using Bethe-Bloch formula, quantitative values of

Fig. 2—Differential energy spectrum of primary protons, helium nucleus and three more representative nuclei (L represents Li, Be, B; S represents those with $Z > 5$ and VH represents those with $Z > 19$) at a time of low solar activity (1965) and of primary protons and helium nucleus at a time of high solar activity (1959) [The different symbols denote different ways of measuring the spectra.]

Fig. 3—Latitudinal variation of cosmic ray ion production rates during solar minimum year (1965) (Experimental and theoretical values)

Fig. 4—Latitudinal variation of cosmic ray ion production rates during solar maximum year (1958) (Experimental and theoretical values)
**Table 4**—Particle and Electromagnetic Radiations of Secondary Cosmic Rays. Their Characteristic Life Times and Decay Modes

<table>
<thead>
<tr>
<th>Secondary Particle</th>
<th>Mean life time ( \tau ) s</th>
<th>Decay modes/interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons ( (\gamma) )</td>
<td>( \infty )</td>
<td>—</td>
</tr>
<tr>
<td>Electrons ( (e^\pm) )</td>
<td>( 6 \times 10^{-9} )</td>
<td>( e^+ + e^- \rightarrow 2\gamma )</td>
</tr>
<tr>
<td>Muon ( (\mu^\pm) )</td>
<td>( 2.22 \times 10^{-6} )</td>
<td>( \mu^- \rightarrow e^- + v + \bar{\nu} + 105.2 \text{ MeV} )</td>
</tr>
<tr>
<td>Pion ( (\pi^\pm) ) (charged)</td>
<td>( 2.54 \times 10^{-8} )</td>
<td>( \pi^- \rightarrow \mu^- + v + 33.9 \text{ MeV} )</td>
</tr>
<tr>
<td>Pion ( (\pi^0) ) (neutral)</td>
<td>( 10^{-13} )</td>
<td>( \pi^0 \rightarrow 2\gamma + 135.1 \text{ MeV} )</td>
</tr>
<tr>
<td>Proton ( (p^+) )</td>
<td>( \infty )</td>
<td>( -e^+ + e^- + \gamma )</td>
</tr>
<tr>
<td>Neutron ( (n^0) )</td>
<td>( 1.1 \times 10^3 )</td>
<td>( n \rightarrow p^- + e^- + \nu + 0.762 \text{ MeV} )</td>
</tr>
</tbody>
</table>

**Table 5**—Ion Production Rates by Secondary Gamma Rays Over Texas (Geomag. lat. 42°)

<table>
<thead>
<tr>
<th>Height km</th>
<th>Integrated photon energy ( q ) keV cm(^{-2}) s(^{-1}) (40-540 keV)</th>
<th>Ion production rate ( (q) ) cm(^{-3}) s(^{-1})</th>
<th>Error in ( q ) cm(^{-3}) s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>( 6.1 \times 10^3 )</td>
<td>18.9</td>
<td>( \pm 4.4 )</td>
</tr>
<tr>
<td>13</td>
<td>( 1.4 \times 10^4 )</td>
<td>29.9</td>
<td>( \pm 3.2 )</td>
</tr>
<tr>
<td>15</td>
<td>( 2.5 \times 10^4 )</td>
<td>32.6</td>
<td>( \pm 3.2 )</td>
</tr>
<tr>
<td>18</td>
<td>( 2.8 \times 10^4 )</td>
<td>25.4</td>
<td>( \pm 1.7 )</td>
</tr>
<tr>
<td>21</td>
<td>( 2.5 \times 10^4 )</td>
<td>15.9</td>
<td>( \pm 1.7 )</td>
</tr>
<tr>
<td>23</td>
<td>( 1.9 \times 10^4 )</td>
<td>8.7</td>
<td>( \pm 0.8 )</td>
</tr>
<tr>
<td>26</td>
<td>( 1.6 \times 10^4 )</td>
<td>4.9</td>
<td>( \pm 1.0 )</td>
</tr>
<tr>
<td>28</td>
<td>( 1.3 \times 10^4 )</td>
<td>3.04</td>
<td>( \pm 0.34 )</td>
</tr>
<tr>
<td>30</td>
<td>( 9.9 \times 10^3 )</td>
<td>1.773</td>
<td>( \pm 0.11 )</td>
</tr>
<tr>
<td>32</td>
<td>( 7.8 \times 10^3 )</td>
<td>1.018</td>
<td>( \pm 0.15 )</td>
</tr>
<tr>
<td>34</td>
<td>( 6.4 \times 10^3 )</td>
<td>0.592</td>
<td>( \pm 0.07 )</td>
</tr>
<tr>
<td>36</td>
<td>( 5.4 \times 10^3 )</td>
<td>0.378</td>
<td>( \pm 0.06 )</td>
</tr>
</tbody>
</table>

