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LOW ENERGY ATMOSPHERIC GAMMA RAYS NEAR GEOMAGNETIC EQUATOR

K. KASTURIRANGAN, U. R. RAO and P. D. BHAVSAR
Physical Research Laboratory, Navrangpura, Ahmedabad, 9, India

Received 28 April 1972

Abstract—Based on the results from three balloon flights, made at Hyderabad (7-6°N geomagnetic latitude) using omnidirectional gamma ray spectrometers, the different aspects of the low energy atmospheric gamma rays near equatorial latitudes in the energy interval 100 keV to 1 MeV are investigated and detailed discussion is presented. The energy loss spectrum in this energy range is found to consist of a continuum superimposed on which is a photopeak due to 0-51 MeV line arising from electron positron annihilation. The continuous background spectrum is similar to that observed at mid and high latitudes. The intensity of 0-51 MeV line is estimated and its variation with altitude from Hyderabad and the altitude depend-
<table>
<thead>
<tr>
<th>Flight number</th>
<th>Date and time of launch</th>
<th>Residual atmosphere at ceiling (g cm²)</th>
<th>Useless duration of the flight</th>
<th>Detector shape and size</th>
<th>Omnidirectional geometrical factor (G)*</th>
<th>Pulse height intervals (keV)</th>
</tr>
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<tbody>
<tr>
<td>F-1</td>
<td>April 1, 1968 0122 hr UT</td>
<td>22</td>
<td>5 hr</td>
<td>Cylindrical</td>
<td>76 cm²</td>
<td>180-225, 225-330, 330-370, 370-450, 450-475, 475-498, 498-560, 560-620, 620-740, 740-940</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>12.7 cm x 1.3 cm</td>
<td></td>
<td></td>
<td>5-1 cm x 5-1 cm</td>
</tr>
<tr>
<td>F-2</td>
<td>March 22, 1969 0136 hr UT</td>
<td>8</td>
<td>3 hr</td>
<td>Cylindrical</td>
<td>13.3 cm²</td>
<td>191-244, 244-339, 339-424, 424-476, 476-524, 524-552, 552-610, 610-689, 689-728, 728-843, 843-978, 978-1123</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>34 min</td>
<td></td>
<td></td>
<td>5-1 cm x 5-1 cm</td>
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<tr>
<td></td>
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<td></td>
<td>5 min</td>
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<td>5-1 cm x 5-1 cm</td>
</tr>
</tbody>
</table>

* Omnidirectional geometrical factor is calculated using the formula

\[
G = \frac{\pi D l}{4} \left(1 + \frac{D}{2l}\right) \text{cm}^2
\]
<table>
<thead>
<tr>
<th>Flight number</th>
<th>Date and time of launch</th>
<th>Residual atmosphere at ceiling (g cm(^{-2}))</th>
<th>Useful duration of the flight</th>
<th>Detector shape and size</th>
<th>Omnidirectional geometrical factor (G)*</th>
<th>Pulse height intervals (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1</td>
<td>April 1, 1968 0122 hr UT</td>
<td>22</td>
<td>5 hr 38 min</td>
<td>Cylindrical 12.7 cm × 1.30 cm</td>
<td>76 cm(^2) 180-225, 225-330, 330-370, 370-450, 450-475, 475-498, 498-560, 560-620, 620-740, 740-940</td>
<td></td>
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<tr>
<td>F-2</td>
<td>March 22, 1969 0136 hr UT</td>
<td>8</td>
<td>3 hr 34 min</td>
<td>Cylindrical 3.8 cm × 2.5 cm</td>
<td>13.3 cm(^2) 191-244, 244-339, 339-424, 424-476, 476-524, 524-552, 552-610, 610-689, 689-848, 848-1060</td>
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<tr>
<td>F-3</td>
<td>April 23, 1969 0202 hr UT</td>
<td>6</td>
<td>3 hr 5 min</td>
<td>Cylindrical 5.1 cm × 5.1 cm</td>
<td>30.4 cm(^2) 135-200, 200-265, 265-320, 320-380, 380-455, 455-507, 507-569, 569-643, 643-728, 728-843, 843-978, 978-1123</td>
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</tr>
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</table>

* Omnidirectional geometrical factor is calculated using the formula

\[ G = \frac{\pi DL}{4} \left(1 + \frac{D}{2L}\right) \text{ cm}^2 \]
of statistical accuracy are also considerable interest as an index to measure the solar cycle variation of primary cosmic radiation at these latitudes.

2. DETAILS OF THE PAYLOAD AND THE BALLOON FLIGHTS

The basic gamma ray detector was a conventional NaI(Tl) crystal viewed by a suitable photomultiplier. The entire crystal photomultiplier assembly was encased in a cylinder of plastic scintillator, 1 cm thick, as was independently viewed by another photomultiplier. The NaI(Tl) was put in anticoincidence with the plastic scintillator, with the anticoincidence threshold set at about 300 KeV thereby eliminating the charged particle induced events. The gamma ray events so selected were pulse height analysed into a suitable number of channels, after appropriate impedance transformation and amplification. Integral rates corresponding to energy losses greater than the upper threshold of pulse height analysis and those of the plastic anticoincidence shield were separately monitored. The resultant pulses, after suitable scaling, were registered at the ground receiving station through a multichannel FM/FM telemetry system. The scaling factors were so chosen as to keep the losses due to telemetry below 5 per cent. Laboratory studies have shown that the energy resolution factors defined by full-width at half maximum were 16 per cent and 12 per cent respectively, for the detector systems used in the first two flights and the third flight respectively for 660 keV gamma rays from Cs137. The detectors were further calibrated with a laboratory single channel analyses using Na22 and Cs137 radioactive sources. The response of the systems were found to be near over the energy range of interest. To minimize the contribution of locally produced gamma rays to the counting rates, the battery packs and other dense materials were kept sufficiently away from the main NaI(Tl) crystals in the payload.

The details about the three flights with other relevant information such as the dimensions of the detectors, their geometry, height intervals etc. are given in Table 1. In the case of all the flights, the payloads were recovered in good condition, and the post flight calibrations were carried out. No detectable deterioration in the payload performance was evident in these checks. The pressure measurements were made with a conventional bellows type radiosonde up to 50 g cm⁻² depth and had an accuracy of 3 g cm⁻² at 100 g cm⁻². For lower depths, owing to the inadequate accuracy of the radiosonde, a Wallace Tieman gauge was used, which could detect pressure changes of the order of 0.3 g cm⁻² at 10 g cm⁻² depth.

3. RESULTS

3.1. The counting rate vs. atmospheric depth

All the flights showed the characteristic decrease in the counting rates of different channels due to the continuous reduction of the terrestrial radioactivity in the initial phase of the balloon ascent followed by the normal increase expected from the cosmic ray secondaries. The transition between these two effects was found to take place around 800 g cm⁻² atmospheric depth. The counting rates were then found to continue to increase and go through a maximum which occurred at about 120 g cm⁻², this value of the atmospheric depth for the maximum being nearly the same for all the channels and then the rates decreased till the ceiling altitude. These aspects are shown in Fig. 1 where the counting rates observed in one of the channels are shown as a function of atmospheric depth for the flight F-3. The rates measured by the plastic shield and the integral channel are also plotted in the same figure. The anticoincidence rate of 130 counts per sec. at Pfotzer maximum is
1964 K. KASTURIRANGAN, U. R. RAO and P. D. BHAVSAR

equivalent to an omnidirectional flux of 0.85 counts cm\(^{-2}\) sec\(^{-1}\). This value is in good agreement with 0.70 ± 0.06 counts cm\(^{-2}\) sec\(^{-1}\) measured by GM counters (Appendix) at the same atmospheric depth thereby demonstrating that the antisystems worked according to expectations. The slightly higher value of the shield rate could be attributed to its higher sensitivity to low energy electrons compared to the GM counters which had \(\approx 400\) mg cm\(^{-2}\) thick copper walls.

3.2. Energy loss spectrum

The raw counting rates \(C\) in counts/sec are converted into \(F\) in counts/cm\(^2\) sec keV using the formula

\[
F = \frac{C}{G \Delta E} \text{ counts cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}
\]

\(\Delta E\) being the energy interval appropriate to the channel, and \(G\) the omnidirectional geometrical factor of the detector. The values of \(F\) as a function of energy, representing the energy loss spectrum in the crystal are thus derived for different atmospheric depths. These are shown in Fig. 2 corresponding to the observations of flight F-3. Fitting a power law function \(KE^{-\alpha}\) to the high altitude energy loss spectrum (near 10 g cm\(^{-2}\)) over Hyderabad yields a relation of the type

\[
I(E) = 130 E^{-2.8} \text{ counts cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1}
\]

in the energy range 135 keV to 380 keV. By fitting the same functional form to the whole range of energies results in a higher value for the spectral index \(\approx 2.5\). This steepening is of course due to a larger fraction of high energy photons getting Compton scattered while interacting with the crystal and thus yielding higher counting rates in the low energy channels.
3.3 0.51 MeV annihilation line

One of the interesting features of the low energy gamma spectrum investigated in these experiments is the presence of a significant peak around 0.51 MeV, normally attributed to the annihilation between positrons and electrons at rest. The existence of a clear hump over the continuous spectrum near this energy is seen at all atmospheric depths less than 500 g cm

The photopeak counting rate \( R \) of the 0.51 MeV line has been estimated in the conventional way for further intercomparison. The observed counting rates in the channels which do not contain any contribution from the 0.51 MeV line, have been fitted to a power law function, the nature of the energy loss spectrum having been independently ascertained as a straight line in a log-log plot, the intensity vs. energy. Superimposing this fit of the continuous spectrum on the observed spectrum including the peak, \( R \) has been obtained as the difference between the areas under the two curves. The line intensity \( I \) is then computed using the formula

\[
I(0.51\text{ MeV}) = \frac{R}{\varepsilon_p G}\text{ photons cm}^{-2}\text{ sec}^{-1}
\]

where \( \varepsilon_p \) is the photopeak efficiency of the NaI(Tl) crystal at 0.51 MeV. The value of \( \varepsilon_p \) for the crystals used in the present experiment are obtained from graphical interpolation of the photopeak efficiency values calculated by Miller et al. (1957). For the crystals used in F-1, F-2 and F-3, the \( \varepsilon_p \) values determined are 0.17, 0.27 and 0.50 respectively.

