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Authors

Heckman, Harry H.
Nakano, George H.

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Harry H. Heckman and George H. Nakano

May 5, 1964

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Harry H. Heckman

Lawrence Radiation Laboratory
University of California
Berkeley, California

and

George H. Nakano

Research Laboratories
Lockheed Missiles and Space Company
Palo Alto, California

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ABSTRACT

Nuclear track emulsions recovered from oriented polar-orbiting satellites are being used to carry out a systematic study of the high-energy geomagnetically-trapped protons ($E > 58$ MeV) in the region of the South Atlantic anomaly. Because the trapped protons are detected only at their minimum mirror-point altitudes, they are confined to a plane normal to the local magnetic field. The east-west asymmetry in the flux of trapped protons is observed and measured. From the magnitude of the asymmetry, particle scale heights are determined. At altitudes near 400 km, the measured scale height is $h \approx 70$ km, in agreement with values of scale-heights deduced from model atmospheres when the averaging effects due to the particle's longitudinal drift and mirror oscillations are taken into account. The omnidirectional differential energy spectrum of protons $58 < E < 600$ MeV is found to be similar in shape to previous measurements of the high energy-proton spectra for L values $\leqslant 1.5$. No significant variations in the absolute flux in the energy interval $58 < E < 70$ MeV have been observed during the period Sept. 1962 to Sept. 1963. However, the number of protons per cm^2 we observe indicates that the flux of protons in this energy interval has increased about 4-fold over that observed with Explorer IV (1958).

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Lawrence Radiation Laboratory
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INTRODUCTION

In September, 1962, we began a series of experiments whose purpose is to systematically study the high-energy geomagnetically trapped protons ($E \geqq 58$ MeV) in the region of the South Atlantic anomaly. Nuclear track emulsions recovered from oriented polar-orbiting satellites after an exposure of two to four days duration are being used in this study. The emulsions are accurately positioned in the satellite so that their spatial orientation while in orbit is known at all times. This feature of precise orientation, when coupled with the high spatial resolution characteristic of nuclear track emulsions has led to experimental results not readily attainable heretofore by other techniques.

Because the altitudes at apogee have been between 340 and 520 km, the trapped protons are detected only in the region of their minimum mirror-point altitudes. This region is over the South Atlantic. Consequently, the detected trapped radiation is largely confined to a plane normal to the local field. We are able, therefore, to determine the vector components of the magnetic field where the particles are detected; hence, the geographic location of the mirroring region.

The mirror-like geometry facilitates measurements of the directional proton flux, pitch angle distributions, east-west asymmetries, and energy spectra. This report presents some of our results on these properties of the geomagnetically trapped protons in the South Atlantic anomaly obtained during the twelve month period Sept. 1962 to Sept. 1963.

GEOMETRY

Four small individual emulsion stacks, each 4 cm in diameter and 0.48 cm thick are mounted on a spherical shell with a known orientation relative to the vehicle. The emulsions are placed immediately beneath the ablative shield of the recoverable section of the satellite (Fig. 1). The cutoff energies vary between 58 and 116 MeV, depending on direction. The i,j,k, reference frame, as shown in Fig. 1, is fixed in the satellite. Throughout the flight the vector $\underline{\hat{i}}$ is normal to the earth's surface, i.e., the zenith direction. The axis of symmetry of the satellite, $\underline{\hat{k}}$, is in the orbital plane. As indicated in Fig. 1, the stacks are placed in each quadrant. Before removing the recovered emulsions from the shell, their orientation is carefully determined.

Figure 2 shows the projected angular distribution of protons that enter the emulsion stacks in no. 4 position with dip angle $< 15^{\circ}$ and come to rest within 3 mm of the edges of the emulsion. The distribution exhibits two distinct peaks 180 deg apart, characteristic of mirroring particles. The inset in Fig. 2 illustrates how the mirror plane intersects the emulsions in this particular position. Here the angle between the mirror and emulsion planes varies between 81 and 90 deg, depending upon the inclination of the satellite orbit plane and the precise location of the emulsion stack on the shell.

The standard deviation of the angular distribution, Fig. 2, is $\sigma = 14^{\circ}$. If we allow for broadening of the angular distribution due to multiple scattering and for variations in the direction of the magnetic field $\hat{\underline{B}}$ in the satellite-reference frame (because of the finite area of the anomaly region) we obtain the result that the standard deviation of the true pitch angle distribution is approximately 7°. This result is consistent with previous measurements.[1] The sharply peaked angular distribution requires that the particles we have detected were encountered in a highly localized region in space. For this reason, and because of the spatial orientation of the emulsions, the absolute direction of the incident trapped radiation detected in the anomaly region is well defined.

GEOGRAPHIC LOCATION OF THE MIRRORING REGION

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. For each flight the average values of the direction cosines of $\hat{\underline{B}} = \hat{\underline{i}} \cos\epsilon + \hat{\underline{j}} \cos\eta + \hat{\underline{k}} \cos\mu$ are obtained from at least three of the four stack positions. From the values of the direction cosines we determine the inclination and declination of the magnetic field vector, $\hat{\underline{B}}$, at the center of the mirroring region. The 48-term spherical harmonic expansion of the geomagnetic field[2] is used at the appropriate altitude to deduce the geographic location of the mirroring region. Figure 3 shows the results of this analysis for the eight flights that we have analyzed. These points cluster about 34 deg S and 34 deg W in the South Atlantic. This location is our determination of the center of the South Atlantic anomaly. In Fig. 4 the B and L coordinates at 400 km altitude are superimposed on these points. Also shown are iso-intensity contours that are derived from Explorer IV counter data.[3] Our designation of the midpoint, i.e., "hot-spot", of the anomaly agrees well with the region of maximum count-rate that is obtained from the Explorer IV data. These results are also in agreement with previous counter measurements.[4-7]

EAST-WEST ASYMMETRY

The first significant result obtained in this experiment was the observation of an east-west asymmetry in the flux of the mirroring geomagnetically trapped protons.[1] The existence of such an asymmetry was predicted by Lenchek and Singer[8] who described the observable effects that are to be expected when the gyroradii of high-energy protons are comparable with the atmospheric scale height.[9] More recently Northrop[10] has pointed out that an asymmetry in the particle flux should appear whenever a flux gradient exists, regardless of the phenomenon producing the gradient. In this experiment it is the atmospheric density gradient that produces the flux gradient and, hence, the east-west asymmetry in the particle flux. Figure 5 shows schematically how the east-west effect is observed. Here it is illustrated that there is a difference in the altitudes of the guiding centers of the eastward flux, $\underline{j}_E$, and westward flux, $\underline{j}_W$, which are recorded simultaneously by the detector. The difference in the altitudes of the guiding centers for particles moving in the east-west direction, that is, in the direction $\pm(\hat{\underline{B}} \times \hat{\underline{r}})$, is proportional to the gyroradius of the particles and to the cosine of the dip angle, I, of the magnetic field.

