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ABSTRACT

The visual detection of geomagnetically trapped protons in the region of the South Atlantic magnetic anomaly is reported. Protons of energy $\gtrsim 57$ MeV were recorded in nuclear emulsions during a 65 orbit, oriented flight of a satellite recovered on September 1, 1962. We observe an east-west asymmetry in the flux of geomagnetically trapped protons, confirming an effect predicted by Lenchek and Singer. From measurements of the east-west asymmetry we obtain a value of $62.0 \pm 5.0$ km for the scale height of the atmosphere at 364 km altitude.

# EAST-WEST ASYMMETRY IN THE FLUX OF MIRRORING GEOMAGNETICALLY TRAPPED PROTONS*

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## INTRODUCTION

We report here on the visual detection of geomagnetically trapped protons in the region of the South Atlantic magnetic anomaly. Protons having kinetic energies of ⩾ 57 MeV were recorded in electron-insensitive Ilford K.2 nuclear emulsions during a four-day, oriented satellite flight recovered on September 1, 1962. More than 90% of all the particles recorded by the emulsions were confined to a well-defined plane. We detected, therefore, protons from the inner radiation belt at, and near, their mirror planes. Because a unique mirror plane was defined by the incident protons, the mirroring particles were necessarily detected in a highly localized region in space. We observe an east-west asymmetry in the flux of geomagnetically trapped protons, confirming an effect predicted by Lenchek and Singer.[1] From measurements of the east-west asymmetry for 60, 107, and 116-MeV protons, we obtain a value of 62.0±5.0 km for the scale height of the atmosphere at 364 km altitude. We have been able to determine from our data the location and approximate area of this region over the South Atlantic, and hence can give an estimate of the absolute flux of protons in the energy interval 60 to 70 MeV.

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* This work was done under the auspices of the U. S. Atomic Energy Commission and the Lockheed Missiles and Space Company.

+ Also Lockheed Missiles and Space Company, Palo Alto, California.

Parameters of the orbit relevant to the analysis of the experiment are: inclination, 65.2 deg; apogee, 407 km; perigee, 178 km; and number of orbits, 65.

## GEOMETRY

Four small individual emulsion stacks, each 4 cm in diameter and 0.48 cm thick were mounted, with a known orientation relative to the vehicle, immediately beneath the ablative shield of the recoverable section of the satellite (Fig. 1). The cutoff energies varied between 57 and 116 MeV, depending on direction. Stacks 1, 3, and 4 were selected for analysis, while stack 2 was used for test processing and background measurements. The i,j,k frame, Fig. 1, is in a fixed position within the satellite. The vector $\hat{\underline{i}}$ is normal to the earth's surface, i.e., the zenith direction. The axis of symmetry of the satellite, $\hat{\underline{k}}$, is in the orbital plane.

The projected angular distribution of protons that entered stack 4 with dip angle of $< 15$ deg and came to rest within 3 mm of the edge of the emulsion is shown in Fig. 2. The distribution separates into two distinct peaks 180 deg apart, characteristic of mirroring particles. The insert in Fig. 2 illustrates how the mirror plane intersects the emulsions in stack 4. The angle between the mirror and emulsion planes fortuitously is 90±1 deg. If we denote the intersection of the mirror and emulsion planes by the unit vector $\hat{\underline{u}}$ (the 90- to 270-deg line in Fig. 2) and the direction of the normal to $\hat{\underline{u}}$ in the mirror plane by the vector $\hat{\underline{v}}$, then the normal to the mirror plane is $\hat{\underline{u}} \times \hat{\underline{v}}$, the unit vector $\hat{\underline{B}}$ of the geomagnetic field. The average values of the direction of cosines of $\hat{\underline{B}} = \hat{\underline{i}} \cos\epsilon + \hat{\underline{j}} \cos\eta + \hat{\underline{k}} \cos\mu$, as obtained from stacks 1, 3, and 4, are $\cos\epsilon = 0.668 \pm 0.029$, $\cos\eta = 0.516 \pm 0.056$, and $\cos\mu = -0.537 \pm 0.026$.

