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Abstract

The interplanetary magnetic field is only slightly perturbed by the presence of the moon in the solar wind flow. A statistical study of the umbral increases and penumbral decreases and increases has been conducted with variation of the solar wind plasma β value, the distance from the moon and the selenographic longitude of the limb regions of the lunar surface in the solar wind flow. All lunar wake anomalies show a strong positive correlation with the plasma β value while only penumbral increases show a marked variation with distance from the moon. There is no clear correlation of penumbral anomaly occurrence with selenographic longitude of the exposed lunar limb in the solar wind flow.

Introduction

When the solar wind interacts with the moon, a plasma void is formed aftward of the solar wind flow due to the absorption of solar plasma flux by the lunar surface. The plasma void perturbs the interplanetary magnetic field, whose characteristic features consist of an umbral increase associated with the plasma void and penumbral decreases on either side (Colburn et al., 1967, Lyon et al., 1967, Ness et al. 1967). In addition, a penumbral increase of the magnetic field is sometimes observed (Ness et al., 1968). High frequency fluctuations of the magnetic field stimulated by the lunar wake have been observed (Ness and Schatten, 1969). Ogilvie and Ness (1969) have already reported on the positive correlation of the magnitude of the umbral increase and penumbral decreases with the plasma β value from correlated measurements on Explorers 34 and 35.

It is the purpose of this paper to present a statistical study of the perturbations of the interplanetary magnetic field, observed by the NASA-GSFC magnetic field experiment on Explorer 35, associated with the lunar wake in the solar wind flow. A study of the positional geometry of these anomalies (Whang and Ness, 1970) has shown an elliptical cross-sectional shape of the lunar Mach cone, defined by the position of the boundary between the penumbral increases and decrease. This non-circular shape can be explained as due to anisotropic propagation of magnetoacoustic waves (Michel, 1968, Whang, 1969). Colburn et al. (1971) were unable to identify the existence or geometry of the lunar Mach cone from the Ames magnetometer on Explorer 35.

This paper discusses the variation of the fractional changes of field magnitude, defined as:

$$\Delta B = B_{max}/B_o - 1 \tag{1}$$

or

$$\Delta B = 1 - B_{min}/B_o$$

with the plasma β value, the relative position downstream from the lunar wake and selenographic longitude, i.e., the possible association with lunar surface features. In the above formula B_{max} represents the maximum field magnitude measured in either an umbral or penumbral increase from a well-developed magnetic signature while B_{min} measures the minimum field magnitude in the penumbral decreases. The reference field, B_o, used in calculating the fractional change of wake anomalies is a ten minute average of field magnitude obtained before entering (or after exiting) the penumbral increase, as shown in Figure 1. The reference field B_o used for the umbral increase is the mean value of the 10 minute averages obtained from the entering and exiting values of B_o.

Principal Anomalies

Computations of the plasma ß value have been obtained by utilizing simultaneous measurements obtained from the MIT plasma probe on Explorer 35. The plasma ß value is defined as

$$\beta = \frac{nk(T_e + T_i)}{B^2/8\pi} \tag{2}$$

Simultaneous data for number density, n, ion temperature T_i and field magnitude, B, are available from Explorer 35 but electron temperature data are not. During the period from July 1967 to July 1968 the spacecraft was outside of the earth's bow shock for a total of 76,700 sets of measured number density, ion temperature and field magnitude. In the absence of electron temperature this permits calculation of the corresponding plasma ion ß value, β_i.

Based upon data obtained from the Vela 4B satellite, Montgomery et al. (1968) reported that the electron temperature remains in the range 10^5 to 1.5×10^5 °K despite large fluctuations of any of the other solar wind parameters. Thus we have assumed that a constant electron temperature of 1.5×10^5 °K existed during this time interval in order to obtain the total plasma ß value for the data set. Figure 2 shows histograms of β_i and ß under these assumptions. Statistically it is found that

Median $\beta_i = 0.31$ Average $\beta_i = 0.42$

Median $\beta = 0.76$ Average $\beta = 1.21$

If a different electron temperature is assumed, median and average values of ß for temperatures of 10^5K and 2×10^5°K are as follows:

$T_e = 10^5$°K median $\beta = 0.68$ average $\beta = 0.96$

$T_e = 2 \times 10^5$°K median $\beta = 1.04$ average $\beta = 1.45$

These values are close to the results derived from the Explorer 34 observations (Burlaga and Ogilvie, 1971), but they are substantially lower than the ß values derived from simultaneous data obtained by Vela 3 and IMP 3 (Ness et al., 1971). This occurs because the plasma density derived from the Vela 3 observations is generally higher than those obtained with either the MIT instrument on Explorer 35 or the GSFC instrument on Explorer 34.