The expression for Δr, i.e., the difference in altitude between the guiding centers of particles with gyroradii a, is

$$\Delta r = a \cos I \, (\cos\varphi_1 - \cos\varphi_2) \qquad (1)$$

where φ_1 and φ_2 are the angles at which the directional proton flux are measured. The angle φ is measured relative to the $\hat{\underline{B}} \times \hat{\underline{r}}$ direction in the mirror plane. Usually, $\varphi_2 = \varphi_1 + 180$ deg and $\Delta r = 2a \cos I \cos\varphi$. Thus the maximum east-west effect is observed when $\cos\varphi = 1$. This case is illustrated in Fig. 5. No asymmetry is expected in the "north-south" direction since $\cos\varphi = 0$ and the guiding centers are at the same altitude..

A useful expression for relating the ratio j_E/j_W of the directional proton flux, and the distance Δr in terms of the scale height, h, is

$$\frac{j_E}{j_W} = \exp\left(\frac{\Delta r}{h}\right). \qquad (2)$$

In this experiment we have chosen to present our east-west asymmetry data in terms of the proton flux scale height, h. The measured values of h are plotted in Fig. 6 as a function of detector altitude over the South Atlantic anomaly. In this figure the dark circles are the values of h determined by the asymmetry measurements of protons at a mean energy of 132 MeV.

The curves of h versus altitude drawn through the data points, Fig. 6, are the effective particle scale heights derived from the CIRA (1961) model atmospheres.[11] The scale heights, h_{atm}, of these model atmospheres have been corrected to account for the averaging effects due to the longitudinal drift and mirror oscillations of the trapped protons. Newkirk and Walt[12] have calculated the average mirror-point atmospheric densities as a function of minimum mirror-point altitude for trapped particles. At L = 1.5 they find that the drift-weighted scale heights are greater than h_{atm} by 4 to 18 percent between the minimum mirror-point altitudes of 300 and 500 km. The corrections due to the mirror oscillations of the particles have been estimated and have been found to be comparable to the drift corrections. The inset in Fig. 6, which presents the results of these estimated corrections, shows the ratio h/h_{atm} as a function of minimum mirror-point altitude when the model atmosphere is averaged over the particle's trajectory around the earth. The drift and mirroring corrections were applied to the scale heights of the CIRA model atmospheres. These modified CIRA curves are compared with the measured values of particle scale heights in Fig. 6.

FLUX VS. ALTITUDE

In each flight the incident time-integrated proton flux between 58 and 70 MeV is measured.[*] Protons in this energy interval enter normal to the surface of the emulsions and are brought to rest. In each experiment the flux detected during the apogee passes is measured. Whenever possible the flux detected during perigee passes is also measured. The omnidirectional flux is obtained from the measured directional flux by taking into account the asymmetric distribution of the proton flux in the mirror plane. Figure 7 shows our experimental data on the altitude variation for the omnidirectional flux, expressed in protons cm^{-2} MeV^{-1}, at the nominal energy of 65 MeV. These data are recorded during four-day orbital periods.

From these measurements, values of particle scale heights can be directly determined. Several representative values of scale height from these data are shown in Fig. 6 as open squares. The scale heights obtained from the east-west asymmetries and from the flux vs. altitude data are in satisfactory agreement. Although these data are of limited statistical accuracy, we feel that the corrections to h_{atm} of the model atmosphere to obtain the effective particle scale height curves are approximately correct. However, the scatter of data points precludes the selection of a preferred model atmosphere. We feel that with greater statistical accuracy much could be learned of the average properties of the atmosphere at satellite altitudes from particle data of this type.

By integration, the flux vs. altitude relationship is obtained from the modified CIRA (1961) curves of particle scale heights shown in Fig. 6. The only assumption introduced is that the proton flux is inversely proportional

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[*] Recorded by the emulsion detectors during the orbit period is the time-integrated proton flux, i.e., protons/cm^2. In this paper we use the term "flux" to refer to this measured quantity, while "count-rate" denotes protons/cm^2 sec.

to the modified atmospheric density. The calculated flux profiles are shown in Fig. 7. Each curve is normalized to fit the experimental data. Excluding the single point at 375 km altitude, the measurements deviate from the modified CIRA (1961) average value and minimum average value curves by 8 and 10 percent, respectively.

In order to detect long term changes in the proton flux, our measurements are compared with Explorer IV, 1958 data. To make this comparison, our ephemerides, expressed in B-L coordinates, are used to time integrate the 1958 count-rate contours. These integrations give the total number of protons with energies greater than 43 MeV incident per cm^2 on the emulsion detectors, had they been exposed in 1958. Using the proton energy spectrum Fig. 8, the differential flux at 65 MeV in terms of the integral flux $N(E > 43 \text{ MeV})$ is given by

$$\left(\frac{dN}{dE}\right)_{65 \text{ MeV}} = \frac{1}{130} N(E > 43 \text{ MeV}).$$

The expected 1958 Explorer IV flux $(dN/dE)_{65 \text{ MeV}}$ is plotted as open circles in Fig. 7. Through these data is normalized the modified CIRA (1961) average value curve. The shape of the flux vs. altitude curve thus obtained is in strikingly good agreement with the emulsion data as well as with the modified CIRA curve. The ratio of the presently measured flux (1962-63) to the flux calculated from the Explorer IV (1958) data is 4.4.

ENERGY SPECTRUM

The energy spectrum for protons greater than 58 MeV energy measured at 408 km altitude in the anomaly is shown in Fig. 8. These data are the composite of two measurements of the spectrum detected during similar satellite flights in December, 1962 and June, 1963. The differential omnidirectional flux given in Fig. 8 is the flux recorded by the emulsion detectors during 4-day exposures. The spectrum between 58 and 144 MeV was determined by range measurements.

Ionization measurements were used to determine proton energies in excess of 125 MeV. Protons up to 600 MeV energy were measured by this latter method and, when necessary, multiple scattering measurements were performed to verify the particle's identity and energy.