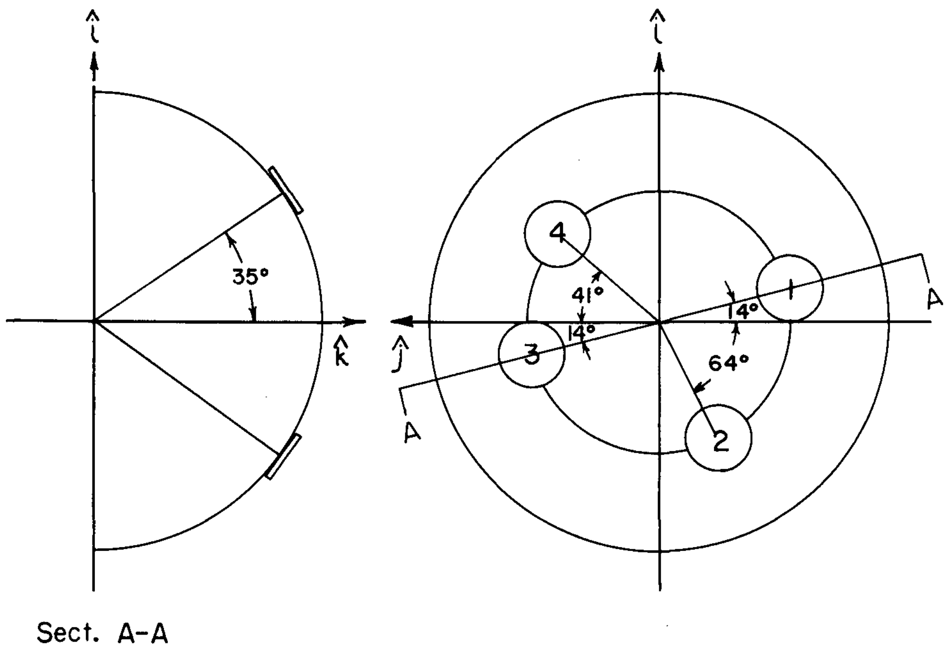


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Fig. 1. Arrangement of the emulsion stacks on a spherical section beneath the ablative shield (not shown).

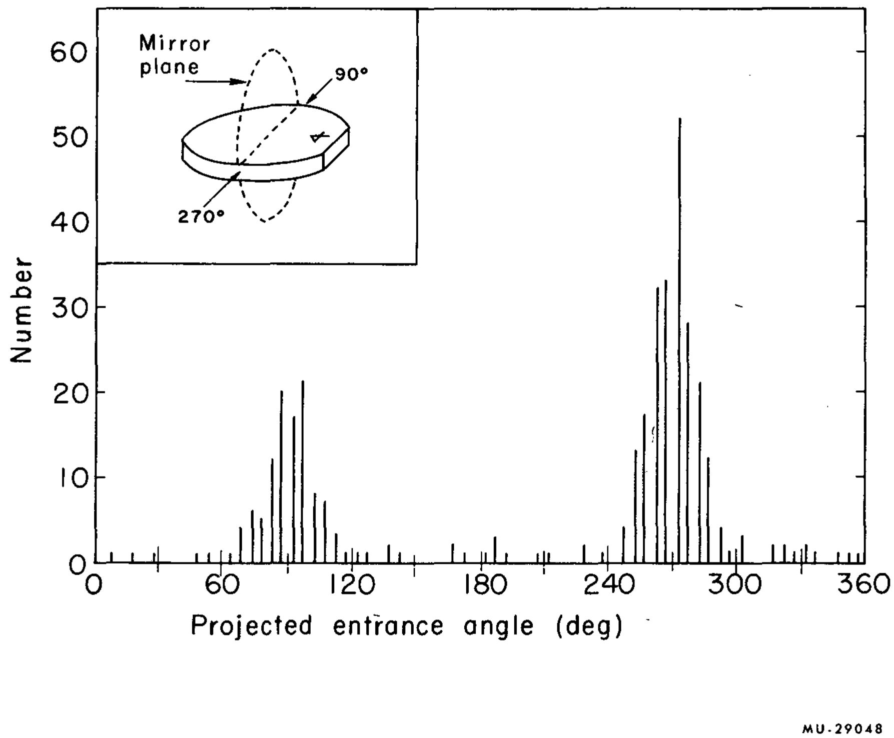


Fig. 2. Angular distribution of stopping protons in stack 4. The unequal number of protons in the two peaks is due to an east-west asymmetry. Cosmic-ray secondaries account for the isotropic background.

