Observation of $Z \geq 1$ Particles below 300 km Near the Geomagnetic Equator

M. A. MIAH

*Space and Environment Studies Laboratory, Department of Mathematical Sciences,
University of Arkansas at Pine Bluff, Pine Bluff, AR 71601, U.S.A.*

(Received June 26, 1990; Revised January 18, 1991)

Precipitation of low energy protons (~ 1 MeV) at low equatorial altitude has been investigated by the Phoenix-1 experiment on board the S81-1 mission. Results of the analysis of data received by the monitor telescope and their geophysical interpretation are presented. Seven months long observation during geomagnetic average conditions in May through early December of 1982 shows that the peak precipitation of protons occurs along the line of minimum magnetic field strength. The full width at half maximum (FWHM) is nearly 13° . The particle flux shows a strong altitude dependence, and below 220 km it shows double peak structures. Spectral index of the precipitation flux has been obtained from the data of previous observations. Further, peak precipitation flux in 1982 is almost three times as large as peak precipitation flux in 1969. Charge exchange mechanism favors a stronger source than AP8MAX model. Particle flux does not depend on geomagnetic longitudes. Finally, investigations into the presence of $Z \geq 2$ particles show that they are virtually absent in the energy range considered.

1. Introduction

Results of the observation of the global equatorial zone of particle precipitation made by the Phoenix-1 experiment on board the S81-1 Air Force mission is presented in this article. The investigation has added the following new results in our knowledge of this previously unexplored equatorial zone in the altitudes range of 160 to 300 km: i) The spatial distribution of protons show that the peak precipitation flux falls along the minimum B -equator. ii) The width of the equatorial zone is approximately 13° . iii) Within the limits of statistics, the peak flux does not show any longitude dependence. iv) The peak flux shows a strong altitude dependence—nearly fifth power of altitude. v) Precipitation of protons show double peaks below 220 km. vi) The peak flux in 1982 is almost a factor of 3 higher than in 1969–70 (MORITZ, 1972; HOVESTADT *et al.*, 1972; MIZERA and BLAKE, 1973). vii) Calculation of source strength demands a stronger source than the AP8MAX model (SAWYER and VETTE, 1976) to cause the observed flux. viii) Presence of $Z \geq 2$ particles is insignificant compared to protons.

Early observations (MORITZ, 1972; HOVESTADT *et al.*, 1972; MIZERA and BLAKE, 1973; GOTSELYUK *et al.*, 1974; SCHOLER *et al.*, 1975) of the equatorial zone of particle precipitation were limited in the altitude range ~ 450 –1000 km. Those localized observations which were scattered in time and place, reported the occurrence of proton peak flux near the minimum B -equator or the geomagnetic equator. Unlike the S81-1 mission, they did not have global data coverage through long time observation to

establish the global profile of the peak proton flux. Of them, only MORITZ (1972) studied the altitude variation of peak proton flux, and reported of altitude independence of proton flux in the above altitude range.

VOSS and SMITH (1984) and this work have investigated the equatorial zone below 300 km. This work finds that the flux varies as the fifth power of altitude. While MORITZ (1972), MIZERA and BLAKE (1973), GOTSELYUK *et al.* (1974), and VOSS and SMITH (1984) reported of observing stormtime inflation of the particle flux, the instrument operation schedule did not permit observation during geomagnetic stormtime in this work.

Although at the same energy of ~ 1 MeV, MORITZ's (1972) observed flux was only 35% of our result. Differing solar conditions in 1969–70 and 1982, through variation of atmospheric density, may have caused this discrepancy.

The current belief about this low altitude belt formation is that the outer belt protons (MORITZ, 1972) make charge exchange collisions with exospheric thermal neutral hydrogen atoms, resulting in the production of energetic neutrals having the speeds of the parent ions. The neutrals cannot be trapped in the geomagnetic field. While most of the neutrals will fly away from the Earth, a fraction of them may be directed toward the Earth. At low altitudes (300–500 km), the neutrals are stripped of their electrons by collisions with the dense atmospheric constituents, resulting in ionization and consequent trapping in the geomagnetic field. Actually, the particles will undergo several cycles of ionization and neutralization before being trapped in the low altitude magnitude field. This picture shows that the source strength in the distant magnetosphere is virtually the rate of production of energetic neutrals, and as such depends on the primary trapped particle flux in the relevant energy range and the exospheric thermal neutral hydrogen density. Solar condition, being a dominating factor over the atmospheric density, influences the particle precipitation flux. A calculation of the source strength from the charge exchange process shows even a stronger source than AP8MAX model (SAWYER and VETTE, 1976).