In Fig. 9 we have superimposed upon the spectrum data of this experiment two previous measurements of the proton spectrum.[13,14] The data are normalized at 65 MeV. The spectrum of Heckman and Armstrong was obtained in October, 1960 in the region of L = 1.35, while the data of Naugle and Kniffen were recorded at L = 1.47 in September, 1960. It is evident that no measurable change in the shape of the proton spectrum above 60 MeV has occured during the past 2-3 years for L values less than ≈ 1.5. Indeed, since the first measurements by Freden and White in 1959,[15] the accumulation of experimental data on the high-energy proton spectrum for L shells < 1.5 attests to its high stability.

SUMMARY

We have shown in this experiment that emulsion detectors placed in an accurately known geometry aboard oriented polar-orbiting satellites can give detailed information on the properties of the trapped proton component in the South Atlantic anomaly. Because of the sharply defined angular distribution of the mirroring protons detected in this region, we are able to (a) locate with good accuracy the central region of the anomaly, (b) conclude that over 90% of the proton flux detected during the orbital flight was recorded in the anomaly region. The principal results of this experiment are as follows:

1. The particle scale height and flux variation with minimum mirror-point altitude is explained by the properties of the atmosphere when proper account is taken of the averaging effects produced by the trapped particle's drift and mirror oscillations around the earth.
2. No change in the flux profile vs. altitude for 65 MeV protons is in

evidence when the present data are compared with Explorer IV (1958) results.

3. The 1962-63 proton flux in the region of the South American anomaly is 4.4 times greater than that expected from the Explorer IV (1958) count-rate curves.
4. No evidence for significant variations in the proton flux was observed in the period Sept. 1962 through Sept. 1963.
5. The shape of the proton energy spectrum above 58 MeV ($L < 1.5$) has remained constant, within the errors of measurement, since 1959.

Although it is not a direct conclusion, we would like to point out that the excellent agreement between the Explorer IV data and the present results (excepting the absolute value of the flux) tends to validate the use of the B-L coordinate system in the region of the South Atlantic anomaly, as well as to support the accuracy of the Explorer IV count-rate data.

ACKNOWLEDGEMENTS

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REFERENCES

1. H. H. Heckman and G. H. Nakano, J. Geophys. Research 68, 2117, 1963.
2. D. C. Jensen and J. C. Cain, J. Geophys. Research 67, 3568, 1962.
3. C. E. McIlwain, J. Geophys. Research 66, 3681, 1961.
4. S. N. Vernov, I. A. Savenko, P. I. Shavrin, and N. F. Pisarenko, Dokl. Akad. Nauk. SSSR 140, 1041, 1961. [Translation: Soviet Phys. Dokl., 6, 893, 1962.]
5. L. V. Kurnosova, T. N. Kolobyanina, V. I. Logachev, L. A. Razorenov, I. A. Sirotkin, and M. I. Fradkin, Planetary Space Sci., 9, 513, 1962.
6. L. G. Mann, S. D. Bloom, and H. I. West, Space Research III, ed. W. Priester (Amsterdam, North Holland Publishing Co., 1963) 447.
7. S. C. Freden, G. A. Paulikas, J. Geophys. Research, 69, 1259, 1964.
8. A. M. Lenchek, and S. F. Singer, J. Geophys. Research, 67, 4073, 1962.
9. G. A. Haerendel, J. Geophys. Research, 67, 1173, 1962.
10. T. G. Northrop, Rev. Geophys. 1, 283, 1963.
11. COSPAR International Reference Atmosphere 1961 compiled by H. Kallman - Bijl et al. (Amsterdam, North Holland Publishing Co. 1961).
12. L. L. Newkirk and M. Walt, private communication.
13. H. H. Heckman and A. H. Armstrong, J. Geophys. Research 67, 1255, 1962.
14. J. E. Naugle and D. A. Kniffen, Phys. Rev. Letters, 7, 3, 1961; J. Geophys. Research, 68, 4065, 1963.
15. S. C. Freden, and R. S. White, Phys. Rev. Letters, 3, 9, 1959.
16. W. F. Dudziak, D. D. Kleinecke, and T. J. Kostigen, Tempo Report, RM 63TMP-2. DASA 1372, 1 April 1963.