## GEOGRAPHIC LOCATION OF THE MIRRORING PROTONS

The direction of cosines of $\hat{\underline{B}}$ given above determine the magnetic inclination or dip, I, and the magnetic declination, D, in the mirroring region:

$$I = 41.9 \pm 2.2 \text{ deg}$$

$$D = 11.1 \pm 3.0 \text{ deg W.}$$

Considering altitudes, magnetic field intensities, and L values, and using the Jensen and Cain (1962)[2] harmonic expansion of the geomagnetic field at 400 km altitude, we deduced a unique location for the mirroring region: 39 deg S, 41 deg W (Fig. 3). At this point the satellite was approaching apogee at an altitude of 364 km. This location is near the center of one of the regions of high counting rates that have been observed by counter techniques.[3-6]

## OBSERVATION OF AN EAST-WEST ASYMMETRY

Haerendel was the first to recognize that the gyroradii for protons with >100-MeV energy are comparable to the scale height of the atmosphere and that, consequently, variations of the atmospheric density over the circle of gyration should lead to observable effects.[7] One such directly observable effect described by Lenchek and Singer is an east-west asymmetry.[1] Briefly, the asymmetry arises because the proton flux, $\underset{\sim}{j}_E$ , moving toward the east has guiding centers at higher altitudes than the flux, $\underset{\sim}{j}_W$ , moving toward the west.* As a result, the atmospheric densities averaged over the two circles of gyration differ.

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* Lenchek and Singer inadvertently reversed the effect and predicted a larger flux from the east; that the opposite may be expected is evident from their Fig. 1.