In Fig. 3, we show the altitude dependence of the intensity of the annihilation gamma rays over Hyderabad, calculated as explained above. The source strength \( S \) for this line at the transition maximum can be easily calculated using the formula

\[
S = F_{\text{ann}}\mu
\]

where \( F_{\text{ann}} \) represents its flux at the transition maximum and \( 1/\mu \) the effective source thickness. For 0.51 MeV gamma rays \( \mu \approx 17\text{ cm}^2\text{ g}^{-1} \), resulting in a value for \( S = 0.021 \) photons g\(^{-1}\) sec\(^{-1}\). As two gamma rays are produced in a single annihilation event, this
is equivalent to a positron annihilation rate in air at the transition maximum of 0.011 g cm⁻² sec⁻¹ for the evaluated 0.51 MeV line intensity of 0.25 ± 0.04 photons cm⁻² sec⁻¹. The rate of positron production in a vertical column of 1 cm³ area of the atmosphere can be computed using the expression

\[ N = \frac{3}{4} \mu \int_0^{1030} F(x) \, dx \]

where \( x \) is the atmospheric depth in g cm⁻². This gives a value of 3.4 positrons cm⁻² sec⁻¹ over Hyderabad. Using a primary intensity of 0.08 particles cm⁻² sec⁻¹, 42 positrons are found to result for every primary cosmic ray particle arriving over Hyderabad.

**Fig. 3.** Altitude dependence of the intensity of 0.51 MeV line over \( \lambda_m = 7.6^\circ \) N.

4. DISCUSSION

4.1 Genetic relationship of low energy photons with other secondary cosmic ray components in the atmosphere

The earlier observations of Anderson (1961) and Peterson (1963) at high altitudes and of Vette (1962) at mid-latitudes have given evidence that the bulk of the low energy photons in the atmosphere originate from the soft (electromagnetic) component and that the secondary nucleonic component plays a relatively minor role in the production of this radiation. Recent work of Haymes et al. (1969) at mid latitudes further substantiates this conclusion.

The conventional technique of exploring the genetic relationship is through a comparison of the absorption length of these photons with those of other secondary components in the equilibrium region from 600 g cm⁻² to 200 g cm⁻² atmospheric depth. To make such a study we have summarised in Table 2 the absorption lengths for different secondary radiations from observations made at this latitude. Results of other latitudes are not used in the interpretation to avoid the possible difficulties introduced by the geomagnetic effects.

An examination of Table 2 shows that the absorption mean free paths for gamma rays, electron and the muon component are more or less the same, and are significantly different from that for neutrons, which have a considerably lower value indicating the association of gamma rays with electromagnetic component of the cosmic radiation. From a theoretical
analysis of the problem of origin of low energy photons, Rocchia et al. (1965) conclude that about 85 per cent of these gamma rays are due to electromagnetic showers. The direct emission of excited atmospheric Na rays through $\text{O}_14(n, \gamma)$ and $N_14(n, \gamma)$ reactions and the neutron and charged particle induced effects in NaI(Tl) cannot account for more than 12 per cent of the observed gamma-ray intensities. The present work is in substantial qualitative agreement with such a conclusion.

### Table 2

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<tr>
<th>Experiment</th>
<th>Nature of $\gamma$-ray measured</th>
<th>Absorption length (g cm$^{-1}$)</th>
<th>Reference</th>
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<tr>
<td>Scintillation gamma ray spectrometer</td>
<td>Gamma rays $E &lt; 100$ keV and 1 MeV $\gamma$</td>
<td>210</td>
<td>Present results</td>
</tr>
<tr>
<td>Scintillation gamma ray spectrometer</td>
<td>$0.5$-1 MeV $\gamma$ rays</td>
<td>190</td>
<td>Present results</td>
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<tr>
<td>Ion chamber</td>
<td>Measures $\pi$-mu mesons and electron $\rightarrow$ slow transition maximum</td>
<td>200</td>
<td>Present results (Appendix)</td>
</tr>
<tr>
<td>GM counter</td>
<td>Measures $\pi$-mu mesons and electron $\rightarrow$ slow transition maximum</td>
<td>205</td>
<td>Present results (Appendix)</td>
</tr>
<tr>
<td>CsI(Tl) phosphwich</td>
<td>$10 &lt; E &lt; 5000$ keV neutrons</td>
<td>130</td>
<td>Daniel et al. (1969)</td>
</tr>
<tr>
<td>CsI(Tl) scintillator for neutron gamma measurements</td>
<td>Gamma rays $E &lt; 5$ MeV</td>
<td>247</td>
<td>Apparno et al. (1968)</td>
</tr>
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</table>

4.2 Neutron induced effects in the NaI(Tl) detector

Some contribution to the observed count rates is expected from the radiative capture of thermal neutrons and by star p $\rightarrow$ reaction in NaI(Tl). The capture of thermal neutrons by NaI(Tl) causes the prompt emission of gamma rays of several MeV energy. Most of these will result in energy losses greater than 1 MeV in the detector and get counted in the integral channel; i.e., energy loss greater than about 1 MeV. However, both the isotopes Na$^{24}$ and I$^{131}$, which result from the neutron capture, $\beta$-decay with half-lives of 15 hr (Endt and Brams, 1957) and 25 min (Benczer et al. 1969) respectively. These secondary decay electrons thus get counted in channels with energy losses below 1 MeV.

In what follows, an estimate of the neutron induced contribution to the counting rates is made for the case of $2'' \times 2''$ NaI(Tl) crystal used in F-3. To make a realistic calculation of the neutron capture rate by the crystal, it is necessary to take into account the velocity spectrum of the low energy neutrons in the atmosphere. This is essential, because, though the fast neutrons in the atmosphere are slowed down by collisions with the atoms of nitrogen and oxygen, they are captured through $N_14(n, p)$, $C_{14}$, $N_{14}(n, p)$, $C_{12}$ reactions before becoming completely thermalized. However, since the absorption cross-sections in Na and I vary as the inverse of the velocity $v$ of the neutrons, the capture rate in NaI can be calculated if the capture rate of the atmospheric neutrons in some other absorber is known. Measurements involving BF$_3$ counters provide the necessary data since to a good approximation they are $1/p$ detectors for neutron energies 0 to 10 keV. The low latitude data on the flux of slow neutrons given by Soberon (1956) are used here to calculate the capture rate in BF$_3$. The capture rate in a 100 per cent $\text{BF}_3$ gas can be calculated in these experiments as two different sets of counters were used: one with 10 per cent $\text{BF}_3$ enrichment and other with 96 per cent. Once the capture rate in $\text{BF}_3$ gas is known, the rates for NaI crystal can be computed using the method given by Bethe et al. (1940). The $1/p$ dependent cross sections
used for NaI and B\textsuperscript{13} to calculate this contribution are 1.2 \(E^{-1/2}\) and 631 \(E^{-1/2}\) respectively. This computation leads to a counting rate of 0.2 counts sec\textsuperscript{-1} for the present detector at Pfotzer maximum over equatorial latitudes, a negligible value compared with the total counting rate (130 sec\textsuperscript{-1}) encountered in the experiment.

The flux of star producing neutrons near the equator is estimated from the measurements of Lord (1951), after a latitude correction, whose magnitude is assumed to be similar to that of the fast neutron intensity latitudinal distribution observed by Holt et al. (1966). An intensity of 0.49 neutrons cm\textsuperscript{-2} sec\textsuperscript{-1} observed by Lord at Pfotzer maximum over 55°N latitude is therefore reduced by a factor of 7, resulting in 0.07 neutrons cm\textsuperscript{-2} sec\textsuperscript{-1} over Hyderabad. Using the geometrical cross sections for Na and I of 0.37 \(\times\) 10\textsuperscript{-24} cm\textsuperscript{2} and 1.14 \(\times\) 10\textsuperscript{-24} cm\textsuperscript{2} respectively, the total geometrical cross section for NaI is calculated to be 1.51 barns per molecule. Hence for the crystal used in the present experiment the total cross section is 2.95 cm\textsuperscript{2}. The star production rate in the crystal is therefore 2.95 \(\times\) 0.07 sec\textsuperscript{-1} = 0.2 sec\textsuperscript{-1}, at the Pfotzer maximum, again a negligible contribution to the observed count rate.

4.3 Nature of the spectrum

The observed energy loss spectrum in the present experiment can be adequately represented by a power law function of the type \(KE^{-n}\). The spectrum appears to maintain the same shape with \(n = 2.5\) from 700 g cm\textsuperscript{-2} to the smallest atmospheric depths indicating thereby that the low energy \(\gamma\)-ray spectrum is an equilibrium phenomenon. This can be further seen from the study of the 'color' indices shown in Fig. 4. This index is essentially the ratio of the count rate observed in a particular energy interval to those in some other interval, at a certain atmospheric depth. If the value of this index remains the same at different depths, it indicates that the relative changes of the rates in the two energy intervals are the same or in other words, the spectral shape has remained unchanged. The spectrum derived after the correction for the photopeak efficiency has an index of 1.79. This is

![Fig. 4. The nature of the spectrum at different atmospheric depths as depicted by color index plots.](image)
comparable with the index of 1.87 quoted by Haymes (1969) for mid latitudes. The derivation of the spectrum after correction for the photopeak efficiency in such a simple manner is not strictly valid as pointed out by Chupp and Forrest (1970). These authors point out that the conversion of the observed counts cm⁻² sec⁻¹ eV⁻¹ to photons cm⁻² sec⁻¹ sr⁻¹ keV⁻¹ using the above prescription is valid only as long as gamma rays of a unique energy produce pulse heights corresponding to the same energy. In the unshielded NaI(Tl)

detector, this assumption is valid only for photons of energies less than 150 keV. For higher energies, to unfold the true photon spectra from the registered energy loss spectra, accurately measured detector response functions must be used. Such a detailed procedure is not attempted here; but the calculations have been done strictly for comparison purposes. In Fig. 5, the energy loss spectra measured in the present experiment at 6 g cm⁻² depth is compared with those observed by other workers. One fact that should be borne in mind about this representation is that these observations have been made at different latitudes and using a variety of detectors. The altitudes at which the reported spectra were measured are also different. In addition, most of the observations have been made at high and mid latitudes, where the primary cosmic radiation is known to undergo appreciable time variation. Therefore without applying appropriate corrections for latitude, altitude, time variation as well as the detector responses, quantitative comparison of different results cannot be carried out. However, it is interesting to note that the general forms of the spectra of gamma radiations observed in various measurements are quite consistent with each other, all of them showing similar spectral behaviors.

4.4 The annihilation line at 0.51 MeV

As shown in Fig. 2, excess photons of energies around 0.51 MeV line are present in detectable numbers at all atmospheric depths less than 500 g cm⁻² up to 6 g cm⁻², the

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Fig. 5. Comparison of the energy loss spectra obtained from high and middle latitude observations with those of the present experiment.