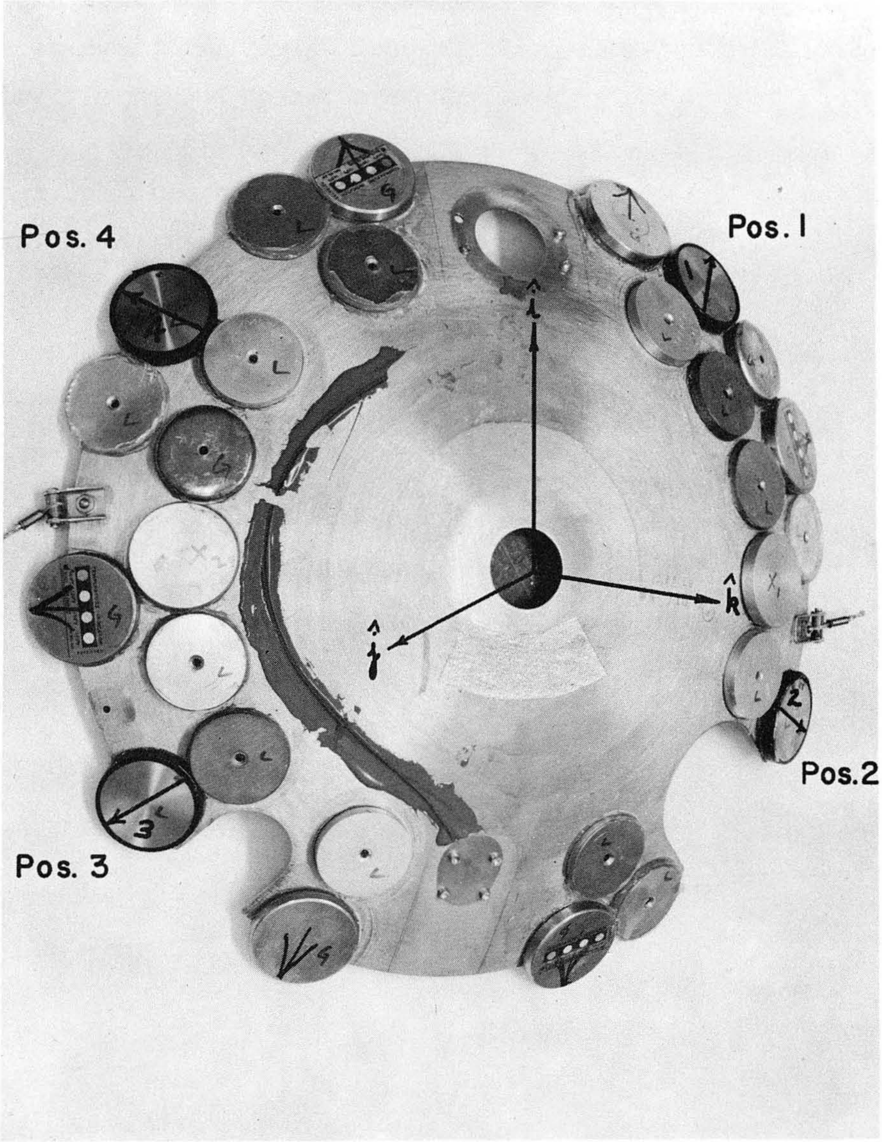
FIGURE CAPTIONS

1. Photograph of the emulsion stacks in position on the spherical section. The numbered, black-rimmed emulsion packets are part of this experiment. The i,j,k reference frame is fixed in the satellite; the $\hat{\underline{i}}$ axis is directed toward the zenith; the axis of symmetry $\hat{\underline{k}}$ remains in the orbital plane. The spherical section is placed immediately beneath the ablative shield.
2. Angular distribution of stopping protons typically observed at position 4 (see Fig. 1). The unequal number of protons in the two peaks is due to an east-west asymmetry in the trapped radiation. The inset illustrates the orientation of the mirror plane relative to the emulsion stack.
3. Geographic locations of the mirroring protons detected in this experiment. The apparent location of the South Atlantic anomaly is determined for each flight. The dark points were obtained from a near circular orbit where the intensity of the radiation encountered during the apogee (S to N) and perigee (N to S) passes were approximately equal. Magnetic declination and inclination angles are indicated by solid and dashed lines, respectively.
4. B-L coordinates of the measured locations of the South Atlantic anomaly. The B-L coordinates appropriate for 400 km altitude were obtained from reference 16. Isointensity cout-rate curves from Explorer IV data are also shown.
5. Schematic illustration of the origin of the east-west asymmetry. Particles observed traveling toward the east have guiding centers at higher altitudes than those observed traveling toward the west. Because of the atmospheric density gradient, a flux gradient is produced. As a result, $j_E > j_W$.
6. Measured values of the proton flux scale heights as a function of detector, i.e., minimum mirror-point, altitude. The dark circles are obtained from the measured east-west asymmetries. The open squares are obtained from the proton flux vs. altitude profile, Fig. 7. The curves drawn through the experimental data, denoted as modified CIRA (1961), are the values of h_{atm} given by the model atmospheres, multiplied by the calculated ratio h/h_{atm}. The ratio h/h_{atm} vs. altitude used to correct the scale heights of model atmospheres to effective proton-flux scale heights is given in the inset.
7. Proton flux $(\frac{dN}{dE})_{65\ \text{MeV}}$ as a function of altitude. The flux values are Those recorded by the emulsions during 4-day orbit periods. The curves

normalized to the data points are derived from the modified scale height values, Fig. 6, which are based upon CIRA (1961) ave. values (solid line) and CIRA (1961) ave. min. values (dashed line). The flux expected from the Explorer IV count-rate data for each flight are shown as open circles.

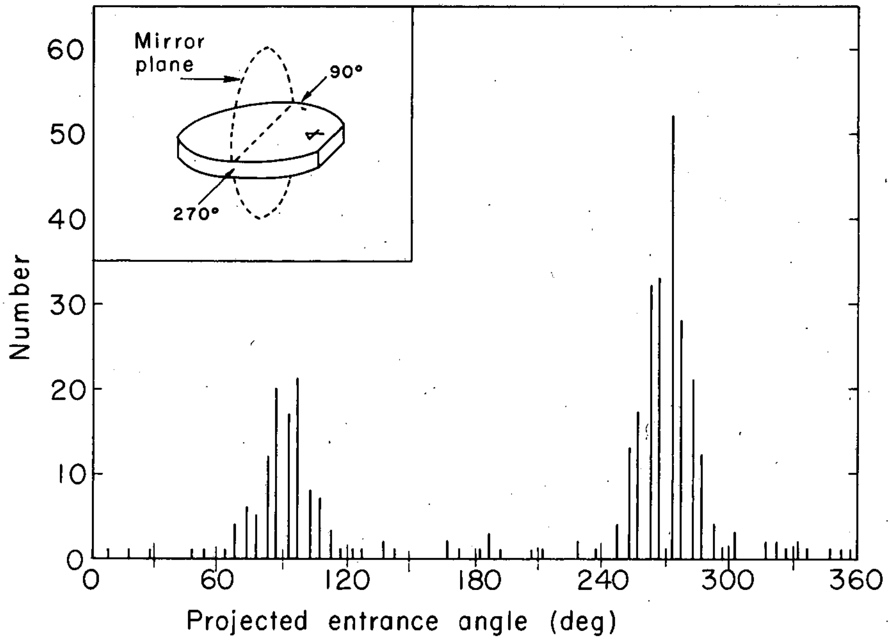
8. Differential proton energy spectrum measured at 408 km altitude in the South Atlantic anomaly.

9. A comparison of the measured proton energy spectrum in the anomaly region, L = 1.40, B = 0.218 gauss, with previous measurements at L values 1.35 and 1.47.