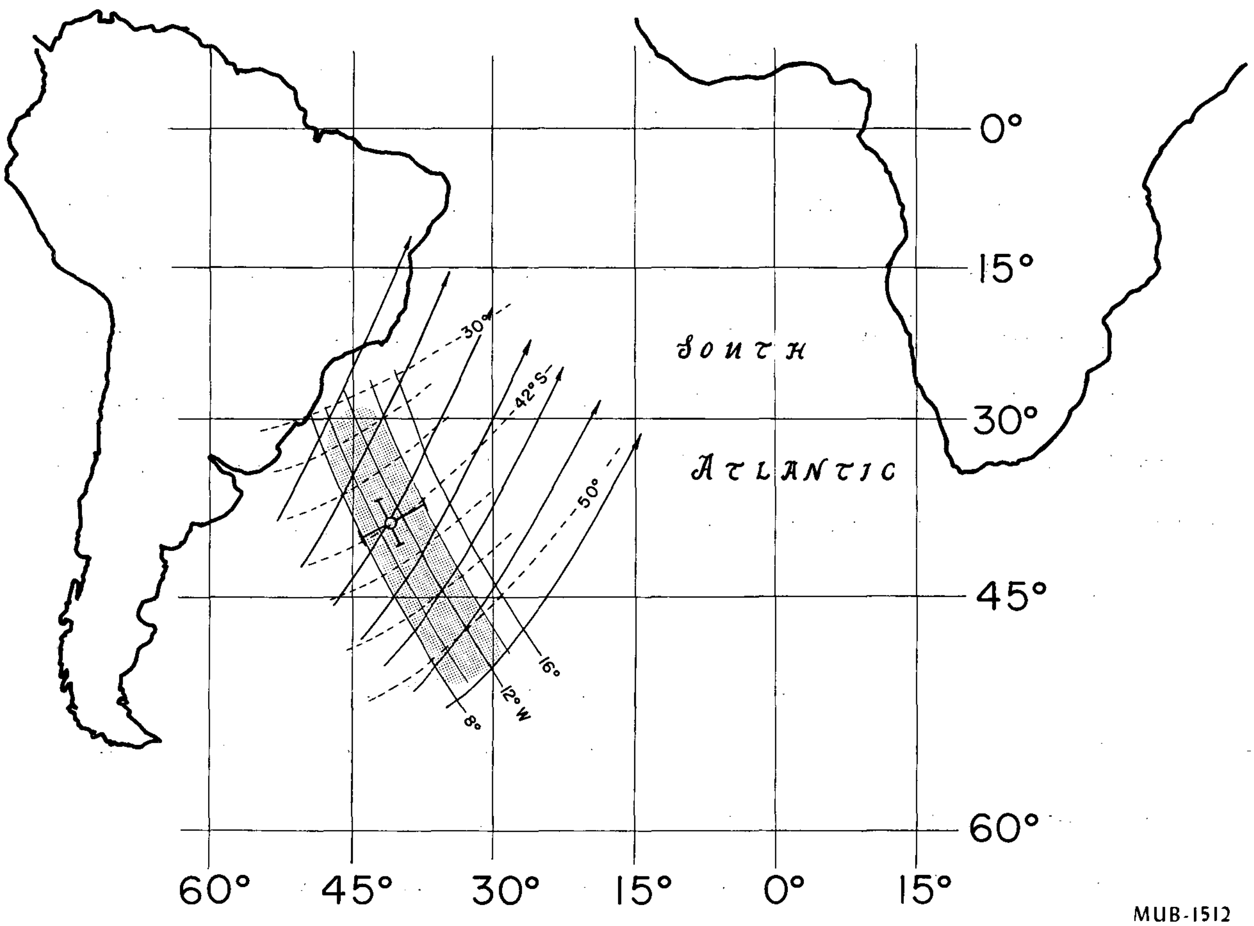


Fig. 3. Geographic location of the mirroring protons. The mean coordinate of the region, 39 deg S, 41 deg W, is shown as an open circle with accompanying error bars. Isogonic lines are solid, isoclinic lines are dashed. Northbound satellite trajectories (near apogee) are heavy solid lines with arrows. The approximate area of the mirroring region as deduced in this experiment is shaded.

Assuming that the unidirectional proton flux $\underset{\sim}{j}$ is inversely proportional to the average atmospheric density over the circle of gyration, Lenchek and Singer derived the following expression for the east-west ratio:

$$\frac{\underline{j}_E}{\underline{j}_W} = \exp[\underline{a}\,(\cos\theta_E - \cos\theta_W)/h] \,, \qquad (1)$$

where $\underline{a}$ is the gyroradius, $\underline{a}\,(\cos\theta_E - \cos\theta_W)$ is the difference in altitudes of the guiding centers of the flux $\underset{\sim}{j}_E$ and $\underset{\sim}{j}_W$, and h is the scale height of the atmosphere. As diagrammed in Fig. 4, if one observes a proton flux $\underset{\sim}{j}_E$ at the origin, the projection of the guiding center onto the zenith is $\underline{a}\cos\theta = \underline{a}\,(\hat{\underline{j}}_E \times \hat{\underline{B}}) \cdot \hat{\underline{i}}$ .

We have measured the flux of protons that enter stacks 1 and 4 from opposite directions and are brought to rest in the emulsion. The average incident-proton energies are 116 MeV and 107 MeV, respectively. We also have compared the flux of 60-MeV protons that entered normal to the emulsion surfaces in stacks 1 and 3. The east-west asymmetry is manifest in Fig. 2, where the ratio of the number of protons entering the west (270 deg) edge of stack 4 to the number entering the east edge is 2.30±0.25. The results of our measurements on the east-west asymmetries are summarized in Table I. By using Eq. (1), we obtain from these data a measurement of the scale height of the atmosphere:

$$h = 62.0\pm5.0 \text{ km},$$

where the error includes the statistical uncertainties in the asymmetry ratio and the angles of magnetic inclination and declination. This result is in satisfactory agreement with measurements of h deduced from observations of satellite drag.[8,9]