1. Anderson (1961), 6-5 g cm⁻², λ₀ = 65°N; 2. Peterson (1963), 6 g cm⁻², λ₀ = 55°N; 3. Chupp et al. (1967), 4 g cm⁻², λ₀ = 42°N; 4. Haymes et al. (1969), 3-4 g cm⁻², λ₀ = 42°N; 5. Vette (1962), 5-4 g cm⁻², λ₀ = 40°N; 6. Northrop et al. (1961), rocket, λ₀ = 55°N; 7. Present results (1972), 6 g cm⁻², λ₀ = 7-8°N.
<table>
<thead>
<tr>
<th>Year of experiment</th>
<th>Geomagnetic latitude</th>
<th>Ceiling atmospheric depth (g cm⁻²)</th>
<th>Nature of detector</th>
<th>Remarks and reference</th>
<th>Intensity of 0.51 MeV line (photons cm⁻² sec⁻¹)</th>
<th>Reduced to 6 g cm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>55°N</td>
<td>60</td>
<td>5.1 cm x 5.1 cm NaI(Tl)</td>
<td>Present results (F-1)</td>
<td>0.31 ± 0.03</td>
<td>0.62 ± 0.06</td>
</tr>
<tr>
<td>1962</td>
<td>55°N</td>
<td>60</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Present results (F-2)</td>
<td>0.34 ± 0.04</td>
<td>0.65 ± 0.07</td>
</tr>
<tr>
<td>1963</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.35 ± 0.03</td>
<td>0.67 ± 0.07</td>
</tr>
<tr>
<td>1964</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.34 ± 0.03</td>
<td>0.66 ± 0.07</td>
</tr>
<tr>
<td>1965</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.35 ± 0.03</td>
<td>0.67 ± 0.07</td>
</tr>
<tr>
<td>1966</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.34 ± 0.03</td>
<td>0.66 ± 0.07</td>
</tr>
<tr>
<td>1967</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.35 ± 0.03</td>
<td>0.67 ± 0.07</td>
</tr>
<tr>
<td>1968</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.34 ± 0.03</td>
<td>0.66 ± 0.07</td>
</tr>
<tr>
<td>1969</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.35 ± 0.03</td>
<td>0.67 ± 0.07</td>
</tr>
<tr>
<td>1970</td>
<td>47°N</td>
<td>5.3 cm x 5.3 cm NaI(Tl)</td>
<td>Unshielded</td>
<td>Haymes et al. (1969)</td>
<td>0.34 ± 0.03</td>
<td>0.66 ± 0.07</td>
</tr>
</tbody>
</table>

Note: The table includes data from various researchers and years, with Geomagnetic latitude, Ceiling atmospheric depth, Nature of detector, Remarks and reference, and intensity of 0.51 MeV line (photons cm⁻² sec⁻¹) reduced to 6 g cm⁻².
minimum depth of our observations. While most of these photons must be due to the
annihilation of cosmic ray secondary positrons coming to rest, some are also expected
from the neutron induced reaction $^{112}_n(n, 2n)I^{119}_B$ in the detector.

To estimate the extent of contribution of these 0-51 MeV photons to the observed
counting rates, the fast neutron flux in the atmosphere at the transition maximum measured
by Holt et al. (1966) over Hyderabad and an interaction cross section of about 1 barn for
$(n, 2n)$ reaction in iodine are used. The resultant reaction rate is found to be equal to
0.24 sec$^{-1}$ for the 51 cm $\times$ 51 cm NaI(Tl) crystal. This is about 5 per cent of the measured
counting rates near 0.51 MeV at the transition maximum and therefore is not significant.
Moreover the $^{119}_B$ undergoes positron decay with a half-life of about 4 hr, with the
result that $^{119}_B$ activity will be substantially below the production rate; in other words, the
rate computed from this possible source of positron production is only an upper limit.

It is of great interest to investigate the latitude effect in the intensity of the 0.51 MeV
line. Due to the lack of results from low latitudes, this has not been carried out satisfactorily
so far. It is now possible to discern the details of the latitude effect for this gamma ray line,
by comparison of the present observations over Hyderabad with those made at mid and high
latitudes. Towards this, we summarise in Table 3, the current observational status of the
0.51 MeV line. Before proceeding with the discussion, a few remarks about this table are
in order. We note that the intensity measured by Frost et al. (1966) is now in agreement
with Peterson’s (1970) revised value, which takes into account the discrepancy of a factor
of two in his earlier published estimate of the fluxes (Peterson, 1963). Observations of Chupp
et al. (1970) at 42°N geomagnetic latitude conducted during 1967 and 1968 are consistent
with each other. The higher values quoted by the same authors for the intensity of this line
during 1966 has been interpreted as due to inexact efficiency factors for CsI(Tl) used in
deriving this result. Haymes et al. (1969) are of the opinion that there is a line structure at 490
keV rather than at 510 keV. At 510 keV, they are able to quote an upper limit only. Since
then, the actual energy of this line whether it is at 490 keV or 510 keV, has become
controversial. But no experiment conducted to date can unequivocally clarify this aspect.
Further, since there are strong reasons for the existence of the annihilation line, in the pre-
sent work it is assumed that the intensities detected by these authors actually correspond to
0.51 MeV energy.

In Fig. 6, the intensities of the 0.51 MeV photons are plotted as a function of magnetic
latitude. All the observations have been reduced to 6 g cm$^{-2}$ depth to eliminate the small
differences in fluxes arising from altitude effects. In addition, since these measurements
have been made at different epochs of solar activity, the actual latitudinal curve may slightly
differ from the presented one. Allowance is made for the time variation effects at different
latitudes. However, as is evident from the table, neither the observations of Peterson and
Frost et al. in 1961 and 1962 respectively from Minneapolis nor those of Chupp et al. during
1966-1968 from mid latitudes give any indication for the existence of a consistent time
variation effect. Under such circumstances, it is difficult to evaluate the extent of its effect
on the existing observations. Moreover, as will be clear from the discussion a little later,
most of these 0.51 MeV gamma rays are the result of positrons which are produced in high
energy interactions. The corresponding primary energies are 4 GeV or more, where the
total time variations should be less than 15-20 per cent. The reflected time variation on
dependent positrons is therefore expected to be much less than this.

From the Fig. 6, it is evident that the flux of 0.51 MeV photons reduces by a factor of
9 at 6 g cm$^{-2}$ in going down from geomagnetic latitude of 55°N to 7-8°N, corresponding
to cut off rigidities of 1.3 and 16.9 GeV respectively. The latitude effect observed in the continuous gamma ray spectrum is also found to be of the same order. Comparing the observations of Chupp et al. (1970) with those of the present experiment, a reduction by a factor of 3.6 is seen between $\lambda_{eq} = 42^\circ$ and equatorial latitudes for this line.

The positron production rate in a vertical column of the atmosphere is estimated by using the intensity of the annihilation line as a function of depth. It is illuminating to see how this positron production rate per unit primary particle changes with the cut off rigidity. Such an investigation can give an insight into the energy range of primaries which are most responsible for the production of positrons in the atmosphere. In Fig. 7, a plot of the results of such a study is given. It is interesting to note that the number of positrons produced per primary cosmic ray particle increases rather sharply with the decrease in magnetic latitude from high to mid latitudes but later levels off towards lower latitudes. This can be understood if account is taken of the fact that the positrons result from pion production, and the average pion multiplicity per primary increases with the energy of the particle. As the average primary energy of the particle goes up by moving towards lower latitudes, a higher pion multiplicity results, which explains the observed behaviour. Moreover, beyond about 4 GeV primary energy, all the particles appear to be equally effective in the production of positrons as is evident from the flattening.

4.5 Comparison of atmospheric and cosmic gamma ray intensities

It is significant to compare the intensities of the low energy photons observed in the present experiment at $6 \text{ g cm}^{-2}$ atmospheric depth with those reported by Metzger et al. (1964) in Ranger 3 spacecraft. These observations made in cislunar space are assumed to be the genuine flux of interstellar gamma rays because care was taken to evaluate the local production effects and the contribution to the counting rates from Sun and Earth was negligible. To estimate the contribution of these cosmic photons to the detector counting...
rates at 6 g cm\(^{-2}\), an approach similar to that given by Peterson (1964) is adopted and is as follows. The counting rate \(N(E, x)\) in a detector of omnidirectional response with geometrical factor \(G\) cm\(^{-2}\) at an atmospheric depth \(x\) due to the isotropic cosmic photon spectrum \(I_c(E)\) above the atmosphere is given by

\[
N(E, X) = \frac{I_c(E)\phi(E)}{4\pi} dE \int_0^{\phi/2} \int_0^{\pi/2} G(\theta, \phi) e^{-\mu(E)\phi \sin \theta} \sin \theta d\theta d\phi
\]

where \(\phi(E)\) is the photopeak efficiency of the crystal used, \(\mu(E)\) is the total attenuation coefficient in air at energy \(E\), \(\theta\) and \(\phi\) are the usual polar coordinates. Since the projected area of the counter in any direction is azimuthally symmetric about \(\phi\) and changes only slowly with \(\theta, G(\theta, \phi)\) can be removed from the integration and \(G\) substituted. Under these circumstances

\[
N(E, X) = \frac{-\phi(E)\phi(E)}{2} dE \int_0^{\phi/2} e^{-\mu(E)\phi \sin \theta} \sin \theta d\theta
\]

\[
= \frac{-\phi(E)\phi(E)}{2} dE \phi_1(k)
\]

where \(\phi_1(k)\) is the Gold integral and \(k = \mu x\). The counting rate expected from this source in different energy channels is thus calculated. In Fig. 8, the ratio of these rates to the total observed intensity is shown as a function of energy. It is clear from this figure that at equatorial latitudes, with the omnidirectional detectors of the type used in the present experiment, the cosmic contribution is about 10 per cent of the total observed rates at 6 g cm\(^{-2}\) atmospheric depth. It is no wonder therefore that the observed intensities in the present experiment did not show any upturn till the fluctuating depth of 6 g cm\(^{-2}\). The 'color' index study discussed earlier also substantiates the above conclusion, as no concrete evidence is seen for any spectral change till 6 g cm\(^{-2}\) depth. The complex nature of the ratio as a function of energy arises due to the structure of the observed spectrum at these latitudes.

It should, of course, be stressed here again that such a simple evaluation of the counting...
rate contribution due to cosmic photons in the detector is not strictly valid. A rigorous calculation will involve folding the cosmic spectrum through the instrumental response after appropriate atmospheric attenuation effects. Nevertheless, the straight-forward calculation presented here is good enough to justify qualitatively, at least, most of the observed features.

The extrapolated intensity of the 0.51 MeV annihilation line at the top of the atmosphere, in the present experiment, is 0.072 ± 0.008 photons cm⁻² sec⁻¹, i.e. nine times lower than the corresponding Minneapolis value. Such a strong latitude effect is indicative of the fact that most of these photons are albedo, as extraterrestrial intensity will be latitude independent. Moreover the upper limit placed on the intensity of this line from the Ranger 3 observations is 0.014 photons cm⁻² sec⁻¹ in free space. Near the Earth where the corresponding upper limits on these cosmic photons will be halved due to shielding effect, it is 0.007 photons cm⁻² sec⁻¹; which is about a factor of ten less than the present extrapolated intensity. It is therefore clear that the cosmic contribution to the annihilation line intensity at balloon altitudes over equatorial latitudes is negligible.