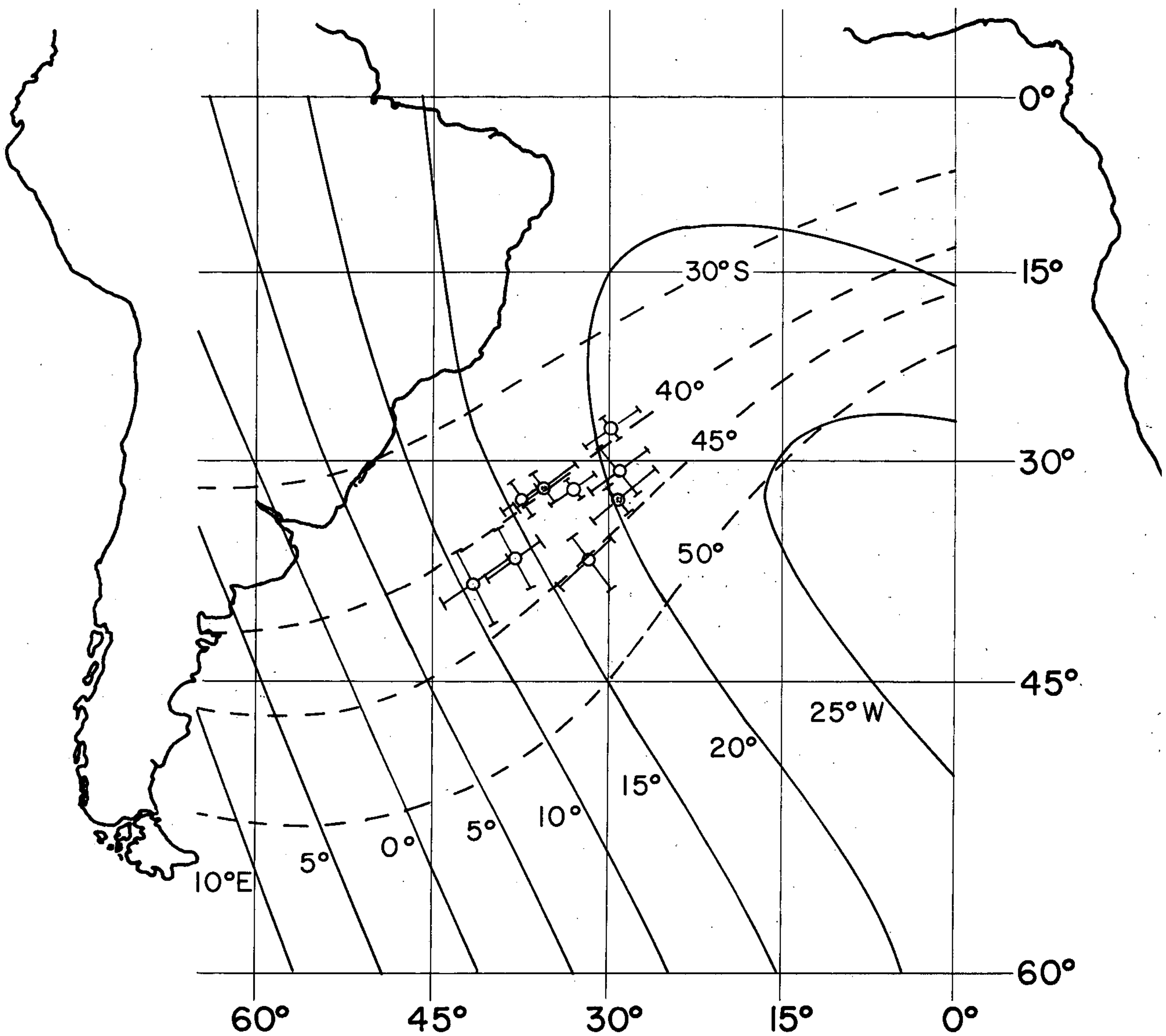
ZN-4256

Fig. 1



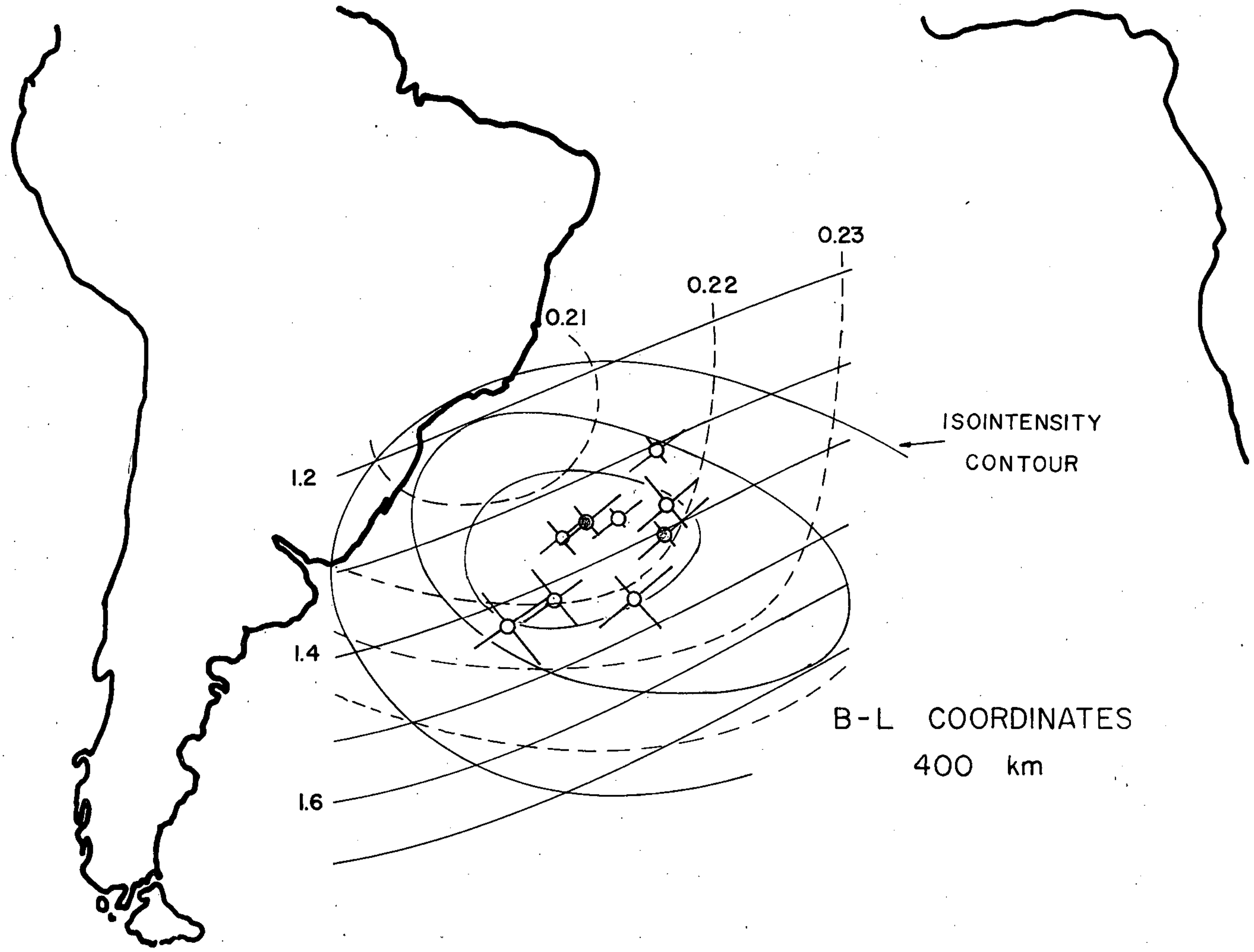
MU-29048