Histograms of the principal field anomalies inside the lunar Mach cone are shown in Figure 3. The total number of observed penumbral decreases (PD) used in this study is 160. The average magnitude of the decrease defined by Equation (1) is found to be 0.26. The average magnitude of the observed umbral increase (UI) is 0.29 based upon a total set of 68 observed umbral increases.

A quantitative relationship between the magnitude of the umbral increase and penumbral decreases and the ß value in the solar wind has been studied by Ogilvie and Ness (1969). Presented in Figure 4 is the statistical summary of the variation of umbral increase and penumbral decrease with ß value. It is seen that these results confirm the earlier work with a positive correlation existing between the umbral increases and the plasma ß value. In this study we find that

$$\Delta B_{UI} = (0.25 \pm 0.06)\, \beta$$

which can be compared with the earlier result of Ogilvie and Ness (1969).

$$\Delta B_{UI} = (0.23 \pm 0.09)\, \beta$$

We have also studied the relationship between the magnitude of the penumbral decreases and the location of the Mach cone crossing. Let X denote the distance between the location of the crossing and a plane passing through the center of the moon normal to the solar wind direction. Using the lunar radius as a normalizing unit to measure the distance X, Figure 5 presents a statistical study of the variation of penumbral decrease for X both less than and greater than 2. The figure shows an increase in the penumbral decrease from an average value 0.24 for X less than 2 to an average value of 0.28 for X greater than 2. This slight change is not statistically significant and so we conclude that there is no clear variation of penumbral decrease magnitude with distance for $X < 5$ the observational range within the orbit of the spacecraft.

Penumbral Increases

Siscoe et al., (1968) postulated that possibly a magnetic field on the lunar surface would be responsible for deflection of plasma flow and the associated increase in the interplanetary field strength in the penumbral regions. Hollweg (1968, 1970) suggested that possibly localized regions of high electrical conductivity existed such that the induced magnetic field caused by the convecting magnetized solar wind would lead to such a deflection.

In the theoretical study by Whang (1969, 1970) an ad hoc mechanism for increasing the magnetic field was introduced at the lunar limb which then propagated downstream immediately outside the lunar Mach cone. He attributed the source to the sharp change in magnetic permeability between the solar plasma and lunar body at the limbs of the moon.

We have observed that the magnitude of field perturbations for penumbral increases is of the order of 0.1. For the purpose of quantitatively studying the penumbral increases we will define those perturbations greater than 0.1 as large penumbral increases (LPI) and those less than 0.1 as small penumbral increases (SPL) which include all cases when $\Delta B = 0$. The occurrence frequency of observed large and small penumbral increases as functions of the two parameters ß and X has been studied and the results tabulated in Table 1. Here it is seen that the ratio of LPI to SPI is an increasing function of the ß value of the solar wind and is a rapidly decreasing function of the distance X. This suggests the following interpretations:

1. The source mechanism responsible for the field increases near the lunar limb is directly related to the ß-value of the solar wind.
2. As the penumbral increases propagate downstream along the lunar Mach

cone, their magnitude attenuates very rapidly. Area attenuation alone does not appear strong enough to produce such a fast rate of attenuation and other dissipation mechanisms must take part in reducing the amplitude of the penumbral increases. We estimate that due to the fast rate of attenuation the penumbral increases disappear at approximately 5 lunar radii downstream from the moon.

A study of the penumbral increases observed by the Ames magnetometer experiment on Explorer 35 has recently been presented by Mihalov et al. (1971). They conclude that the sources for observed penumbral increases are non-uniformly located on the moon's surface with most of them restricted to the highland regions on the far-side of the moon. They did not consider other parameters such as plasma β value or spatial distance from the moon in their studies.