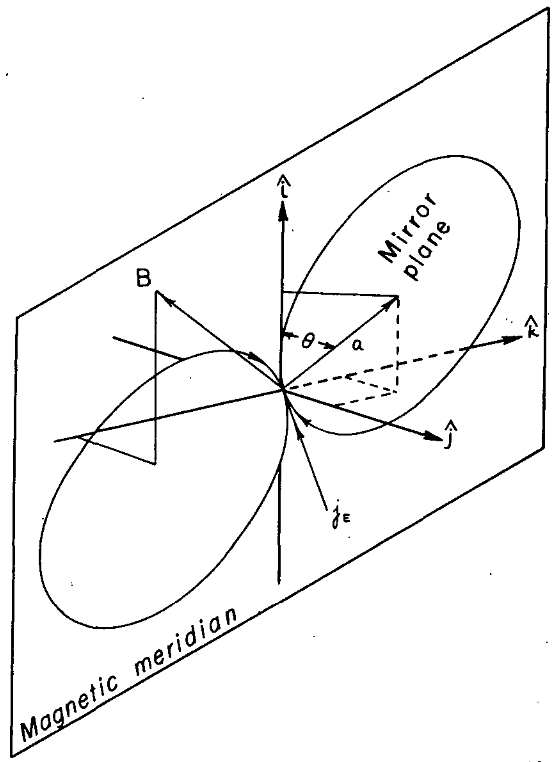


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Fig. 4. Proton flux $\pm j_E$ with gyroradii $\underline{a}$ have guiding centers at altitudes $\pm \underline{a}$ $\cos\theta$ relative to the point of observation at the origin. The $\hat{\underline{i}}$-axis in the satellite coincides with the zenith. The $\hat{\underline{k}}$-axis lies in the orbit plane. Vectors $\hat{\underline{i}}$ and $\hat{\underline{B}}$ lie in the magnetic meridian.

Table I. Observed east-west ratios and calculated scale heights of the atmosphere at an altitude of 364 km, and field B of 0.222 Gauss.

| Stack | Proton energy (MeV) | $\cos\theta_E-\cos\theta_W$ | $j_E/j_W$ | h (km) |
|---|---|---|---|---|
| 1 | 116 | 1.466 | 5.49±0.77 | 62.2± 6.9 |
| 4 | 107 | 0.714 | 2.30±0.25 | 59.5± 8.1 |
| 1,3 | 60 | 0.620 | 1.57±0.16 | 69.6±15.0 |
| | | | Average: | 62.0± 5.0 |

PITCH-ANGLE DISTRIBUTION

Figure 5a shows the observed pitch-angle distribution for $\gtrsim$130-MeV protons that entered stack 4 normal to the plane of the magnetic meridian, i.e., in the direction $\hat{\underline{i}}\times\hat{\underline{B}}$, Fig. 4. The angle $\delta$ is the angle between the direction of the incident proton and the mirror plane. Mirroring protons have $\delta=0$, those with $|\delta|>0$ mirror at lower altitudes. The distribution is Gaussian with a statistical standard deviation of 7.77±0.15 deg.

We are able to show that a Gaussian pitch-angle distribution is expected when it is assumed that the mirror point density is inversely proportional to the density of the atmosphere at the mirror point of the guiding center.[10] If we express the density of the atmosphere as a function of altitude in the form $\rho \propto e^{-r/h}$, we obtain

$$N(\delta)d\delta \propto \exp(-K\sin I\,\delta^2/2h)\,d\delta \qquad (2)$$

for the distribution of pitch angles at low altitudes. The factor $K \sin I$ is equal to $\frac{4}{3}\,r\,(2+\cos^2 I)^{-1}$, where r is the dipolar distance and I is the magnetic dip. To carry out the calculation, we further assume the adiabatic,