Table 5 arise due to the fact that the secondary gamma ray spectra measured by Haymes are over different height ranges and in the present calculations of ion production rate the average over height ranges has been used. The density variation over these height ranges gives rise to the error bars in the ion production rate values. The experimental data of ion production rates by Neher and Haymes from balloon experiments over the same region are shown in Fig. 5 along with the values calculated in the present work. Though the computed ion production rates compare well with those of experimental values, it can be noticed that the computed ion production rates are higher than those produced by secondary gamma rays. This is attributed to the dominance of ion production by primary cosmic rays above this altitude of about 28 km. From this, it can be established that for generating models of ion production rates, the theoretical computations using the primary cosmic rays spectrum should be limited to an altitude of about 30 km, below which it is better to use the available balloon borne experimental data.

**5 Models of Cosmic Rays Ion Production Rate and Ion Densities in the Middle Atmosphere**

Ion productions as a function of altitude and latitude calculated by using Bethe-Block formula for height starting from approximately 30 km to 100 km are joined smoothly with experimentally observed ion production rates from 5 to 30 in order to get a model for ion production rates for an altitude range 0-100 km. Figs 6 and 7 show the model plots for 0°, 11°, 30° and 55° geomagnetic latitudes.

**5.1 Variations in the Ion Production Rates**

When any new experiment is conducted for the measurement of ion production rates the observed values are to be compared with the model values plus its variations due to the particular condition of atmospheric density and solar activity. In view of this,
we examine the possible variations in the models due to the seasonal variation of atmospheric density and extreme solar activity conditions. For a worst case we have considered that the above two perturbations are additive. Based on these input variables the ion production rates are computed up to 30 km using Bethe-Bloch formula and extrapolated below this height. Figs 8 and 9 give the variations in the model $q$ values due to the extreme conditions of density and solar activity fluctuations. It can be noted that the variations in $q$ values are found to be more at $\lambda = 30^\circ$ than that at $\lambda = 11^\circ$ as there is effect of solar cycle variation in the case of high latitudes and not for lower latitude stations. The result of the ion production rate from any new experiment carried out over the latitudes are expected to fall within the extreme values of the model in the absence of any other major solar perturbations.

5.2 Variations in Ion Densities

Based on the variation in the model ion production rates, the corresponding expected variations in ion densities can be calculated using Eq.(1). Such calculations show that for low latitudes, where the effect of solar activity is negligible, the average variation in ion densities can be up to about 13%. Hence it can be concluded that the measured values of ion densities over low latitudes should show very small

Table 6—Ion Production Rates by Background and Cosmic $\gamma$-rays and X-rays

<table>
<thead>
<tr>
<th>Energy</th>
<th>Ion production rate (cm$^{-3}$ s$^{-1}$) for heights (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>20 keV</td>
<td>$-1.34 \times 10^{-6}$</td>
</tr>
<tr>
<td>30 keV</td>
<td>$4.99 \times 10^{-5}$</td>
</tr>
<tr>
<td>20 MeV</td>
<td>$1.01 \times 10^{-4}$</td>
</tr>
<tr>
<td>30 MeV</td>
<td>$1.18 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
changes due to the variations in ion production rates. However, the expected variation in ion densities will be quite large for higher latitudes on account of the increasing influence of solar activity.