We also investigated the distribution of selenographic longitudes of the lunar limb locations associated with each penumbral increase observed by NASA-GSFC Explorer 35 magnetic field experiment. The distribution of possible number of observational data associated with varying selenographic longitudes is not uniform. This is because the immersion of the moon behind the earth's bow shock, radio shadows, the orbital configuration of the spacecraft and unavailability of data for some orbits. For approximately one-third of the lunation, the moon is located in a region of space in which the solar wind flow is either absent (the geomagnetic tail) of highly disturbed and modified (the magnetosheath). This corresponds to selenographic longitudes of approximately 30° to 150° East and also West longitude. Thus these regions have a limb probability of only one-half occurrence throughout an entire lunation. A weighting factor which is defined as the actual total number of observations for each 30° wide longitude interval used in this study divided by the average number is plotted in Figure 6.

The normalized number of LPI and SPI associated with each interval of selenographic longitudes is then defined as the actual number divided by the weighting factor. For the purpose of making a meaningful quantitative study of experimental data, only those well-developed magnetic signatures with complete data coverage ($\sim$22% of total orbits) were selected for our present study. The normalized numbers of LPI and SPI are also shown in Figure 6. We find no clearly defined localization of sources in selenographic longitude except in the interval 60-90° W. It appears to have both an anomalously high number of SPI while simultaneously a low number of LPI. Since this is immediately adjacent to an interval with the opposite occurrence frequencies (90-120° W), we attribute this to the particular choice of quantizing intervals of longitude and not any real effect attributed to the lunar surface. A similar situation occurs to the pair of longitude intervals 30-60°E and 0-30°E. Our results are not consistent with the conclusions reported by Mihalov et al. in that there does not appear to be any restricted longitude regions in which the occurrence frequency of penumbral increases appears to be higher than other regions.

The low inclination of the orbital plane of Explorer 35, 169° with respect to the ecliptic and with respect to the lunar equator precludes a uniform sampling of polar area regions in any attempt to identify lunar surface regions which are preferentially responsible for producing the penumbral increases.

We have considered further the possibility that finite Larmor radius effects might be responsible for the penumbral increases. We have studied this problem statistically by utilizing the ion temperature data but do not find any clear indication that the occurrence of penumbral increases is to be associated with a varying proton Larmor radius.

One of the major problems faced in the interpretation of these penumbral increase phenomena is that the total sample size available is small (160) and when attempting to study the variability with multiple parameters the sample sizes decrease rapidly. At the present time we do not consider the source mechanism for the penumbral increases as clearly indicated to be local lunar surface features. Our results do indicate that the plasma ß value is an important parameter determing the presence and size of the penumbral increase.

Conclusions

A quantitative study of the umbral increases and penumbral decreases and increases in the lunar wake of the solar wind flow show a strong dependence and positive correlation with plasma ß value. In addition, a decreased magnitude of penumbral increase with distance from the moon is observed. There does not appear to be a correlation in the frequency of occurrence of penumbral increases with restricted selenographic longitude regions of the moon. However, the transitory nature of the phenomena: penumbral increases are not always observed and the clear association of the penumbral increases with the plasma ß value may indicate that upstream plasma conditions contribute to the cause of the penumbral increases. Direct correlation of lunar surface magnetic field measurements and penumbral increases observed from orbiting satellites will be essential to resolve the enigmatic problem of the source mechanism of the penumbral increases.

Acknowledgements

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TABLE 1 Number of Large Penumbral Increases/Small Penumbral Increases

	$x < 1$	$1 \leq x < 2$	$x \geq 2$	all x
$\beta \leq 0.06$	1/10	3/8	0/5	4/23 = 0.17
$0.6 < \beta \leq 1.2$	10/6	11/26	2/22	23/54 = 0.43
$1.2 < \beta \leq 1.8$	4/3	7/8	3/7	14/18 = 0.78
$\beta > 1.8$	4/1	4/3	3/9	11/13 = 0.85
All β	19/20=0.95	25/45=0.56	8/43=0.19	52/108 = 0.48

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Figure Captions

Figure 1 Sample Explorer 35 NASA-GSFC magnetic field data measured during transit of lunar wake. Identifiable penumbral increases and decreases and the umbral increase are illustrated and the position of the lunar Mach cone crossing defined.