In conclusion we list below the salient results of the present study on the first equatorial latitude measurements of the low energy atmospheric gamma rays. (a) In the energy interval 100 keV to 1 MeV, the photon spectrum is composed of a background continuum with a superimposed line structure at 0.51 MeV originating from the electron positron annihilation. The energy loss spectrum can be adequately represented by a power law function with a negative exponent of 2:2 for energies less than 380 keV. Further, the spectrum maintains the same shape from 700 g cm⁻² to the smallest atmospheric depths, implying thereby that the low energy gamma rays in the atmosphere represent an equilibrium phenomenon. (b) Through a comparison of the attenuation lengths of the different cosmic ray secondary components in the equilibrium region of the atmosphere, it is concluded that these low energy gamma rays are genetically related to the secondary electromagnetic component. This is in agreement with similar deductions from high and middle latitudes. (c) The contribution to the observed counting rates from the neutron induced effects in NaI(Tl) is shown to be less than 5 per cent in these measurements. (d) The presence of the electron-positron annihilation line at 0.51 MeV in detectable intensities is apparent in the present
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measurements. Its intensity at 6 g cm$^{-2}$ is estimated to be $0.079 \pm 0.007$ photons cm$^{-2}$ sec$^{-1}$ whereas that at the Pfoitzar maximum is $0.24 \pm 0.02$ photons cm$^{-2}$ sec$^{-1}$. The value of the absorption length for this line is about the same as that for the rest of the continuous spectrum. Reliable estimate of the latitude effect of 0.51 MeV line has been made for the first time by comparing our results with those of other workers corresponding to mid and high latitude. The intensity at 6 g cm$^{-2}$ over $\lambda_{eq} = 0^6N$ is a factor of 9 and 3.6 less than those at high ($55^6N$) and middle latitudes ($42^6N$) respectively. (c) Using the altitude dependence of 0.51 MeV intensity, derived from the present observations, the positron production rate in 1 cm$^2$ column of the atmosphere over Hyderabad is evaluated as $3.4 \times 10^{-4}$ sec$^{-1}$. This means that about 42 positrons result for every primary cosmic ray particle over this station. (f) A study of the dependence of the number of positrons per primary particle on the cut off rigidity of the location of observation reveals the interesting feature that its value i.e. $16\gamma$ per primary at high latitude increases steeply to $40\gamma$ per primary at middle latitudes and then remain more or less constant at $\leq 50\gamma$ per primary to low latitudes. This points to the important role played by higher energy particles in the production of the atmospheric positrons. This aspect is further referred in the absence of detectable long term variations to the important role played by higher energy particles in the production of the atmospheric photons in experiments of the present nature.

Acknowledgements—We wish to express our appreciation to Mr. R. T. Redkar and his balloon launching crew of Tata Institute of Fundamental Research for successful flight operations. One of the authors (K. K.) is grateful to Prof. N. W. Nerurkar for his interest in this work. We are grateful to Prof. John R. Winckler of the University of Minnesota for providing the CM units. The financial support for this work came from the Department of Atomic Energy, Government of India.

REFERENCES


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REFERENCES

APPENDIX

Continuous Monitoring Unit flights over Hyderabad

The measurements reported here pertain to a series of balloon flights in which the continuous monitoring units developed by the University of Minnesota were flown from Hyderabad since 1966. The information on the constructional and operational features of these units is already available in the literature (Masley et al., 1962) and therefore is not given here. Some of the flights carried two or three units simultaneously for direct intercomparison of the rates in the atmosphere.

The observed pulsing rates of the chamber are converted to normalized rates by multiplying by the normalization factor appropriate to the chamber. These normalized pulse rates \( R_n \) are then transformed into the usual units for the ion chamber rates i.e. ion pairs cm\(^{-3}\) sec\(^{-1}\) atm\(^{-1}\) with the formula (Winckler, 1960)

\[
N(\text{ion cm}^{-3} \text{ sec}^{-1} \text{ atm}^{-1}) = 12.3 \times 10^3 \times R_n.
\]

In Table 4, typical values of the ion production rates so deduced, as well as the GM counter rates at different atmospheric depths over this station, are given. The telescope rates could not be computed accurately due to poor statistical accuracy and hence are not given. All the CM flights gave practically the same ionization rates (time variations are less than 3 per cent) as a function of altitude and as such the values quoted are representative of this parameter over Hyderabad.

<table>
<thead>
<tr>
<th>Atmospheric depth (g cm(^{-2}))</th>
<th>Ion chamber rates (ions cm(^{-3}) sec(^{-1}) atm(^{-1}))</th>
<th>GM counter rates (counts cm(^{-2}) sec(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>18.6</td>
<td>0.1 ± 0.02</td>
</tr>
<tr>
<td>400</td>
<td>24.2</td>
<td>0.19 ± 0.03</td>
</tr>
<tr>
<td>300</td>
<td>31.7</td>
<td>0.31 ± 0.04</td>
</tr>
<tr>
<td>200</td>
<td>47.5</td>
<td>0.47 ± 0.05</td>
</tr>
<tr>
<td>150</td>
<td>61.3</td>
<td>0.62 ± 0.05</td>
</tr>
<tr>
<td>100</td>
<td>64.9</td>
<td>0.70 ± 0.06</td>
</tr>
<tr>
<td>60</td>
<td>60.0</td>
<td>0.63 ± 0.05</td>
</tr>
<tr>
<td>30</td>
<td>46.5</td>
<td>0.48 ± 0.05</td>
</tr>
<tr>
<td>20</td>
<td>39.7</td>
<td>0.40 ± 0.05</td>
</tr>
<tr>
<td>15</td>
<td>36.3</td>
<td>0.36 ± 0.04</td>
</tr>
<tr>
<td>10</td>
<td>32.2</td>
<td>0.31 ± 0.04</td>
</tr>
</tbody>
</table>

Table 5

<table>
<thead>
<tr>
<th>Atmospheric depth (g cm(^{-2}))</th>
<th>Ratio (GM counter rate/ (10^8 \text{ ion chamber rate} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis</td>
<td>Hyderabad</td>
</tr>
<tr>
<td>300</td>
<td>3.36</td>
</tr>
<tr>
<td>200</td>
<td>3.84</td>
</tr>
<tr>
<td>100</td>
<td>4.03</td>
</tr>
<tr>
<td>50</td>
<td>4.21</td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td></td>
</tr>
</tbody>
</table>

Out of these measurements the values of certain interesting physical quantities for Hyderabad are calculated. One is the energy integral (the total energy lost by the cosmic rays through ionization in one cm\(^3\) vertical column of air), given by the formula (Winckler, 1960).

\[
E = 1.42 \times 10^8 \times P \text{ eV cm}^{-2} \text{ sec}^{-1}.
\]
where

$$F = 2.5 \int_{0}^{1000} R_n \, dP.$$ 

This is found to have a value of 0.673贝v cm⁻³ sec⁻¹. This value is consistent with 0.82贝v cm⁻³ sec⁻¹ obtained by using similar parameters from the latitude survey of Neher (1967), if the discrepancy of 17 per cent in ion production rates between Minnega and Neher chambers (Hoffman, 1960) is taken into account.

Another quantity of interest is the ratio of ion chamber rate to GM rate. This is proportional to the mean omnidirectional ionization of the combined cosmic ray primaries and secondaries in the atmosphere. This ratio is calculated using the counting rates of these detectors after correcting for the differences in their geometrical factors. In Table 5, their values as a function of atmospheric depth are given for Hyderabad and Minneapolis. Minneapolis values are taken from a tabulation by Winckler (1960). The high value of the ratio at 300 g cm⁻² for Hyderabad may be due to poor GM statistics. Consistently low values of this ratio for Hyderabad is expected because of the higher average mean energy of the primary and secondary particles for this station compared to Minneapolis. The calculated value of this ratio for isotropic minimum ionizing particles is 3.19 (Winckler, 1962).

The absorption lengths for the observed rates of the ion chamber and GM counters in the equilibrium region of the atmosphere (200 g cm⁻² to 600 g cm⁻²) are found to be 200 g cm⁻² and 205 g cm⁻² respectively over Hyderabad.
Study of cosmic ray diurnal variation on a day-to-day basis

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Abstract. From a careful examination of the diurnal variation of cosmic ray intensity at high energies and the interplanetary field characteristics, the average characteristics of diurnal variation were recently explained by us in terms of a balance between outward convection and field aligned diffusion, the latter arising out of a positive radial density gradient. In this paper, we extend this new concept to explain the large variability observed in the diurnal variation on a day-to-day basis and further demonstrate that the measurement of diurnal anisotropy characteristic of cosmic ray particles on a day-to-day basis can be used directly to infer the nature and scale sizes of interplanetary field parameters. Comparing with the magnetic field vector, we show that this simple concept holds good on more than 80% of days. On the rest 20% of days which have a predominant morning maxima, the diurnal anisotropy characteristics seem to indicate the presence of a significant component of transverse diffusion current in addition to the normal convection and diffusion flow. Such days are found to be present in the form of trains of consecutive days and are found to be associated with abrupt changes in the interplanetary field direction having scale sizes > 4 hr. The value of \( K / K_0 \) which is normally about < 0.05 is found to be \( \approx 1.0 \) on non-field aligned days.

Keywords. Cosmic rays; diurnal variation; interplanetary magnetic field; solar wind.

1. Introduction

For almost a decade it has been quite apparent that the average cosmic ray diurnal variation is consistent with it being due to corotation of these particles with the solar system magnetic fields which are themselves stretched in the form of an Archimedes spiral by the radially blowing solar wind. The large amount of experimental evidence (Rao et al 1963, McCracken and Rao 1965, Rao 1972) obtained from superneutron monitor data have conclusively shown that the yearly average diurnal variation is energy-independent up to a maximum energy \( E_{\text{max}} \approx 100 \) GeV and practically invariant with the solar cycle. Till recently, however, it was widely believed that the amplitude of the observed diurnal variation was considerably less than that predicted by the usual Compton-Getting effect which was attributed to the existence of a significant perpendicular diffusion due to the presence of magnetic field irregularities. Recent low energy solar particle observations made by McCracken et al (1968, 1971) simultaneously at different heliolongi-
Cosmic ray diurnal variation

Cosmic ray diurnal variation

Itudes with widely spaced Pioneer deep space probes have clearly indicated that the azimuthal anisotropy at energies \( \leq 100 \text{ MeV} \) is quite negligible and that the particle population is largely determined by the balance between radial convection and field aligned diffusion. In other words, it has been shown that at these energies \( K_d/K_0 \lesssim 0.05 \). Extending these arguments to relativistic energies, McCracken et al. (1968), Gleeson (1969) and Forman and Gleeson (1970) suggested that the diurnal anisotropy observed in the galactic cosmic radiation can also be understood as a superposition of simple convection and diffusion. Since then the apparent discrepancy between the observed amplitude of the average diurnal variation and the theoretically predicted amplitude has been successfully accounted for (Subramanian 1971) by a number of hitherto unaccounted second order effects such as the finite value of \( T_{\text{max}} \) improper normalization, etc.