For information on the S81-1 mission, the instruments, and the data coverage/reduction for the equatorial zone, reference is being made to the paper entitled "The ONR-602 Experiment and the Investigation of Particle Precipitation" by the same author.

2. Data Analysis and Results

2.1 Spatial distribution of *ML* flux maxima

In investigating global distribution of peak proton flux, the latitude range (-30° to $+30^\circ$) was binned into 60 bins of width 1° and longitude range (0° to 360°) into 72 bins of width 5° . Average *ML* flux was calculated in all the $60 \times 72 = 4320$ bins. Thus, each of the 72 longitude bins had 60 latitude bins and the average *ML* flux in them. Tektronics plots of average flux vs latitude bins were made for all the 72 longitude bins. Figure 1 is one such plot for the 37th longitude bin. Gaussian curves were approximated through all the 72 plots, and the mean μ , the standard deviation σ , and the width (FWHM) Γ were determined thereof. The standard deviation σ was taken as the latitude bin uncertainty in the location of the mean μ which was also the location of the peak flux. One longitude bin width was taken as the uncertainty for the longitude bin in the location of the peak flux.

Knowing the locations of the peak flux in all the 72 plots, a profile plot of *ML* flux maxima was made. The top panel of Fig. 2 shows this plot. The middle panel of the figure

Fig. 1. Plot of average count rate in latitude bins for the longitude bin in the range 180° to 185° .

Fig. 2. (a) Global profile of ML flux maxima, (b) plot of the minimum magnetic field equator.

shows the location of the minimum magnetic field line (STASSINOPOULOS, 1970). It is found that the peak flux profile occurs along the line of minimum magnetic field strength.

2.2 Width of the Equatorial Zone

Superposed passes have been used to find the latitudinal width of the equatorial zone. A Gaussian curve was approximated through the plot. Full width at half maximum (FWHM) was determined from the curve to be $\sim 13^\circ$. The plot of the superposed passes are shown in Fig. 3.

Fig. 3. Latitudinal width of the equatorial zone. The peak of the curve lies over the minimum B equator.

2.3 Longitude dependence of ML flux

To study the longitude dependence, the altitude range of the peak flux in the equatorial portion of the satellite passes were grouped into high, medium, and low altitudes. The longitude range of the satellite passes was binned in intervals of 30° . Figure 4 which illustrates the investigation, shows statistically insignificant longitude dependence. The little enhancement of the flux in the high altitude range near the South Atlantic Anomaly region is due to the region's influence.

Fig. 4. Longitude dependence of peak ML flux.

2.4 Local time dependence of peak flux

The satellite's orbit being sun-synchronized, no data acquisition was made at any other LT than the 10:30–22:30 LT. Further, it is found that the low altitude passes, which have flux value a little over the background ($0.01/(\text{readout-degree latitude-pass})$), fall at 10:30 LT, whereas the high altitude passes with high flux values fall at 22:30 LT. Thus, LT and altitude are coupled in the data set. Because of this coupling, the study of the LT dependence of ML peak fluxes required looking at the altitude dependence first.

2.5 Altitude dependence of ML flux

To study the altitude dependence of ML flux, plots of ML counts per readout vs latitude, longitude, altitude, L , B , UT , and LT were made for every pass of the spacecraft. Next, the altitude range was binned in 5 and 15 km widths so as to keep comparable number of passes in each bin. All satellite passes with their peak fluxes falling in a certain altitude bin were superposed peak-to-peak to find the average flux in that altitude bin. Then a study of peak flux vs altitude shows a power-law dependence shown in Fig. 5. The power-law representation is

$$\frac{dJ(h)}{dE} = ah^n = 4.11 \times 10^{-16} h^{4.963} \quad (1)$$

where the flux $J(h)$ is in # of protons/($\text{cm}^2\text{-s-sr-keV}$), and the altitude h is in km. The exponent n varies in the range

$$5.354 > n > 4.572$$

and the intercept a , in the range

Fig. 5. Altitude dependence of peak proton flux.

$$3.443 \times 10^{-15} > a > 4.91 \times 10^{-17}.$$

Thus, the *ML* flux varies as the fifth power of altitude.