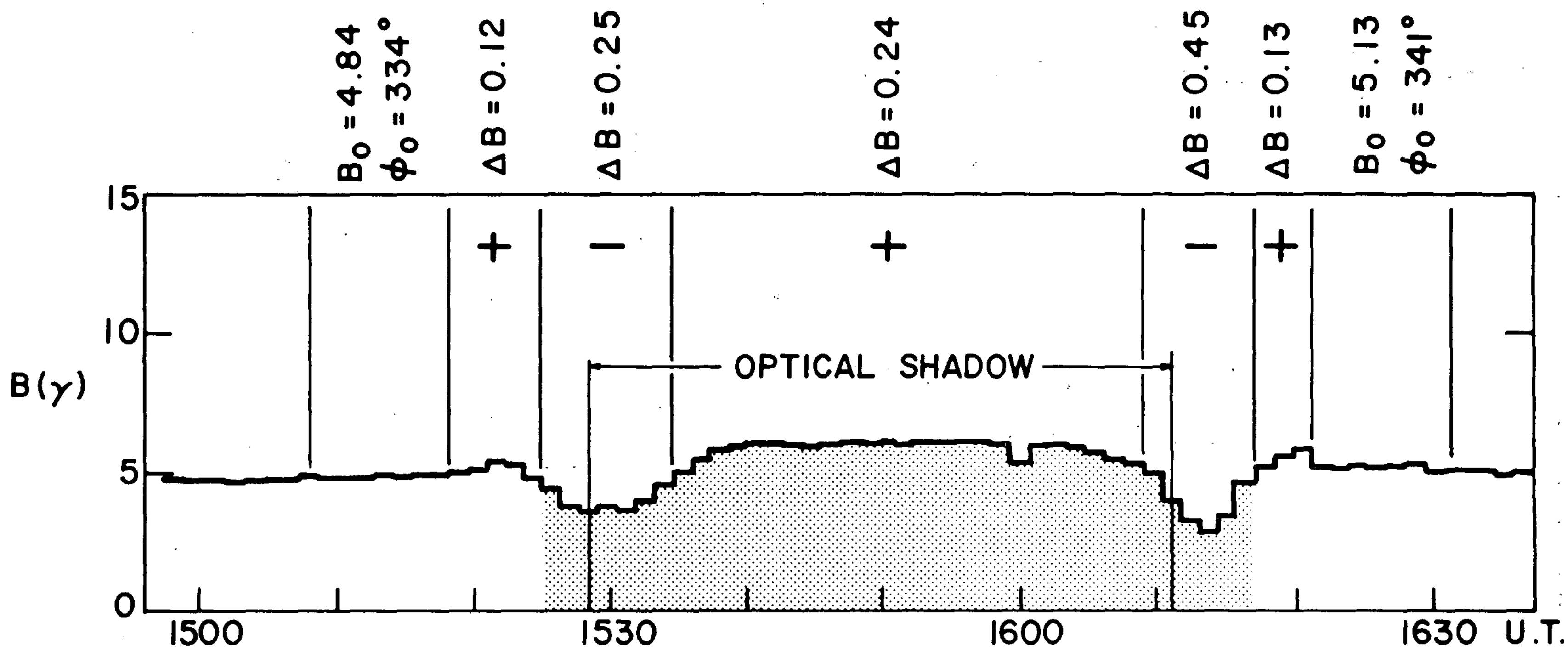
Figure 2 Statistical distribution of measured plasma β_i by Explorer 35 MIT experiment and the NASA-GSFC magnetic field experiment. In addition the distribution of the total plasma β value, assuming a $T_e = 1.5 \times 10^{5}$ °K, is indicated.

Figure 3 Occurrence frequency of umbral increases and penumbral decreases observed by the NASA-GSFC magnetic field experiment on Explorer 35 during July 1967-July 1968.

Figure 4 Variation of plasma β value with penumbral decreases is shown in the upper figure, that with umbral increases in the lower one. These results confirm the earlier studies by Ogilvie and Ness (1969).

Figure 5 Occurrence frequency of observed penumbral decreases for two ranges of distance from the moon. No significant variation of penumbral decrease magnitude with distance from the moon can be interpreted from the slight differences in the averages.

Figure 6 Normalized selenographic longitude distribution of large (LPI) and small (SPI) penumbral increases observed by NASA-GSFC Explorer 35 magnetic field experiment. No non-uniform distribution is apparent in penumbral increase occurrence although a suggestion of more frequent occurrence of large penumbral increases at longitudes between 60° and 180° East is possible. The dash line on top indicates the weighing factor which is the ratio of the actual number of observational data associated with varying selenographic longitudes to the average number.