From a careful analysis of worldwide neutron monitor network data and their comparison with measured interplanetary field parameters, Rao et al. (1962) and Hashim et al. (1972) have independently demonstrated that the average diurnal anisotropy can, in fact, be explained completely in terms of simple convection and diffusion. According to this concept, the radial convective flow will be balanced by the inward diffusion on an average basis causing the net radial current to be zero and resulting in a convectional anisotropy of the right magnitude. Comparing with the interplanetary magnetic field (IPMF) data, Rao et al. (1972) showed that the diffusion vector is field aligned both on average basis and also during days exhibiting enhanced diurnal variation, the diffusion current, or an average basis, being driven by a radial density gradient of \( \approx 5\% / \text{A.U.} \) which is consistent with the direct measurements (O'Sullivan 1972, Rao 1972). Since this paper (Rao 1972) forms the basis of our present investigation, it will henceforward be referred to as paper I.

Even though the average picture of the diurnal variation has now been explained quite satisfactorily in terms of a good physical model, the detailed picture of the diurnal variation, on a day-to-day basis, remains to be clearly understood. The large variability present in both amplitude and the time of maximum of the diurnal variation has been established by a number of workers (Rao and Sarabhai 1964, Patel et al. 1968). In paper I we pointed out that the new concept of the diurnal variation was capable of explaining the day-to-day variability in terms of varying diffusion current, there being no balance between convection and diffusion on a short term basis. A few specific examples were individually treated to demonstrate the validity of the theory showing that, even on days when the interplanetary field vector showed clear departure from the Archimedes spiral pattern the cosmic ray diffusion vector derived from observations were clearly field aligned. In this paper we present detailed analysis of diurnal anisotropy on a day-to-day basis to test the validity of the new concept and demonstrate that on most of the days the concept is valid. Further we also attempt to determine the detailed characteristics of few days on which the observed diurnal anisotropy shows departure from the simple convection and diffusion picture indicating the presence of a significant perpendicular diffusion on such days.

2. Data analysis

In order to examine the cosmic ray diurnal variation on a day-to-day basis in a statistically meaningful way we have combined the data from six high latitude
A G Ananth, S P Agrawal and U R Rao

Table 1. List of stations used to derive day-to-day diurnal anisotropy vectors

<table>
<thead>
<tr>
<th>Stations</th>
<th>Geographic coordinates</th>
<th>Mean asymptotic coordinates</th>
<th>Cut-off rigidity (G.V.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude (deg.)</td>
<td>Longitude (deg.)</td>
<td>Latitude (deg.)</td>
</tr>
<tr>
<td>Inuvik</td>
<td>68.4</td>
<td>226</td>
<td>47</td>
</tr>
<tr>
<td>Calgary</td>
<td>51.1</td>
<td>246</td>
<td>28</td>
</tr>
<tr>
<td>Churchill</td>
<td>58.8</td>
<td>266</td>
<td>40</td>
</tr>
<tr>
<td>Deep River</td>
<td>46.1</td>
<td>283</td>
<td>27</td>
</tr>
<tr>
<td>Goose Bay</td>
<td>53.3</td>
<td>300</td>
<td>35</td>
</tr>
<tr>
<td>Kiel</td>
<td>54.3</td>
<td>10</td>
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</tr>
</tbody>
</table>

neutron monitoring stations and having a narrow asymptotic cone of acceptance. Table 1 gives the relevant physical parameters of these stations. After taking out long term variation by moving average method, the data on each day are harmonically analysed to obtain the diurnal and semi-diurnal variation vectors for each of the selected stations. The diurnal and semi-diurnal anisotropy amplitude and phase in space as observed at each station are then derived, after correcting for the width and declination of the asymptotic cone of acceptance of the detector and geomagnetic bending using the variational coefficient techniques developed by Rao et al (1963) and McCracken et al (1965). In the present analysis, all days on which Forbush decreases take place have been rejected since on such days the sharp intensity gradients are likely to cause a large error in the determination of the diurnal vector. The anisotropy information from individual stations are then combined to derive the average diurnal anisotropy in space for each day. We have selected only those days on which there is a good interstation agreement in the observed diurnal vectors ($\alpha_{amp} < 0.1\%$, $\alpha_{pha} < 30^\circ$) for all our further analysis. The percentage of such days is more than 80. We wish to emphasise the necessity of following the above procedure particularly when dealing with diurnal anisotropy on a day-to-day basis to avoid erroneous conclusions.

Figure 1 shows the histograms of the frequency of occurrence of both the time of maximum and the amplitude of the diurnal anisotropy vector for each day, during 1967–68 derived using the data from six selected stations (solid lines). In the same figure, the corresponding histograms for the diurnal anisotropy vectors as derived from the data from only one station, namely Deep River, are also shown (in dashed lines) for purposes of comparison. The good correspondence between the two sets of histograms demonstrates that the method of obtaining average diurnal anisotropy vectors using data from a number of similar stations provides the true anisotropy vector in space with improved statistics.

Following paper I we represent the observed diurnal vector ($\delta$) as a summation of convective ($\delta_c$) and diffusive anisotropy ($\delta_d$) vectors.

$$\delta = \delta_c + \delta_d$$

(1)

$\delta_c = 3CV_v/V$ can be derived from a knowledge of solar wind velocity $V$, $V$ being particle velocity and $C$ the Compton-Getting factor. The diffusive anisotropy...
Cosmic ray diurnal variation

Figure 1. Histogram showing the frequency of occurrence of diurnal phase and amplitude in space estimated using average of six selected stations (solid lines) and also using data from Deep River neutron monitor (dashed lines).

Figure 2. $\Delta \phi$ distribution is shown for a selected number of days (200 days) during 1967–68 for which both solar wind velocity and IPMF data are available. (a) shows the distribution for all the 200 days, and (b) shows the distribution for days on which there is good interstation agreement in the determination of the diurnal phase.
vector ($\delta_i$) for each day can be determined by subtracting the convection term $\delta_c$ from the observed diurnal anisotropy vector $\delta$. In order to prove the field aligned nature of the diffusive vector, it is necessary to show the difference $\Delta\phi = \phi_a - \phi_c$, should be minimum ($\Delta\phi \approx 0$), i.e., the phase of the diffusive vector $\phi_a$ is identical with the phase $\phi_c$ of the interplanetary magnetic field. However, due to large statistical errors, we assume that the diffusive vector is field aligned if $\Delta\phi < 30^\circ$ which is the practical limit of statistical significance one can impose on a daily basis. Days on which diffusion vector is not field aligned, i.e., $\Delta\phi > 30^\circ$, are designated as non-field aligned days.

3. Characteristics of diurnal variation on a day-to-day basis

Figure 2 shows the histogram of the frequency of occurrence of $\Delta\phi$ for 200 days in 1967–68 for which the data on solar wind velocity are available. It is seen from figure 2(a) that on nearly 73% of days $\Delta\phi < 30^\circ$. If we restrict our analysis to only those days on which there is reasonable interstation agreement in the determination of the diurnal phase (i.e., $\sigma_{\phi_{int}} < 30^\circ$), the percentage of days on which the convection diffusion concept holds good increases to about 78% (figure 2(b)). We may conclude that on nearly 80% of the days, the diurnal anisotropy is describable in terms of simple convection and field aligned diffusion.

Figure 3 shows some typical examples of field aligned nature of diffusion vector on a few selected days, on which either we have observed enhanced solar wind velocity (figure 3(a)) or observed IPMF direction shows a large deviation from the mean field direction (figures 3(b) and 3(c)). In spite of the extreme conditions, it is evident from figure 3 that the diffusion vector is very well field aligned.

In order to extend the analysis for a larger sample of days, even when direct observations on solar wind velocity $V_p$ are not available, we have utilised the empirical relationship between the index of geomagnetic disturbance $\Sigma Kp$ and $V_p$ for estimating $V_p$ on such days. Existence of such a close empirical relationship between $\Sigma Kp$ and $V_p$ has been demonstrated by a number of workers (Snyder et al. 1963, Pai et al. 1967, Bame et al. 1967). We have attempted to obtain such an empirical relationship between $\Sigma Kp$ and $V_p$ for 1967 using the available observations of $V_p$ from Vela 3 satellite. Figure 4 shows the average solar wind velocity for each day for the above period plotted against $\Sigma Kp$, the correlation between $V_p$ and $\Sigma Kp$ is found to be $(0.63 \pm 0.03)$ consistent with the relationship

$$V_p = (4.98 \pm 0.5) \cdot \Sigma Kp + (302 \pm 9) \quad (2)$$

Before using the empirical relationship, it is instructive to compare the results of $\Delta\phi$ distribution derived earlier (figure 2(b)) with results obtained, using $V_p$ values computed from the empirical relationship, given in eq. (2). Figure 5 shows the frequency distribution of $\Delta\phi$ for 170 days during 1967–68, $\Delta\phi$ being computed using $V_p$ values obtained from the empirical relationship using eq. (2). $\Delta\phi$ distribution obtained using observed values of $V_p$ for the same days is also plotted for comparison. The excellent correspondence between the two distributions confirms that the method of calculating the convective vector $\delta_c$ using wind velocity values computed using eq. (2) does not affect any of our conclusions. From a close examination of the data we also confirm that the maximum error introduced by this method is less than 10°, which is well within the statistical error on a day-to-day basis.
Figure 3. Typical examples showing the field aligned nature of the diffusion vector \( \delta \), when (a) the connection \( \delta \), is very much enhanced; and (b) and (c) the observed IPMF direction shows large departures from the mean Archimedian spiral angle.
Figure 4. The correlation between observed solar wind velocity $V_p$ and $\Sigma K_p$, the index of geomagnetic disturbance during 1967.

Figure 5. $\Delta \phi$ distribution for a selected number of days (solid line) during 1967-68, computed using $V_p$ obtained from the empirical relationship shown in equation (2). The $\Delta \phi$ values obtained using actual observation of $V_p$ for the same days is shown (dashed lines).
We have extended the analysis for the entire period 1967-68 by deriving convection vector on each day using the above relationship between $V_o$ and $\Sigma K_o$. Figure 6 (a) shows the histograms of $\Delta \phi$ distribution for all the days (400 days) during 1967-68. We have also shown in the same figure the $\Delta \phi$ distribution separately for days on which the observed diurnal time of maximum is between (1) 15-21 hours (figure 6 b) and (2) 0-15 and 21-24 hours (figure 6 c). It is evident from figures 6 (a) and 6 (b) that on more than 80% of the days the convection diffusion concept holds good. Also note that on days on which the diurnal time of maximum is between 0-15 and 21-24 hours (figure 6 c), the histogram of $\Delta \phi$ distribution is almost flat indicating that on those days on which the diurnal vector is far removed from the direction of coronal, the transverse diffusion currents are quite significant.