Fig. 2



MUB-2777

Fig. 3



MUB-2778

Fig. 4

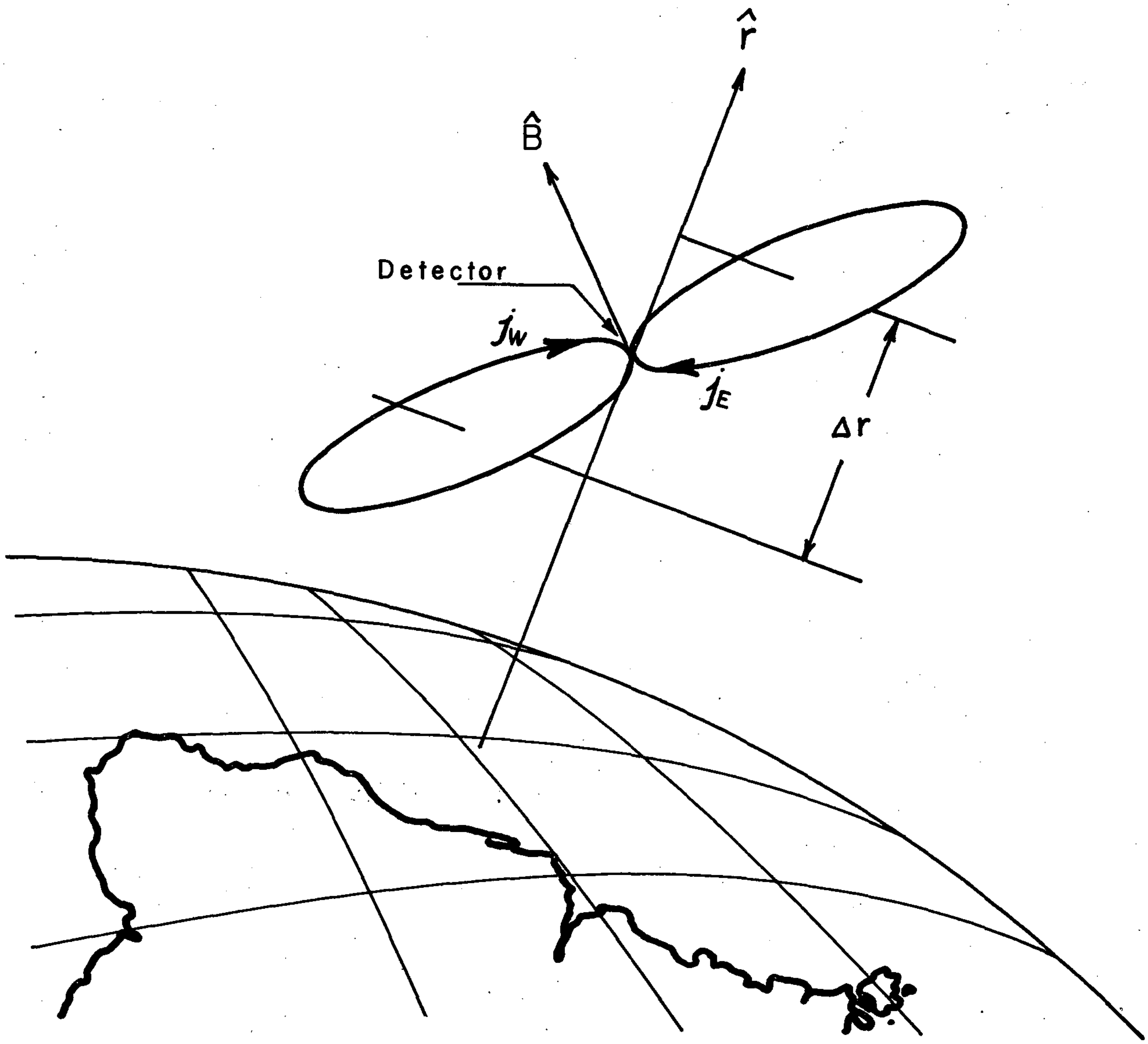


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