2.6 Low altitude double-hump structures

Most of the low altitude passes show double hump structures below 220 km. The double-peak passes were superposed peak-to-peak. Figure 6 shows the plot of the superposed passes.

2.7 Energy spectra

The monitor did not have multiple energy channels to detect protons to yield a spectral index. The results of the previous observations (MORITZ, 1972; HOVESTADT *et al.*, 1972; MIZERA and BLAKE, 1973) have been plotted in Fig. 7 to determine the spectral index. The graph shows differential flux values during prestorm and poststorm times, as well as the average value during a period of time. The graph reflects the stormtime inflation of low energy particles, and decreasing inflation with the increase of particle energies. For flux values above 100 keV (prestorm and average data), a least square fit has been done to find the power law for the energy spectra (shown as the solid line). The power-law has the form

$$\frac{dJ(E)}{dE} = bE^{-k} = 5.96 \times 10^5 E^{-2.55} \quad (2)$$

where dJ/dE is in ($\text{cm}^2/\text{s-sr-keV}$), and E is in keV. The intercept b has the range

$$1.5 \times 10^6 > b > 3.09 \times 10^5$$

and the exponent k has the range

Fig. 6. Double peak structures at low altitudes.

Fig. 7. Energy spectra of proton flux.

$$2.66 > k > 2.44.$$

The power-law distribution yields 1.3 MeV as the mean energy of the ML flux. The Phoenix-1 observed average peak flux at the observed altitude of 277 km is shown at 1.3 MeV in Fig. 7. Since the least altitude of previous observations was ~ 450 km, in order to compare with those fluxes the established power-law altitude dependence was used to extrapolate ML flux at 450 km.

To check for the agreement, the power-law spectra established by previous observations was integrated within the energy range of ML rates and then converted to counts per readout. A big discrepancy was found. The power-law spectra predicted only 35% of what the Phoenix-1 experiment expected to observe at 450 km. Table 1 lists the comparison.

A further fact about Fig. 7 is that the power-law represented by the dotted line can account for the observed flux in the Phoenix-1 experiment. The power-law that describes the dotted line is

$$\frac{dJ(E)}{dE} = 11.475 \begin{matrix} + 0.225 \\ - 0.875 \end{matrix} \times 10^3 \cdot E^{-1.85} \quad (3)$$

which, obviously, does not fit the previous results.

2.8 Source strength

Following MORITZ (1972), calculation of source strength has been carried out taking charge exchange as the precipitation mechanism, for the Phoenix-1 observed flux. For this order of magnitude calculation, energy dependence of the outer belt proton population was not taken into account. The results are shown in Table 2. The order of magnitude of the result shows disagreement with the outer belt proton population given by AP8MAX (SAWYER and VETTE, 1976). We see that the observed flux in 1982 favors a stronger source than AP8MAX.

2.9 $Z \geq 2$ ions

Search was made $Z \geq 2$ ions in all the equatorial passes reported here. These ions are very scanty as shown by their locations in Fig. 8.

3. Discussion of Observation

3.1 Spatial distribution of peak flux

The occurrence of the global peak flux profile along the line of minimum magnetic field strength is a natural expectation in the real geomagnetic field. It is the line of minimum B -field which is the common position of particles of all pitch angles for the

Table 1. Discrepancies between fluxes.

Extrapolated at 450 km (counts/readout)	Integration over ML energy (counts/readout)
108 ± 13	38 ± 5

Table 2. Results of source strength calculation.

From Phoenix-1 data ($\text{cm}^2\text{-s-sr-MeV}^{-1}$)	From power-law ($\text{cm}^2\text{-s-sr-MeV}^{-1}$)	AP8MAX model ($E=1$ MeV) ($\text{cm}^2\text{-s-sr-MeV}^{-1}$)
$1.7^{+0.2}_{-0.1} \times 10^8$	$6.9^{+1.2}_{-0.8} \times 10^7$	3.2×10^6

Fig. 8. Location of $Z \geq 2$ particle read outs.

bounce harmonic motion. The flux will be highest at the common crossing point.