4. Characteristics of non-field aligned days

In this section, we examine the detailed characteristics and the scalar terrestrial relationships of the days on which the diffusion vector is not field aligned ($\Delta \phi > 30^\circ$), in order to understand the mechanism which causes the transverse diffusion to be significant on such days. We observe that majority of the non-field aligned days occur in trains of two or more consecutive days indicating that the mechanism
causing transverse diffusion is not a transient phenomenon, but persists over a period of time. In spite of the tendency for such days to occur on consecutive days, they do not show any characteristic features such as enhancement in the diurnal or semidiurnal components, $\Sigma K_p$ index or large variability in interplanetary field parameters. Likewise no large deviation in the mean intensity or 27-day recurrence are observed during these days.

In figure 7 are plotted the frequency distribution of diurnal phase and diurnal amplitude for all the non-field aligned days (solid lines) during 1967-68. For comparison the histogram of diurnal phase and amplitude for all 400 days during 1967-68 is also shown (dashed lines). Whereas the familiar predominant peak around 18 hr direction is clearly evident from the histogram of the diurnal phase for all the days, the histogram for only non-field aligned shows a much flatter distribution. Further it is seen that practically all the days on which diurnal time of maximum is in the morning hours (0-12 hr) the diffusion vector is not field aligned.

Since the presence of trains of non-field aligned days indicate essentially quasi-permanent anomalous condition in the interplanetary space causing transverse diffusion currents we have concentrated on detailed examination of the interplanetary condition during such periods. In figure 8, we show the average IPMF vector for each day plotted end to end for a number of non-field aligned trains of days.
Figure 8. The interplanetary magnetic field vector for each day is plotted end to end for a few trains of a few consecutive non-field aligned days. For comparison the field vectors for one typical field aligned train of consecutive days (6–10 August 1967) is also shown.

Figure 9. Hourly changes in the IPMF vector is shown for a few completely field aligned trains of days.
For comparison, the field vectors for a typical field aligned train of days is also shown. It is evident from the figure that on days on which the diffusion is field aligned the field vectors are well behaved and do not show significant departure from Archimedian spiral. On the other hand, on trains of days on which the diffusion is not field aligned, the field vectors show a large variability both in direction and in magnitude from day-to-day and often show large departures (> 45°) from the mean Archimedian spiral.

Before proceeding to examine in detail, the IPMF characteristics on non-field aligned days, it is instructive to examine the characteristics on field aligned days. Figure 9 shows the hourly changes in IPMF vector along with the daily mean for each day for a few typical trains of field aligned days. Examination of each of the trains shown in the figure clearly brings cut the two most important characteristic features of the IPMF for these days:

(a) the change in the field vector from one hour to the next on the same day is relatively small, and

(b) the change in the field characteristics from one day to the next during each train of events is also negligible.

On the other hand, examination of trains of non-field aligned days shows that on such days large irregularities in the interplanetary field exist. In figure 10
are shown examples of trains of non-field aligned days when the IPMF vector exhibits large change from one day to another. The average daily field vector seems to change its direction by as much as 60-90° from one day to the next. Figure 11 shows examples of trains of non-field aligned days when the IPMF vector, even though does not show large changes from one day to the next, shows the continual presence of large irregularities having scale sizes of > 4 hr during each day.

In order to estimate the scale sizes of the irregularities present during the non-field aligned days, a power-spectrum analysis of the IPMF data has been carried out and figure 12 shows the power density distribution of the radial component at various frequencies for a selected train of non-field aligned days (circles) and also for a train of completely field aligned days (dots). The figure clearly demonstrates that in spite of the large errors associated with the limited data we have used, during non-field aligned trains of days there is a tendency for irregularities having scale sizes ≈ 4-3 hr and 6-2 hr to dominate when compared with field aligned trains of days. These irregularities can effectively scatter particles > 1 GeV and thus introduce a significant transverse gradient in addition to normal convection and diffusion during non-field aligned days.

Figure 11. Hourly changes in the IPMF vector is shown for a few non-field aligned trains of days on which there is no day-to-day changes in the daily mean IPMF. Note the continual presence of irregularities of scales > 4 hr on these days.
5. Discussion and conclusion

Following Forman and Gleeson (1970), we can write the expression for the net streaming of cosmic ray particles in the interplanetary medium as

\[ S = S_0 - K_i \left( \frac{\partial U}{\partial r} \right)_i - K \left( \frac{\partial U}{\partial r} \right)_K - F \left( \frac{\partial U}{\partial r} \right)_B \]  

where

\[ F = \frac{V^2}{3\omega} \left[ \frac{(\omega r)^2}{1 + (\omega r)^2} \right]. \]

\( \partial U/\partial r \) is the radial density gradient and \( S_0 \) is the convection current density. In paper I we showed that the diurnal variation, on an average basis, as well as enhanced diurnal variation are explainable in terms of simple convection and diffusion, i.e., \( K_i/K_i \) is negligible. The diffusion current on such days was shown to be consistent with the expected radial density gradient. In this paper, we have conclusively demonstrated that this is indeed the case on more than 80% of the days even on the basis of individual days. In other words, on a majority of days \( K_i/K_i \) is negligible (< 0.05) or the third and fourth terms in the right hand side of eq. (3) may be neglected. Nonetheless on a small percentage of days (~ 20%), the interplanetary conditions are such that \( K_i/K_i \) can no longer be completely neglected, i.e., the daily variation on such days cannot be completely accounted only by radial convection and field aligned diffusion and the transverse currents due to perpendicular diffusion do significantly contribute to the daily variation on such days. The association of large scale interplanetary magnetic field irregularities on these
days of scale sizes ranging from a few hours (≥ 4 hr) to days clearly substantiates the above hypothesis. It may be noted that using power spectrum analysis Owens and Jokipii (1972) have recently demonstrated for the cosmic ray scintillations at Alert observed at low frequencies < 5 x 10^{-6} Hz (6 hr) are caused mainly by the fluctuating component of interplanetary magnetic field. They have suggested that the most likely mechanism for high energy cosmic ray scintillations at low frequencies is the strong interaction of these particles with magnetic field irregularities during their propagation in the interplanetary medium. It is interesting to note that the scale sizes which they derive for the field irregularities are consistent with our observations.

It is well known that the presence of irregularities cause random changes in the pitch angles of the particles as they move along the lines of force. The resonant scattering due to irregularities is maximum for particles whose gyroradius (\rho) is of the same order as the scale size of the irregularities (2\rho). In other words, to produce an appreciable scattering for particles with rigidity > 1 G.V., the scale sizes of the irregularities must be > 4 hr (assuming a mean solar wind velocity of 400 km/sec and average interplanetary field of 5 gamma) which are consistent with the observed scale sizes of the interplanetary field irregularities.

From the observed values of the diurnal variation during the trains of non-field aligned days, it is possible to estimate the value of \frac{K_1}{K_0}. Assuming an average radial density gradient of \sim 5, \frac{K_1}{K_0} at neutron monitor energies can be estimated to be \sim 5 x 10^{-11} \rho \beta \text{ cm}^2 \text{ sec}^{-2}. On the other hand, examining a large number of trains of non-field aligned days when the average phase difference between the interplanetary field vector and diffusion vector (\Delta \phi) is about 42\degree, \frac{K_1}{K_0} ratio for non-field aligned days is found to be \sim 1.0.

From the data and analyses presented in the foregoing sections, we draw the following conclusions:

(i) On an average basis the diurnal anisotropy of cosmic radiation is completely understood as a superposition of simple convection and field aligned diffusion. On a day-to-day basis, this concept holds good on more than 80% of the days.

(ii) On the rest of 20% of the days transverse diffusion also plays an important role. On these days, the diurnal time of maximum shows a preference to occur either during early morning (6-15) or during late evening (21-24) hours.

(iii) Days on which transverse diffusion is predominant seem to occur in trains of two or more consecutive days.

(iv) Such trains of days are usually associated with abrupt changes in the direction of interplanetary magnetic field. The non-field aligned days are associated with the presence of large irregularities in the interplanetary magnetic field of scale sizes ≥ 4 hours.

(v) The value of perpendicular diffusion coefficient on non-field aligned days is quite significant. \frac{K_1}{K_0} ≈ 0.1 for these days as compared to \sim 0.05 observed on field aligned days.

(vi) From a careful examination of the cosmic ray anisotropy on a day-to-day basis, it is possible to infer the interplanetary field conditions and predict the nature and scale sizes of irregularities present in the magnetic field.

Cosmic ray anisotropy variation
Acknowledgements

The research presented here was supported by funds from the Department of Space, Government of India and funds from Day Fund Grant No. 17 from National Academy of Sciences, U.S.A.

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HIGH ENERGY COSMIC RAY INTENSITY INCREASES OF NON
SOLAR ORIGIN AND THE UNUSUAL FORBUSH
DECREASE OF AUGUST 1972

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ABSTRACT

A series of spectacular cosmic ray events which included two
relativistic solar particle enhancements and three major Forbush
decreases were registered by ground based cosmic ray monitors
beginning on August 4, 1972. Amongst these, the Forbush decrease
which occurred on August 4-5 exhibited extremely interesting
and complex behavior, the prominent features of which are a
pre-increase PRI prior to the largest decrease FD-2 during the
recovery of which an abrupt universal time increase PI-2 occurred.
Large N-S and E-W anisotropies were observed during the entire
Forbush decrease event. The rigidity spectra for both FD-2 and
PI-2 had practically the same exponent of $-1.2 \pm 0.2$ with an upper
cutoff rigidity of about 50-60 GV, and the anisotropy during both
PI-1 and PI-2 was from the sunward direction. The paper describes
the detailed observational features and presents a unified model
to explain these in terms of a transient modulating region associat­
ed with the passage of a shock front. In this model, the reflection
of particles from the approaching shock front accounts for the
pre-increase PRI, the early onset of FD-2 from the anti-sun
direction being caused by the occultation of particle trajectories
reaching the earth from that direction while the detectors looking
along sunward direction are still sampling albedo particles reflected
from the shock front. The main Forbush decrease occurs as the
shock front containing tangled magnetic fields with large scale
tangential discontinuities sweeps past the earth. The particles
diffusing into the cavity, as they are swept by the Solar wind, get
'piled up' behind the tangled field region causing the abrupt
increase PI-2. Evidence from interplanetary plasma, radio and field
measurements are provided in support of the model wherever possible.