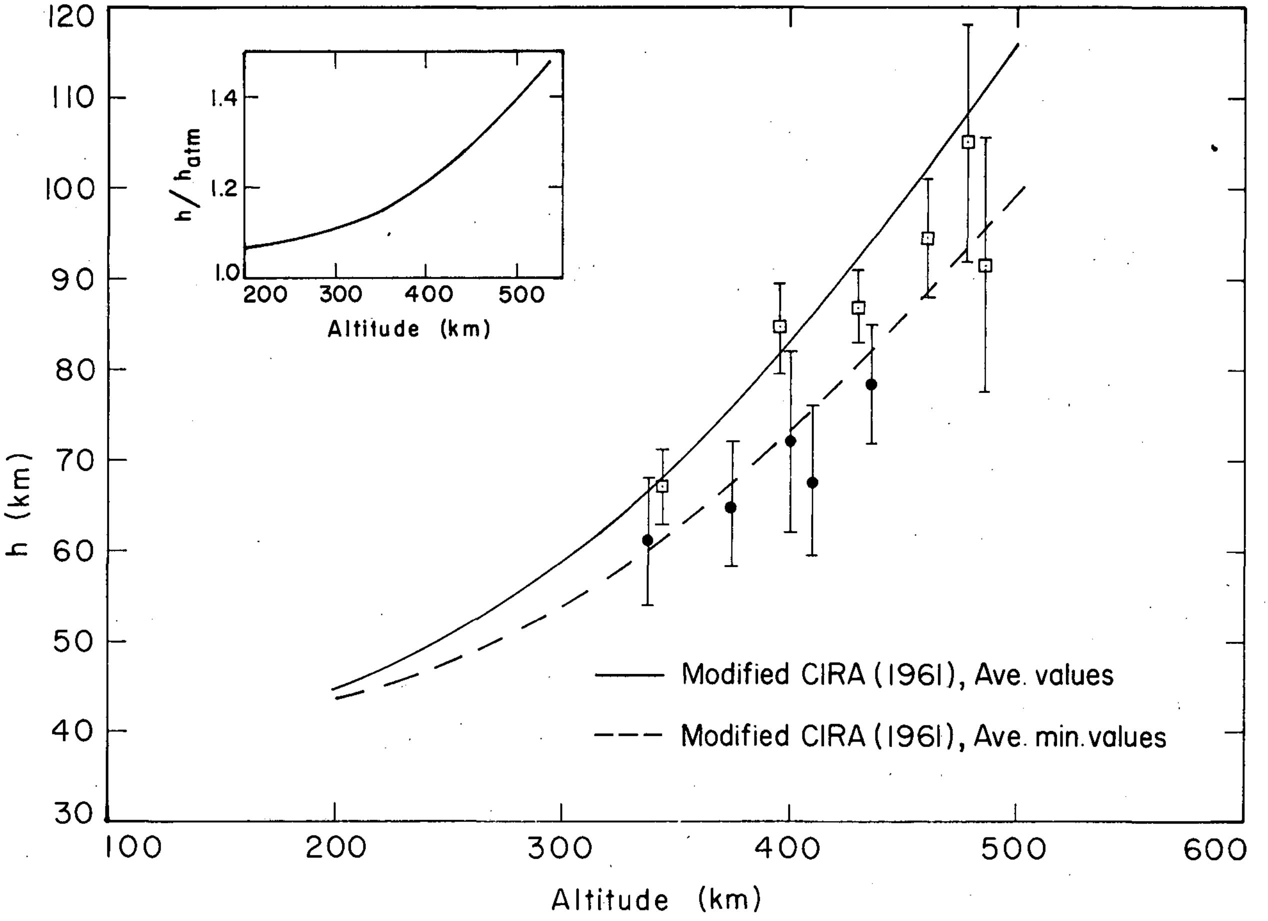
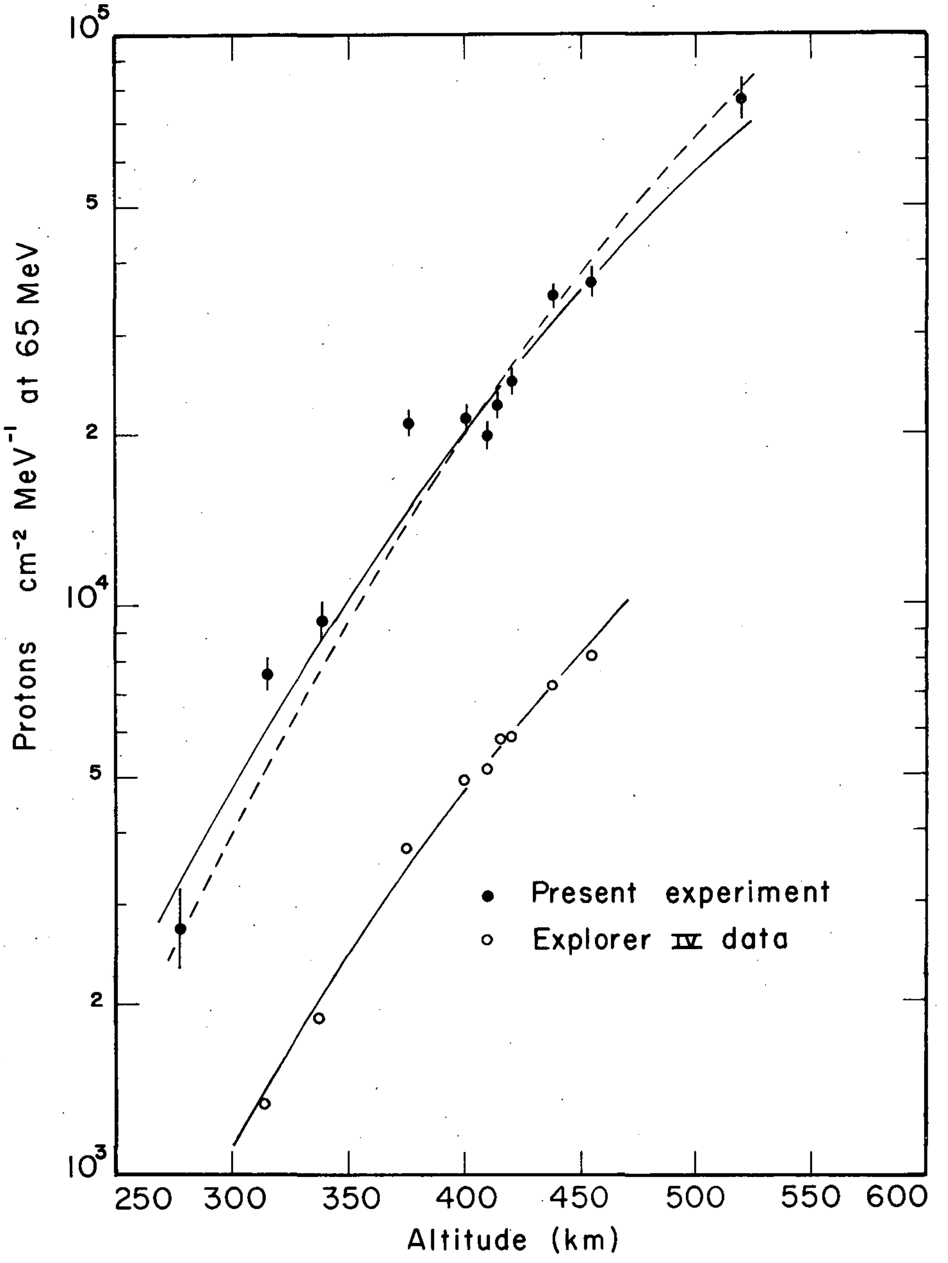
Fig. 5