The FWHM of $\sim 13^\circ$ is associated with the equatorial pitch angle distribution function which has the form $\sin^q \alpha$. If the anisotropy index q is high, the distribution is sharply peaked at 90° , and the FWHM becomes shorter. The pitch angle distribution index $q = 13 \pm 3$ was found following VALOT and ENGELMANN's (1973) relation:

$$J(l) \propto (B_e/B)^{q/2} \quad (4)$$

where $J(l)$ is the omnidirectional flux, B is the magnetic field and B_e is the magnetic field at the equator. It is already explained in the first paper in instrument performance that the monitor telescope detected omnidirectional flux of particles. A plot of flux vs latitude bins will be similar to the Fig. 3. Taking the latitude bin of the highest flux at zero degree, the logarithm of the ratio (B_e/B) was calculated for the latitude bins and a plot of $J(l)$ vs $\log(B_e/B)$ was made. The slope of the curve was used to determine q . The comparison of the pitch angle distribution function is shown in Fig. 9. A moderate value of q has yielded a moderate zonal width.

Fig. 9. Pitch angle distributions for equatorially mirroring protons calculated by HECKMAN and NAKANO (1969) curve 1, calculated by MORITZ (1972), curve 3, and measured by MIZERA and BLAKE (1973), open circles and curve 5, compared to distributions of $\sin^q \alpha$ for $q=15$, curve 2 $q=10$, curve 4, and $q=7$, curve 6.

3.2 Altitude dependence of peak flux

The strong altitude dependence is a result of rapid depletion of proton flux at low altitude. Since both the generation and production of protons depend on atmospheric density which is a function of altitude, we should expect this altitude dependence. A preliminary calculation shows that the altitude of first impact of the neutrals is ~ 290 km. In the lower altitudes, the particle are lost by these effects: i) protons capture electrons by charge exchange interaction with the atmospheric gases, ii) protons lose energy through ionization in the atmosphere and fall below the instrumental threshold, and iii) protons are lost through diffusion in the loss cone. A description of these processes at the level of average readers is the subject matter of another paper. However, main points are briefly mentioned below.

At any altitude h , the flux of protons is determined by:

$$dJ_P/dt = v n \sigma_{01} J_H - v n \sigma_{10} J_P \quad (5)$$

where v is the velocity of the particle, n is the atmospheric density, σ_{10} is the cross section for interaction with the atmosphere to be neutralized, σ_{01} is the electron stripping cross section of neutral hydrogen. The steady state solution for this is

$$J_P(h) = J_H(h)(\sigma_{01}/\sigma_{10}) \quad (6)$$

which shows the proton flux generated at an altitude h from a beam of incident neutrals J_H . The gradual degradation in density of $J_H(h)$ as it passes through the atmosphere is given by

$$W_{NL}(E, h) = \exp \left\{ - \sum_i S^i(h) \sigma_{01}^i(E) \right\} \quad (7)$$

where $S^i(h)$ is the column density of the i -th atmospheric constituent, and the sum runs over all the atmospheric constituents.

Protons created at the altitude is subjected to energy loss in the atmosphere which may result proton energy loss and consequent drop in energy below instrumental threshold. At 150 km, a proton of equatorial pitch angle $\alpha_e = 90^\circ$ and $E = 1$ MeV has an electron capture lifetime of 0.4 sec and during this time it loses ~ 162 keV and still remains proton for a long time. The same proton loses 2.64 keV at 300 km during its lifetime of 34.3 secs. Proton surviving probability from ionization loss was defined to be

$$W_{IL}(h, E) = 1 - E_{\text{loss}}/(E - E_{\text{thrs}}). \quad (8)$$

If energy loss is zero, $W_{IL} = 1$, and if $E_{\text{loss}} = E - E_{\text{thrs}}$, $W_{IL} = 0$.

Weighted averages of W_{NL} and W_{IL} were taken over the entire energy range based on an $E^{-2.55}$ energy spectrum.