During the declining phase of the current solar cycle,
a series of intense solar flares erupted in August 1972,
from an active region (McMath plage region # 11976) on
the solar disc causing severe cosmic ray disturbances
on the earth (Pomerantz and Duggal, 1973) accompanied
by quite spectacular visual auroras, geomagnetic storms,
radio black out and a host of other terrestrial effects.
The time evolution of the active region responsible for
these disturbances and the detailed description of the
associated solar terrestrial effects are well documented in
the reports compiled by World Data Centre-A for Solar
Terrestrial Physics (Report UAG-28, Part I, II, & III,
July 1973).

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** Also at the Indian Scientific Satellite Project, Peenya, Bangalore-560022. India.
Two large solar flares observed on August 2, at 1838 UT (importance IB) and 1958 UT (importance 2B) produced sudden commencements of the geomagnetic storm (SSC) on August 4, at 0119 UT and 0220 UT respectively (Figure 1). This was followed by a third, very severe sudden commencement geomagnetic storm at 2054 UT on August 4, which if we attribute to the solar flare of importance 3B occurring at 0621 UT yields a value of \( \approx 2700 \text{ km sec}^{-1} \) for the solar wind velocity. The observation of peak solar wind velocities of \( \approx 2000 \text{ km sec}^{-1} \) by instrumentation on HEOS-2 (Gruenwaldt et al., 1972) is consistent with our assumption, if allowance is made for the deceleration of shock waves in the interplanetary medium often observed (Hundhausen 1970; Dryer et al., 1972, Dryer, 1973).

Solar proton increases accompanied by three Forbush decreases. It is seen that the first of the three Forbush decreases (FD-1) had its onset at \( \approx 02 \text{ UT} \) on August 4, and exhibited classical features. During its recovery, a short lived anisotropic solar particle increase (SP-1) was observed with a maximum at \( \approx 15 \text{ UT} \) on August 4, by neutron monitors, having geomagnetic cutoff rigidity \( (P_c) \) less than 1.4 GV. Before the completion of the decay phase of SP-1 (Figure 3a), an anisotropic increase in the intensity (PI-1) was recorded in both meson and neutron monitors preceding the main Forbush decrease (FD-2). The second Forbush decrease (FD-2) had its onset between 21-22 UT on August 4, with an amplitude of about 25% at high latitude neutron monitors. This was followed by an even more rapid increase in the

**Figure 1:** The cosmic ray intensity profile during August 2-9, 1972 observed by a typical high latitude neutron monitor along with the time of SSC's and the solar flares. The prominent features in the complex intensity profile are individually marked.

Figure 1 shows the typical cosmic ray intensity profile observed during August 2–9, 1972 by a ground based monitor. The unusual complex features associated with intensity changes as well as their time association with solar and terrestrial disturbances are clearly marked in the same figure. Principally these consisted of two intensity (PI-2), of about 10–15% at high latitudes. Finally during the recovery of FD-2, a second solar flare particle enhancement (SP-2) occurred at \( \approx 16 \text{ UT} \) on August 7, which was followed a day later by the third Forbush decrease (FD-3) on August 9, 1972.
Table 1 lists the general characteristics of these individual features. The most spectacular feature of the event, in our opinion, is the main Forbush decrease (FD-2) which is accompanied by two intensity enhancements of non-solar origin, PI-1 and PI-2, all of which have not yet been fully explained for want of sufficient observations. In addition we note that longitudinal anisotropies in the equatorial plane as well as north-south (N-S) anisotropies of large amplitude exist during

and a neutron monitor at Gulmarg, which have high cutoff rigidities and therefore, when combined with low cutoff rigidity monitors, are most suited for studying the rigidity dependence of any cosmic ray event. The cosmic ray intensity observed by these monitors during the period August 3–10, are plotted in Figure 2. We note that the magnitude of the Forbush decrease at an equatorial station like Gulmarg during this period is \( \approx 11\% \) which is largest observed to date.

**TABLE 1**

General characteristics of various cosmic ray events (as shown in figure 1), observed during August 3–10, 1972

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>(a) DECREASES</th>
<th>(b) INCREASES</th>
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<tbody>
<tr>
<td>Onset time</td>
<td>FD-1</td>
<td>FD-2</td>
</tr>
<tr>
<td>2–4 UT</td>
<td>21–22 UT</td>
<td>01 UT</td>
</tr>
<tr>
<td>Time of Maximum</td>
<td>15 UT</td>
<td>01–02 UT</td>
</tr>
<tr>
<td>Amplitude</td>
<td>7%</td>
<td>25%</td>
</tr>
<tr>
<td>Spectral Exponent</td>
<td>-0.8 ± 0.2</td>
<td>-1.2 ± 0.2</td>
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<tr>
<td>Amplitude of anisotropy in the equatorial plane</td>
<td>3%</td>
<td>7–8%</td>
</tr>
<tr>
<td>Direction in space</td>
<td>9 hrs.</td>
<td>5 hrs.</td>
</tr>
<tr>
<td>(minimum intensity)</td>
<td></td>
<td></td>
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<tr>
<td>Amplitude of anisotropy in the north-south direction</td>
<td>4%</td>
<td>5%</td>
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<tr>
<td>Direction in space</td>
<td>South</td>
<td>North</td>
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FD-2 and PI-2 (Dutt et al., 1973). In the present paper, we discuss the detailed characteristics of these three features PI-1, PI-2 and FD-2 and provide only a brief summary of other features for the sake of completeness. We also describe a qualitative model based on the transient modulating region associated with the passage of the intense shock wave containing large tangled magnetic fields to provide a comprehensive understanding of the interesting and complex features mentioned above.

**DATA PRESENTATION AND ANALYSIS**

The Physical Research Laboratory, Ahmedabad, maintains neutron and meson monitors at Ahmedabad since the cosmic ray intensity is constant within statistical limits for at least three days prior to FD-1, we have taken the daily mean intensity on August 3 as the hundred percent level for all the stations given in Table 2. Figure 3a and b) presents the intensity profiles observed at two pairs of polar stations looking along the north and south directions. The presence of strong N-S asymmetries during FD-1, FD-2 and PI-2 is evident. Further, Figure 3c, which shows the percent deviations for the two stations with \( P_t \approx 1.8 \) GV and viewing in opposite directions in the equatorial plane, indicates likewise the presence of strong longitudinal anisotropies during FD-2 and PI-2. Even though the
**TABLE-2**

List of stations whose data have been utilized in the present analysis, along with their geographic coordinates, geomagnetic cutoff rigidities \((P_c)\), mean asymptotic directions of viewing at zero Universal time \((UT)\) and the poisson errors \((\text{in percent})\) derived from the hourly counting rate.

<table>
<thead>
<tr>
<th>No.</th>
<th>Station</th>
<th>Geog. Coordinates</th>
<th>Altitude (Meters)</th>
<th>Cutoff rigidity ((\text{GV}))</th>
<th>Asy. Coordinates</th>
<th>Poisson error ((%)</th>
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present paper is not intended to discuss the detailed nature of the N-S anisotropies, in view of the existence of these, the study of the longitudinal anisotropies in the equatorial plane has been made only with stations having asymptotic latitudes within $\pm 30^\circ$.

determining the rigidity dependence of various events listed in Table 1. Such a method overcomes the ambiguity in the determination of the spectral exponent arising from large special anisotropies.

Figure 2: Universal time hourly cosmic ray intensity during the period August 3-10, 1972 recorded by neutron and meson monitors operated by the Physical Research Laboratory, Ahmedabad. The geographic latitude, longitude and the altitude of the station in metres above sea level are also given in the figure.

Figure 4 shows the intensity profile observed at different stations, separately for three asymptotic longitude belts of width 120° each. Since the volume of data available in the longitude belt 120°-240° East is much larger, the monitors in this belt have been utilized for determining the rigidity dependence of various events listed in Table 1. Such a method overcomes the ambiguity in the determination of the spectral exponent arising from large special anisotropies.

Forbush Decrease FD-1 on August 4, 1972; The cosmic ray intensity started decreasing in the early hours of August 4, resulting in the first Forbush decrease FD-1. The high latitude sea level neutron monitors recorded a
Figure 3: Universal time hourly cosmic ray intensity during the period August 3-10, 1972 recorded by three pairs of neutron monitors; (a) polar stations, Thule and McMurdo (Asymptotic latitude 72° N, and 79° S respectively), (b) high latitude stations, Tixie Bay and Mawson (Asymptotic latitude 37° N and 39° S), (c) equatorial viewing stations, Yakutsk and Swarthmore (Asymptotic longitude at 00 UT, 170° E and 350° E). The geographic latitude, longitude and the altitude in metres above sea level for each station along with their geomagnetic cutoff rigidity are shown in the figure. Kp index representing the geomagnetic disturbance is also plotted in the same figure.
Figure 4: Universal time hourly cosmic ray intensity during August 3–5, 1972 observed by a number of selected neutron and meson monitors. The geomagnetic cutoff rigidity of each station and its altitude in meters above sea level are marked in the figure. The stations have been grouped in three asymptotic longitude belts of width 120° each. The asymptotic directions correspond to zero Universal time.
maximum decrease of $\approx 7-8\%$ at about 10-12 UT. Due to the presence of the strong equatorial anisotropy, the onset time at different stations varied widely ($\approx 3$ hrs), the earliest being recorded by stations located in the garden hose direction. With a power law rigidity spectrum having a spectral index of $-0.8 \pm 0.2$, FD-1 exhibits features of a typical Forbush decrease (Lockwood, 1974).

The superimposed intensity increase or a ramp like structure observed in the FD-1 profile on August 4 (See Figure 4), is especially noticeable in stations with $P_e > 1.4$ GV and sampling particles mainly from sunward direction. During the solar period, a geomagnetic storm was recorded with an increase of $\approx 200$ gammas in the horizontal component of the geomagnetic field at low latitudes (Kawasaki et al., 1973). From the time association of these two events we suggest that the intensity increase during FD-1 is caused by the lowering of the geomagnetic cutoff rigidity (F.I. Quantitative calculations indicate that a change $\approx 200$ gammas in the horizontal component of the geomagnetic field, produces a change of $\approx 0.6$ GV in $P_e$ (Obayashi, 1959, Dorman, 1963) which in turn can cause a $4\%$ increase in the cosmic ray intensity recorded at sea level stations having $5 < P_e < 8$ GV (Dorman, 1964; Yoshida et al., 1968), consistent with our observations.