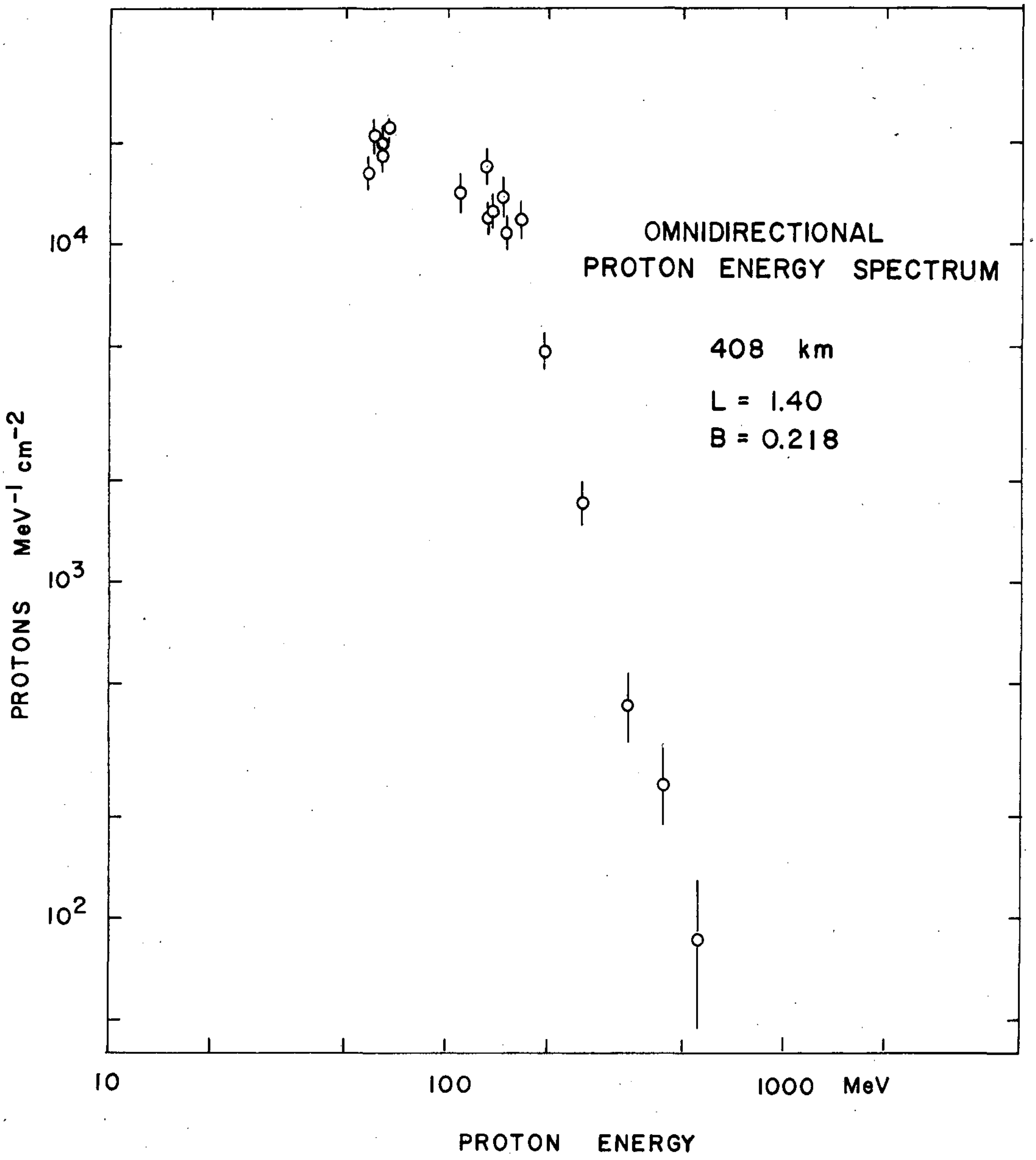
MUB-2780

Fig. 6



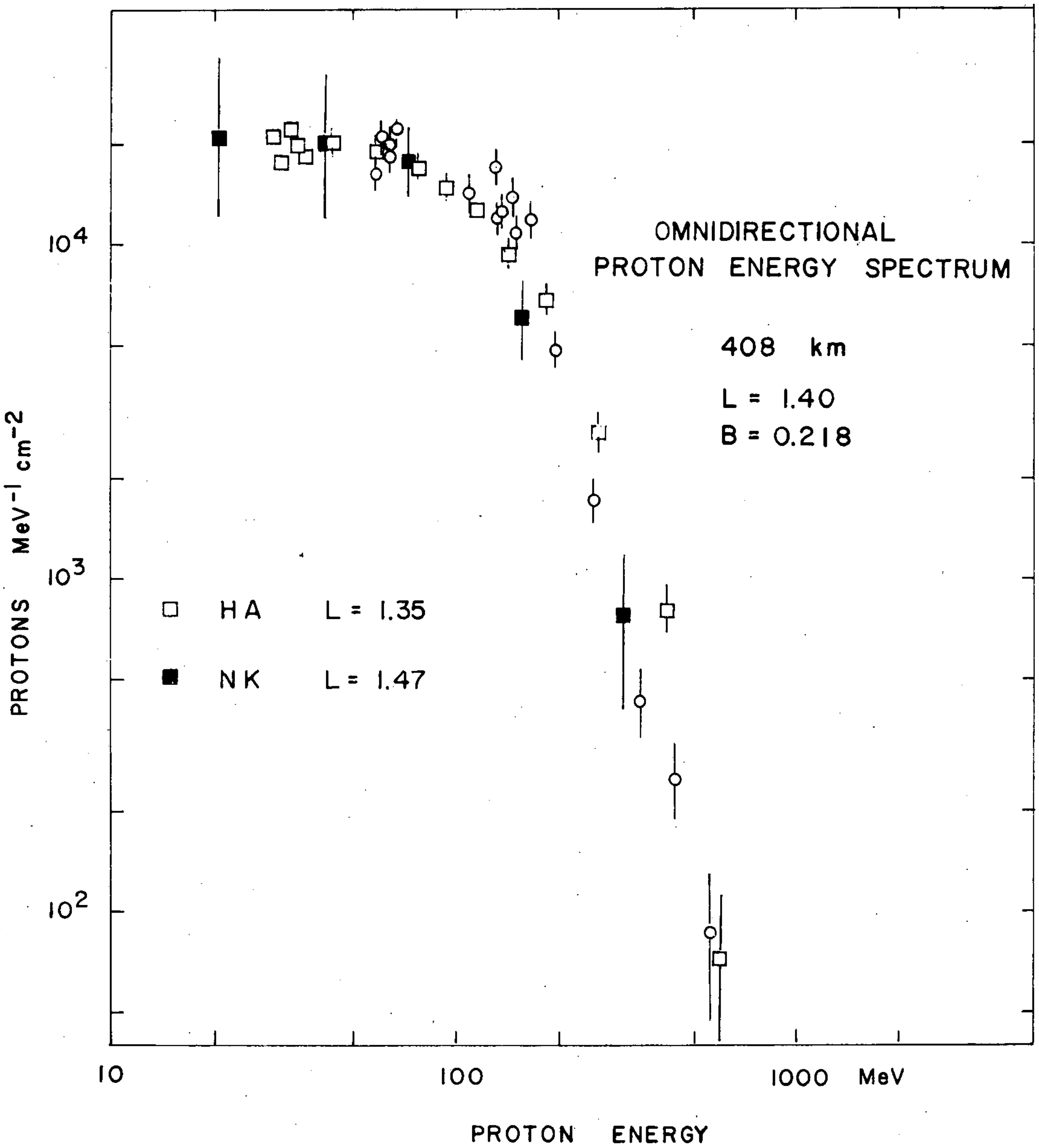
MUB-2781

Fig. 7



MUB-2782

Fig. 8



MUB-2783

Fig. 9