The third process is the pitch angle diffusion loss. Protons undergo pitch angle change due to multiple Coulomb scattering in which case if the pitch angle is lowered, it may be dumped in the loss cone, and is lost. At 175 km, the size of the pitch angle cone is such that $\alpha_e = 90^\circ \pm 12^\circ$ particles can be quasitrapped. At 800 km the pitch angle range is increased to $90^\circ \pm 36^\circ$. The loss cone effect, thus, favors more particle trapping at higher

altitude than at lower altitude. Instrument response function (ability to detect particles of different pitch angles) is also dependent on the pitch angle. The integral of the product of the instrument response function and the pitch angle distribution function is taken to represent the third effect:

$$W_{LC}(h) = \int_{a_1(h)}^{a_2(h)} \sin^q \alpha f(\alpha) d\alpha. \quad (9)$$

Combination of these effects have been incorporated in calculating fraction of protons survived at any altitude as illustrated in Fig. 10. This model does not show any altitude dependence above ~ 450 km. EXOS-C satellite data will be used to get the answer beyond that limit.

3.3 Double-peak passes

Equatorial passes below 220 km show double-peak structures in ML count rates. It is yet to establish whether this phenomena continues all round the globe or located at certain longitude ranges. Several possibilities need to be explored. These are: i) Below 220 km, particles of 90° equatorial pitch angles may be rapidly depleted. ii) Double humps are produced by ionized neutrals. iii) These are the particles which have high equatorial crossing points, and are detected at their mirror points. iv) These are traces for the adjoining low-latitude region. Further investigation needs to be done to get the more probable answer.

4. Discrepancies between Fluxes Observed by Phoenix-1 and Previous Missions

To account for the observed discrepancies between the fluxes observed in the Phoenix-1 and previous missions, investigation has been made on the influence of the atmospheric density variation due to i) solar EUV effect and ii) day-night effect, and their impact upon flux. Further, the differences in the response functions of the two instruments—MT in S81-1 mission and MORITZ's (1972) telescope in Azur mission—

Fig. 10. Fraction of protons survived at any altitude h .

have also been considered in the flux enhancement.

To study the influence of solar ultraviolet effect, calculation has been made, following DRAGT (1971), the monthly average atmospheric density for 1966 through 1983. Figure 11 shows the plot of the monthly average of this density along with the plots of the monthly average sunspot numbers and 10.7 cm radio flux (H. Coffey, personal communication; SOLAR GEOPHYSICAL DATA, 1984). Since solar EUV radiation cannot be measured at low altitudes, and since 10.7 cm radio flux correlates well with solar EUV flux (BOURDEAU *et al.*, 1964; NEUPERT, 1965, 1967), solar 10.7 cm radio flux has been shown in the figure. The time of the previous observations were late 1969 and early 1970, while the Phoenix-1 observation time was May through early December of 1982. During the 1982 observation time atmospheric density is found to increase by a factor of $(14^{+8}_{-5})\%$ compared to what it was in November, 1969. It is known that (HECKMAN and NAKANO, 1969) during periods of minimum solar activity trapped particles experience a less dense atmosphere, and consequently less probability of energetic neutral production through charge exchange interaction in the distant magnetosphere. Following this, we would expect a slightly reduced flux in 1969–70.

It is also known that (JOHNSON, 1962; FAHR and SHIZGAL, 1983) there is more hydrogen escape to extraterrestrial space during solar maximum condition than during minimum condition. Solar maximum in 1980's is more pronounced than 1960's. This could lead to more hydrogen escape to exosphere causing generation of more neutrals in 1980's, and consequently precipitation of more protons in 1982 than in 1969–70.

The discussion above favors differing solar conditions in the two epochs as a probable cause of enhanced proton flux in 1982.

Local time factor comes under consideration because Azur's observation time (MORITZ, 1972; HOVESTADT *et al.*, 1972) was 0530–1730 LT (dawn-dusk), whereas the Phoenix-1 observation time was 1030–2230 LT. At the altitude of 450 km, the number density of oxygen atoms at 1700 hr is ~ 2.2 times higher than at 2200 hr (HARRIS and PRIESTER, 1962; JACCHIA, 1977). In the more dense atmosphere, proton flux can be lost through atmospheric ionization (i.e. electron capture). This may even favor the low flux observed by Azur compared to the Phoenix-1. In the actual situation, atmospheric

Fig. 11. Monthly average atmospheric density and solar 10.7 cm radio flux.

density differentially reduces proton life-time over the altitude range.