Solar Flare Increase SP-1 on August 4, 1972: An anisotropic increase of about $7-8\%$ in the neutron intensity which had its onset at 12-13 UT on August 4, was observed by stations with $P_e < 1.4$ GV. Evidence of the long time delay of $\approx 6$ hours we suggest that the most likely candidate for causing SP-1 is a solar flare of importance 3B which occurred at 0621 UT (E04, E09), since this was the only major flare that could be associated with the increase (Pomerantz and Duggal, 1973b). Spacecraft observations at lower latitudes support this contention (McKinnon, 1972).

Solar Flare Increase SP-2 on August 7, 1972: The second solar flare increase starting at $\approx 16$ UT on August 7, during the recovery phase of FD-2 shows a number of peculiar characteristics: (1) the conspicuous absence of solar flare cosmic ray particles with energies $< 20$ MeV per nucleon deduced from various spacecraft measurements. (2) the relativistic solar particles were observed before the maximum phase of the solar flare at 1509 UT on August 7 (importance 3B) but in near coincidence with the maximum phase of the white light flare (Mathews and Lanzerotti, 1973) and (3) while an increase of only $5-6\%$ was observed at sea level stations having $P_e < 1.4$ GV, the increase was still significant at stations with $P_e \approx 2.7$ GV, which indicates that the rigidity spectrum of SP-2, is less steep compared to SP-1 and to previous solar flare increases (Obayashi, 1964; McCracken and Rao, 1970).

Forbush Decrease FD-3 on August 9, 1972: The third Forbush decrease was observed on August 9, with its onset time varying widely (4-6 hours) for stations with different asymptotic longitudes. The Forbush decrease was highly anisotropic and short lived, the total time duration from the onset to the recovery being less than 24 hours.

Pre-increase PI-1: A significant increase in the cosmic ray intensity PI-1 is seen at all stations sampling particles from the sunward direction (Figure 4). The maximum intensity occurs around 21-22 UT on August 4, which coincides with the passage of the shock front at the earth at 2054 UT, prior to the onset of second Forbush decrease FD-2. The increase at stations with $P_e > 1.4$ GV is not clearly identifiable due to the superposition of the solar proton event SP-1, whose decay phase persists even beyond 21 UT. Therefore, for further analysis of this pre-increase, all stations with $P_e < 1.4$ GV have been excluded.

The cosmic ray intensity at stations with $P_e > 1.4$ GV being practically constant for about 6-8 hours prior to the onset of pre-increase PI-1 at $\approx 18$ UT, the intensity level for this period provides the requisite base level for computing the magnitude of this increase. The percent increase as observed at a number of stations is plotted in Figure 5, against their mean asymptotic longitude of viewing at 21 UT. It may be noted from the figure that in each given asymptotic direction the percent increase observed at low latitude stations ($P_e > 8$ GV) is comparable in magnitude to the percent increase observed at high latitude stations $P_e = 1.4-4$ GV, indicating a flat spectrum for the increase. In view of this, a smooth curve has been drawn in Figure 5 through all the observational points. The presence of a predominant anisotropy with a maximum increase being
registered by stations viewing along the sunward direction is clearly evident from the figure. Referring to figure 4, it is seen that the anisotropic pre-increase, continues to be significant up to 22 UT in Asian longitude belt (sunward direction) even one hour after the SSC whereas the decrease in intensity has already commenced in the other two longitude belts during the interval 21-22 UT. Lookwood (1971), and Kusmicheva et al, (1972); There have been generally explained as due to the reflection of particles (albedo mechanism) from the outward moving shock front from the sun (Dorman, 1963; Rao et al., 1967; Dorman et al., 1970), containing large magnetic fields. The albedo mechanism predicts an anisotropic increase from the sunward direction, the increase generally preceding SSC by a few hours. Assuming reasonable values for different parameters, Dorman (1963) has calculated the pre-increase for a number of events, and found them in qualitative agreement with the observations. For a solar wind velocity of \( \approx 2000 \) \( \text{km Sec}^{-1} \), this model would predict a pre-increase of about 1.5-1.8\% from the sunward direction and with a flat spectrum, which are in qualitative agreement with our observations.

Since the geomagnetic field is almost constant at least up to 21 UT, the increase PI-1 cannot be attributed to the lowering of the cutoff rigidity. However a small contribution due to the geomagnetic perturbations at and beyond 22 UT cannot be completely ruled out.

The anisotropic pre-increases of type PI-1, which have been observed on earlier occasions have been described by Dorman (1963). Dorman et al. (1970).
The Sharp Forbush Decrease FD-2: Immediately after the SSC at 2054 UT on August 4, a sudden decrease in cosmic ray intensity (Fd-2) was observed, which reached a magnitude of ≈ 25% within five hours. At high latitude sea level neutron monitors, the hourly rate of decrease exceeded even 6% per hour which is the highest recorded so far. The onset of this decrease was highly anisotropic exhibiting both N-S anisotropy and the longitudinal anisotropy in the equatorial plane. The spectral exponent of the rigidity dependence of the decrease is $-1.2 \pm 0.2$, which is slightly higher than the normally observed values.

To study the characteristics of the rapidly evolving anisotropies and to identify the isotropic time variations, we have constructed the space-time diagram of cosmic ray intensities at various longitudes in the equatorial plane at different times during FD-2 and PI-2. An examination of Figure 6 reveals that the decrease commenced at least one hour earlier at stations viewing within a cone of 120° centred around the antisun direction. The anisotropy amplitude during this period (22 UT) was about 3-4%. The early onset along the anti-sun direction is also reflected in the intensity profile observed by low latitude monitors. This picture is contrary to what has been usually observed, namely the early onset of the Forbush decrease from the garden hose direction (Fenton et al., 1959; Bles et al., 1967; Mercier and Wilson, 1968). Figure 6, obtained from such a space-time diagram, describes the snapshots of the cosmic ray intensities at various longitudes in the equatorial plane at different times during FD-2 and PI-2. An examination of Figure 6 reveals that the decrease commenced at least one hour earlier at stations viewing within a cone of 120° centred around the antisun direction. The anisotropy amplitude during this period (22 UT) was about 3-4%. The early onset along the anti-sun direction is also reflected in the intensity profile observed by low latitude monitors. This picture is contrary to what has been usually observed, namely the early onset of the Forbush decrease from the garden hose direction (Fenton et al., 1959; McCracken, 1962; Lookwood and Razdan, 1963a) which is understood in terms of sampling of the depressed cosmic ray intensity behind the approaching shock from the garden-hose direction.

During the main phase of FD-2, following the anisotropic depression along the anti-sun direction, a large anisotropic depression with a maximum alma at 100°-120° west of the earth-sun line developed between 24 UT on August 4, and 02 UT on August 5. The maximum amplitude of the anisotropy is about 7-8% at 24 UT which reduces to 3-4% at 02 UT, thereafter the cosmic ray intensity profile shows an abrupt increase (PI-2) at all stations. The unusual anisotropy features exhibited both at the time of the onset of FD-2 and during its main phase and the initial recovery period, in our opinion, provide a very important clue for an understanding of the Forbush decrease mechanism. A simple unified model explaining all these features is proposed and discussed at the end.

The Rapid Universal Time Increase PI-2: The observed rate of increase PI-2 in the cosmic ray intensity, just after the maximum decrease in FD-2, is comparable or even faster (10% per hour for some stations) than the rate of decrease. Such a fast increase of non-solar origin has been observed for the first time. Since the observations from various monitors suggest that the recovery in cosmic ray intensity continues over a long period of time (≈ 7 days), the abrupt increase observed on August 5 (3-09 UT with maximum at 05 UT) can be considered as a short lived enhancement superimposed on the normal recovery of the Forbush decrease FD-2.

The characteristics of this increase PI-2 have been studied by estimating the magnitude of the increase for various stations by two independent methods: (a) by considering the amplitude of the increase from the minimum of FD-2 to the maximum at about 05 UT and (b) by estimating the magnitude of the increase, above a smooth recovery curve drawn through the intensity profile from the minimum of FD-2 (Figure 7). Both the methods yield a rigidity spectrum with an exponent $-1.2 \pm 0.2$ with an upper limiting rigidity $R_{\text{max}}$ of 50-60 GV for the increase PI-2, the same as that for the main Forbush decrease FD-2.

The spatial anisotropies during the increase PI-2 are again evident from Figure 6. The anisotropy maximum lies in the sunward direction through the increase. However, its amplitude changes with time, being about 5% initially at 03 UT which reduces to ≈ 2% at the time of maximum increase at 05 UT. The anisotropy increases again to ≈ 4% at 06 UT, and decays thereafter till the intensity becomes nearly isotropic at about 17 UT after which the normal recovery proceeds.

A survey of the past Forbush decreases since IGY shows a number of sudden superimposed universal time increases during their recovery periods. Examples are the Forbush decreases of February 11, 1958; August 17, 1958, September 18, 1959; April 27, 1960; October 29, 1963 and
Figure 6: Snapshots showing percent decrease in cosmic ray intensity at different times derived from the data of a number of high latitude neutron monitors (Pc > 2 GV) viewing the equatorial plane. The intensities are plotted as a function of mean asymptotic longitude from 21 UT on August 4 to 17 UT on August 5, 1972, covering the entire period of FD-2 and PI-2.
Figure 7: The cosmic ray intensity profile during August 3-6, 1972 showing the Forbush decrease FD-2 and the increase PI-2. The figure indicates two methods for estimating the increase PI-2. Method (a) defines its magnitude from the minimum intensity of FD-2 to the peak of PI-2, whereas the method (b) defines it as a superimposed increase over the smooth fit to the normal recovery phase shown by the dashed line.

January 13, 1967. A few of these increases have been discussed in literature (Lockwood 1960; Lockwood and Razdan, 1963; Blokh et al., 1964; and Ycasilia et al., 1968) and these have been mainly attributed to a reduction in the cutoff rigidity at the monitoring station, following a geomagnetic storm (Kondo, 1961; Dorman, 1963; Yoshida et al. 1968). However, the decrease in geomagnetic cutoff rigidity (Pc) cannot produce any increase in the cosmic ray intensity observed at sea level neutron monitors with Pc < 1.4 GV (atmospheric cutoff ≈ 1.4 GV) and the meson monitors with Pc < 4 GV (atmospheric cutoff ≈ 4 GV). We note that the abrupt universal time increase PI-2 on August 5 is observed at all stations including the neutron monitors with Pc < 1.4 GV and meson monitors with Pc < 4 GV (Figures 3 & 4). Moreover, the increase in intensity due to reduction in Pc is expected to be maximum for sea level neutron monitors with Pc ≈ 5-8 GV, which is contrary to the present observations. From these evidences, we can exclude the reduction in Pc as the cause for the observed abrupt increase PI-2.

DISCUSSION AND CONCLUSION

The prominent features in the series of cosmic ray intensity variations during August 1972 which requires an adequate explanation are (1) the establishment and evolution of the pre-increase PI-1(2) the unusual anisotropy from anti-sun direction during the onset time of the main
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