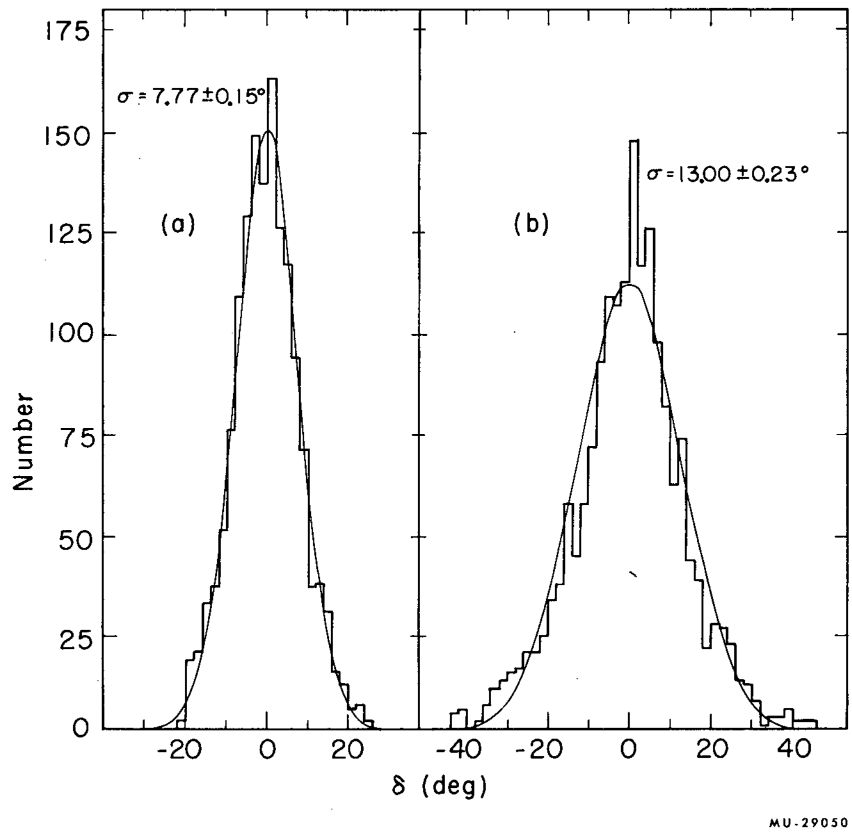


Fig. 5. Observed pitch-angle distributions of proton flux (a) normal to and (b) in the plane of the magnetic meridian.

or magnetic-moment, invariant is a constant of the particle motion, and that the magnetic field over small distances can be represented by that of a magnetic dipole. The calculated distribution is a Gaussian whose variance $\sigma^2$ is proportional to h, the scale height of the atmosphere:

$$\sigma^2 = \frac{h}{K \sin I} . \qquad (3)$$

If we take the value $h = 62.0 \pm 5.0$ km obtained from the east-west asymmetry as the scale height of the atmosphere, the calculated standard deviation of the pitch-angle distribution is $\sigma_{calc.} = 7.36 \pm 0.30$ deg. The $\sigma$ of the observed pitch-angle distribution is necessarily larger than $\sigma_{calc.}$ owing to variations in the direction of the magnetic field and the orientation of the satellite in the mirroring region, and to scattering and measurement errors.

We have measured pitch-angle distributions for two incident proton directions. As mentioned above, one direction is normal to the plane of the magnetic meridian. Referring to Fig. 4, we see that the observed pitch-angle distribution for particles traveling in this direction is directly broadened by changes in magnetic declination, i.e., by rotations of the mirror plane about the axis $(\hat{\underline{i}} \times \hat{\underline{B}}) \times \hat{\underline{B}}$. On the other hand, the pitch-angle distribution for particles lying in the magnetic meridian is broadened by changes in magnetic dip, i.e., by rotations of the mirror plane about the axis $\hat{\underline{i}} \times \hat{\underline{B}}$. The standard deviation of the observed pitch-angle distribution shown in Fig. 5a (corrected for scattering and measurement errors only, the error in satellite orientation being assumed small) is only slightly larger than $\sigma_{calc.}$, but indicates that the deviation of the magnetic declination in the region of the mirroring particles was $\sigma_D = 2.5 \pm 0.9$ deg. Figure 5b presents the pitch-angle distribution observed in the magnetic meridian plane. Here, we have

$\sigma = 13.00 \pm 0.23$ deg, from which we conclude the distribution is largely due to variations of magnetic inclination in the mirroring region. For this reason, the distribution need not be Gaussian. The deviation in I necessary to account for the observed width is $\sigma_I = 10.7 \pm 0.3$ deg.

## ABSOLUTE PARTICLE FLUX

The above estimates of the "wobble" of the magnetic declination $\sigma_D$ and inclination $\sigma_I$ enable us to roughly estimate the size of the geographic area in which the mirroring particles were detected. The shaded area in Fig. 3 is delineated by the isogonic lines $11.1 \pm \sigma_D$ deg (8.6 and 13.6 deg) and the isoclinic lines $41.9 \pm \sigma_I$ deg (31.2 and 52.6 deg). The flight paths of the satellite that traversed this area, shown as dark lines with arrows, represent a total flight time of about 720 sec in the region. If we consider the directionality of the proton flux due to the east-west asymmetry, preliminary measurements give an omnidirectional flux $N = 2.0 \pm 0.2 \times 10^4$ protons $cm^{-2}$ $MeV^{-1}$, averaged over 60 to 70 MeV. Since about 44% of this flux was detected in the area shown, the mean rate of detection for 65-MeV protons is $\approx 12$ $cm^{-2}$ $MeV^{-1}$ $sec^{-1}$. The peak counting rate is about 15 $cm^{-2}$ $MeV^{-1}$ $sec^{-1}$ if we assume that the counting rate contours are Gaussian.

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