The last and the most important factor to consider for the solar-induced enhancement of particle flux is the difference in the performance of the instruments. We have calculated the efficiency function (MIAH *et al.*, 1989) for both the telescopes—the monitor telescope and the one on the Azur mission (MORITZ, 1972). Figure 12 shows the plot of the efficiency functions at the equator. It is shown below that if the efficiency or response function is to be included in the comparison, then the correct quantity for flux comparison is the flux normalization constant J_n . The observed counting rate R by a particle telescope of detector area A having the efficiency function $f(\alpha)$ between energy range E_1 to E_2 for $E^{-\delta}$ spectrum, and pitch angle range α_1 to α_2 for pitch angle distribution characterized by $\sin^q \alpha$ at the magnetic field B , magnetic shell L , latitude λ , longitude ϕ , and time t is given by

$$R = 1/T \int_0^T dt \int_{E_1}^{E_2} dE E^{-\delta} \int_{\Omega} dw \int_A dA \cdot r(w) J_n(B, L, \lambda, \phi, q, t). \quad (10)$$

Numerical evaluation yields

$$R = AFJ_n Q \quad (11)$$

where

$$F = \int_{\alpha_1}^{\alpha_2} \sin^q \alpha f(\alpha) d\alpha \quad (12)$$

and

$$Q = \int_{E_1}^{E_2} E^{-\delta} dE. \quad (13)$$

Fig. 12. Response function of the monitor telescope and the Azur telescope.

From Eq. (11), we can calculate J_n which includes the detector efficiencies, and also different epochs, t . At the equator $\lambda=0$, $B \propto L^{-3}$ for a dipole field. Within the altitude range of ~ 300 km to 450 km concerning MT observation and Azur observation, the range of L is very small, and so is the dependence of J_n on L . For a longitudinally symmetric distribution of particles at the equator, the dependence of J_n on ϕ is very insignificant. Finally, J_n is found to be dependent upon the exponent q and the time t .

We have evaluated F and Q pertaining to the observations made by the MT in 1982 and Azur telescope (MORITZ, 1972) in 1969–70, and the plotted J_n for $5 \leq q \leq 35$ in Fig. 13 in which circles represent J_n s for S81-1 observation at 277 km, squares represent J_n s for Moritz's observation at 450 km, and triangles represent J_n s for flux extrapolation to 450 km. It clear that within the limits of uncertainties the J_n s for the two observations do not differ, whereas they differ by an order of magnitude from the predicted values by the extrapolation model.

A complete study of this global zone is underway in combination with the observation made by the Japanese EXOS-C satellite which was not sun-synchronized and which had an altitude range of 350–850 km. Besides, the telescopes on board the satellite acquired data on differential energy spectra of protons energy spectra.

5. Conclusion

Results of the survey of the particle precipitation near the geomagnetic equator in the altitude range ~ 170 –290 km have been presented. Protons have maximum precipitation with the precipitation peak along the line of minimum magnetic field strength. The full width at half maximum is $\sim 13^\circ$. Further, the peak particle flux varies as the fifth power of altitude which can be explained in the observed altitude range, by the combined effect of electron capture, ionization loss diffusion loss. At altitudes below ~ 220 km, particle precipitation shows double peaks. Additionally, enhanced particle flux is observed in 1982 compared to that in 1969–70, favoring a stronger particle source than AP8MAX model, due to, possibly, differing solar conditions and local times. Finally,

Fig. 13. Comparison of the flux normalization constants for fluxes measured by the monitor telescope in 1982, by the Azur telescope in 1969–70, and obtained by the extrapolation method.

fluxes of $Z \geq 2$ particles are orders of magnitude less than proton flux.

Further work is in progress in conjunction with the analysis and interpretation of the Japanese EXOS-C satellite data to develop a complete theoretical picture of the observed spatial-temporal features of this low altitude zone.

The work is a continuation of the work earlier supported at Louisiana State University by ONR under Contract N-0014-83-K-0365. The work is currently supported at University of Arkansas at Pine Bluff by AFOSR under Contract F49620-89-C-0071. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

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