We have considered variation of ion densities due to variation in $q$. However, even if $q$ remains fixed, ion densities can change when large number of aerosols are present in the atmosphere. To study this aspect, Mitra’s 13-ion scheme has been used with measured aerosol concentration profiles. When the background aerosol number density profile given by Hake et al. is used then the average variation of ion density over low latitudes is found to be 4% for the height range 10-25 km and 0.7% over the range 30-40 km. These variations are, over and above, due to variations in $q$.

In order to compare the available ion density measurements over Hyderabad (geomag. lat. 7.6°) with the model ion densities and its likely variations, different profiles are collected and shown in Fig. 10. Fig. 10 shows that observed values have large variation from one measurement to the other. Several techniques have been used in these measurements using Gerdien Condenser (GC), Spherical Probe (SP) and Langmuir Probe (LP). In February 1985, the same balloon flight carried three different payloads (GC, SP, LP). Large differences in measured ion densities with these three techniques can be seen from Fig. 10. It also shows the model ion density profile and its possible variation due to $q$ and background aerosol. Any measured ion density profile is expected to have values defined by this range of variation in ion density. However, available observations do not satisfy this requirement. More observational data will be necessary before making a definite conclusion. It is possible that a large day-to-day variation in aerosol concentration may give rise to varying results when measured with balloon payloads on different days. Subbaraya’s measurement of aerosol density over Hyderabad (disturbed and undisturbed) shows large variations in aerosol concentrations over Hyderabad. Once there is a volcanic eruption, the time sequence decides about the building up and decay of aerosol concentrations in the stratosphere. This will effect the measurements which are carried out during different phases of build-up and decay of aerosol layers. Quantitative estimates of changes in ion density and in conductivity from such aerosol build-ups will be presented later.

6 Conclusions

(i) The galactic cosmic rays is one of the main sources of ionization in the middle atmosphere. Very few direct experiments have been made over the low latitudes to measure the ion production rates. Efforts have been made in this paper to review the observational status, extend the ion production rate calculations below 50 km and suggest a model for the low latitudes. The possible variations in the model value due to changes in cosmic ray intensity, atmospheric density and aerosol concentrations are also presented.

(ii) The balloon borne ionization chamber has been used by a number of experimentors to measure the ion production rates. Some of the measurements have been carried out by using conductivity probes and
mobility spectrometers. Measurements of \( q \) carried out by different experimentors for a particular latitude and solar activity compare within 10%. The observed data indicate a variation of \( q \) with solar activity above 30° geomagnetic latitude. In India a few balloon experiments for measuring ion densities have been carried out from Hyderabad (geomag. lat., 7.6°). At this latitude solar cycle variation in \( q \) is negligible, but the variation in \( q \) owing to seasonal density changes can be up to +15%.

(iii) Using the experimental values up to 30 km altitude and theoretical calculations of \( q \) using Bethe-Bloch formula down to about 20-25 km, models of \( q \) have been proposed for low and high latitude stations during high and low sunspot activity periods. The maximum range of variations of \( q \) due to density and solar activity changes are of the order of 60%.

(iv) Calculations of ion production rates have also been carried out below 35 km using secondary \( \gamma \)-ray spectrum produced due to nuclear interactions of the primary cosmic ray particles with the atmospheric constituents. This computation needs the measured primary cosmic ray particles with the atmospheric solar activity changes are of the order of 60%. The computed \( q \) values compared reasonably well with the \( q \) values measured during the same balloon experiment. The comparison shows that the effect of cosmic ray secondaries in producing ionization becomes dominant below about 28 km. This result has been used in the presentation of models of ion production rates.

(v) Using the model ion production rate values, the ion densities have been calculated with the help of Mitra’s 13-ion scheme. The background aerosol concentration profile has been given as input data to the ion scheme. This provides a variation in ion density in excess of ion production rate. The overall variation in ion density due to density variations and background aerosols is found to be of the order of 30-35% over Hyderabad. However, the measured values of ion density over Hyderabad indicate a much larger variation. More data needs to be collected before arriving, at a definite conclusion on the ion densities over Hyderabad.

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