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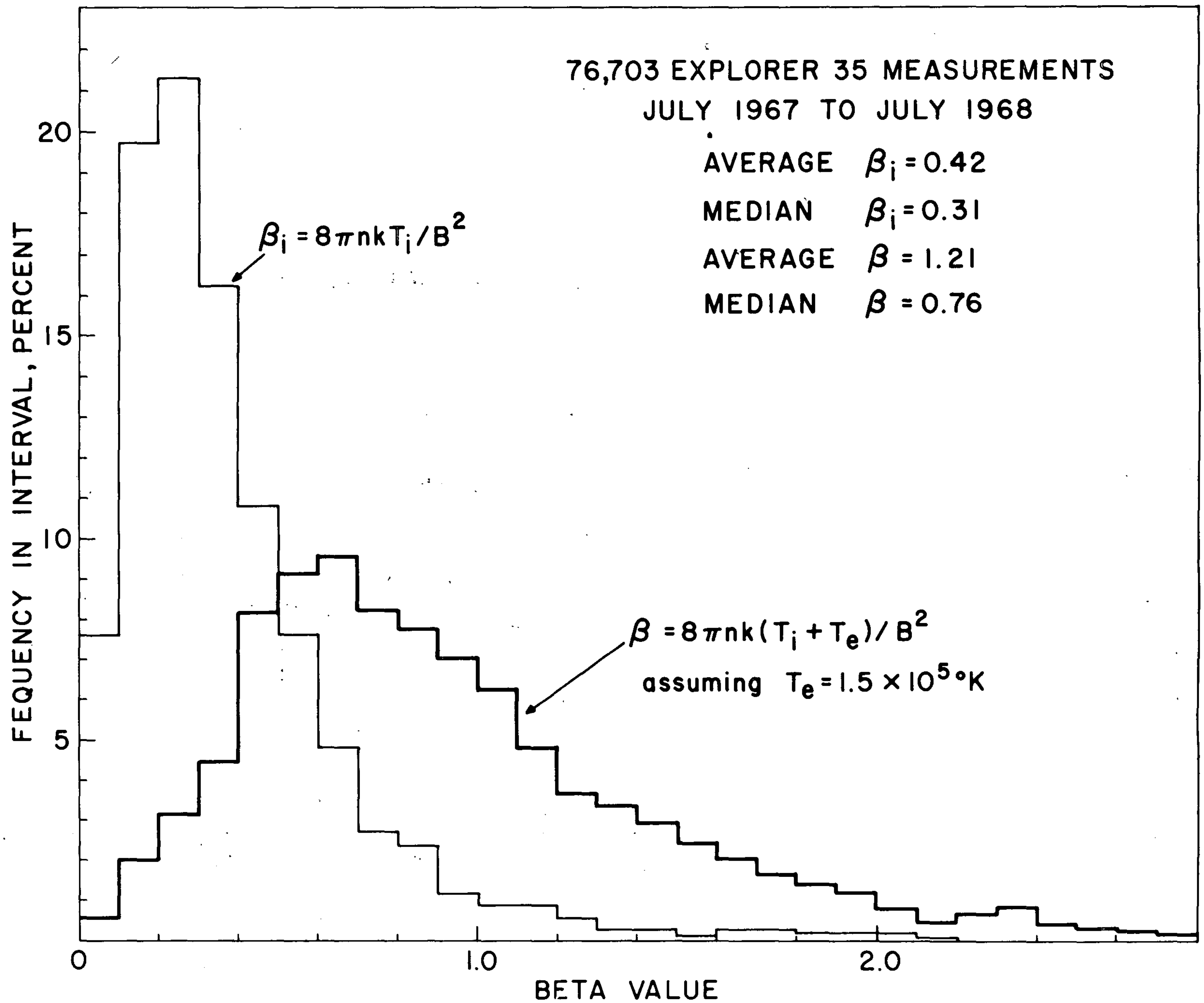
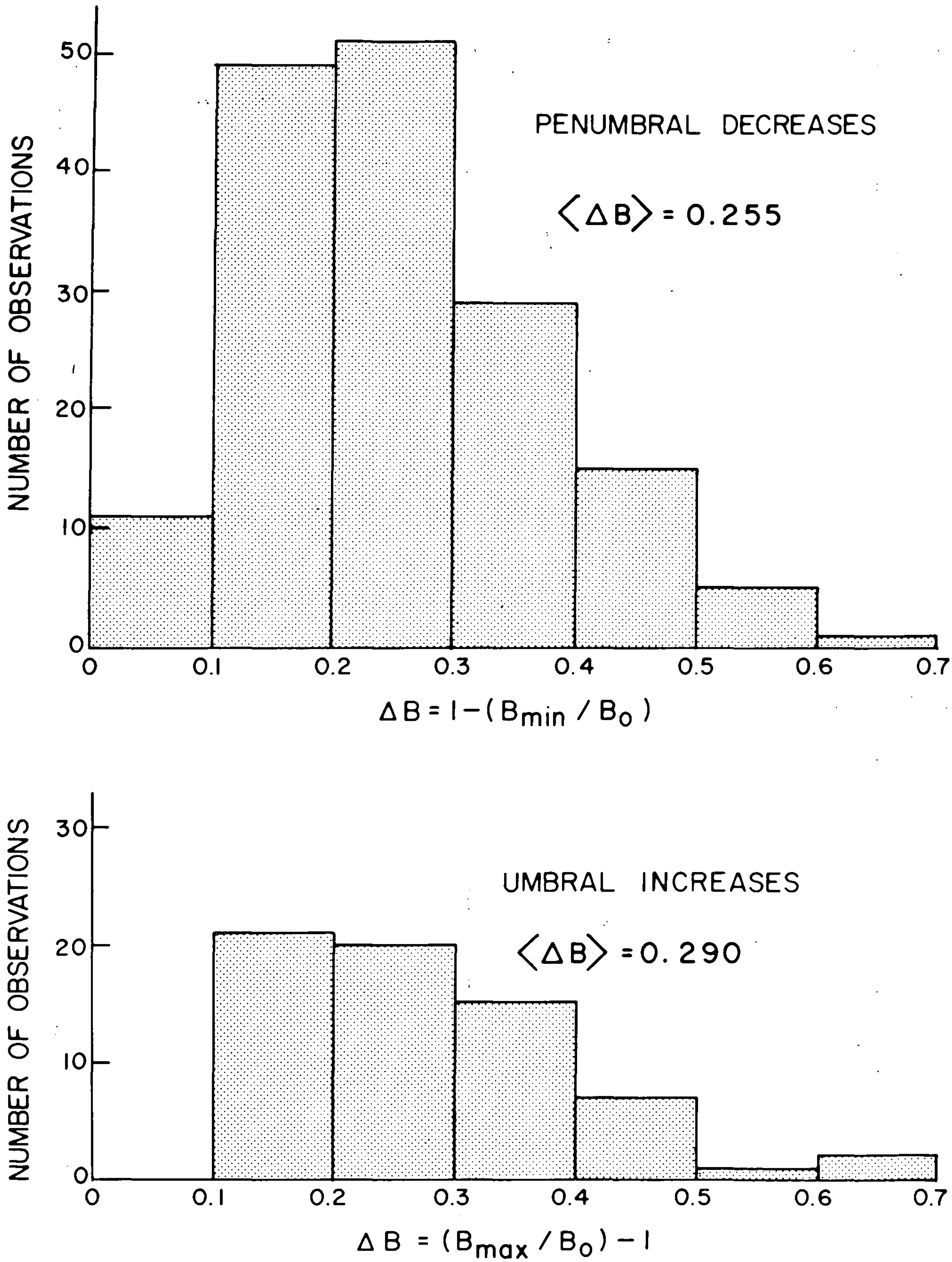
$$\Delta B = (B_{max} / B_o) - 1 \quad \text{OR} \quad 1 - (B_{min} / B_o)$$

Figure 1



76,703 EXPLORER 35 MEASUREMENTS
JULY 1967 TO JULY 1968
AVERAGE $\beta_i = 0.42$
MEDIAN $\beta_i = 0.31$
AVERAGE $\beta = 1.21$
MEDIAN $\beta = 0.76$
$\beta_i = 8\pi nkT_i/B^2$
$\beta = 8\pi nk(T_i + T_e)/B^2$
assuming $T_e = 1.5 \times 10^5$ °K
FEQUENCY IN INTERVAL, PERCENT
BETA VALUE
0
1.0
2.0
5
10
15
20

Figure 2



NUMBER OF OBSERVATIONS
PENUMBRAL DECREASES
⟨ΔB⟩ = 0.255
0
10
20
30
40
50
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\Delta B = 1-(B_{min} / B_o)$
NUMBER OF OBSERVATIONS
UMBRAL INCREASES
⟨ΔB⟩ = 0.290
0
10
20
30
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\Delta B = (B_{max} / B_o) - 1$

Figure 3

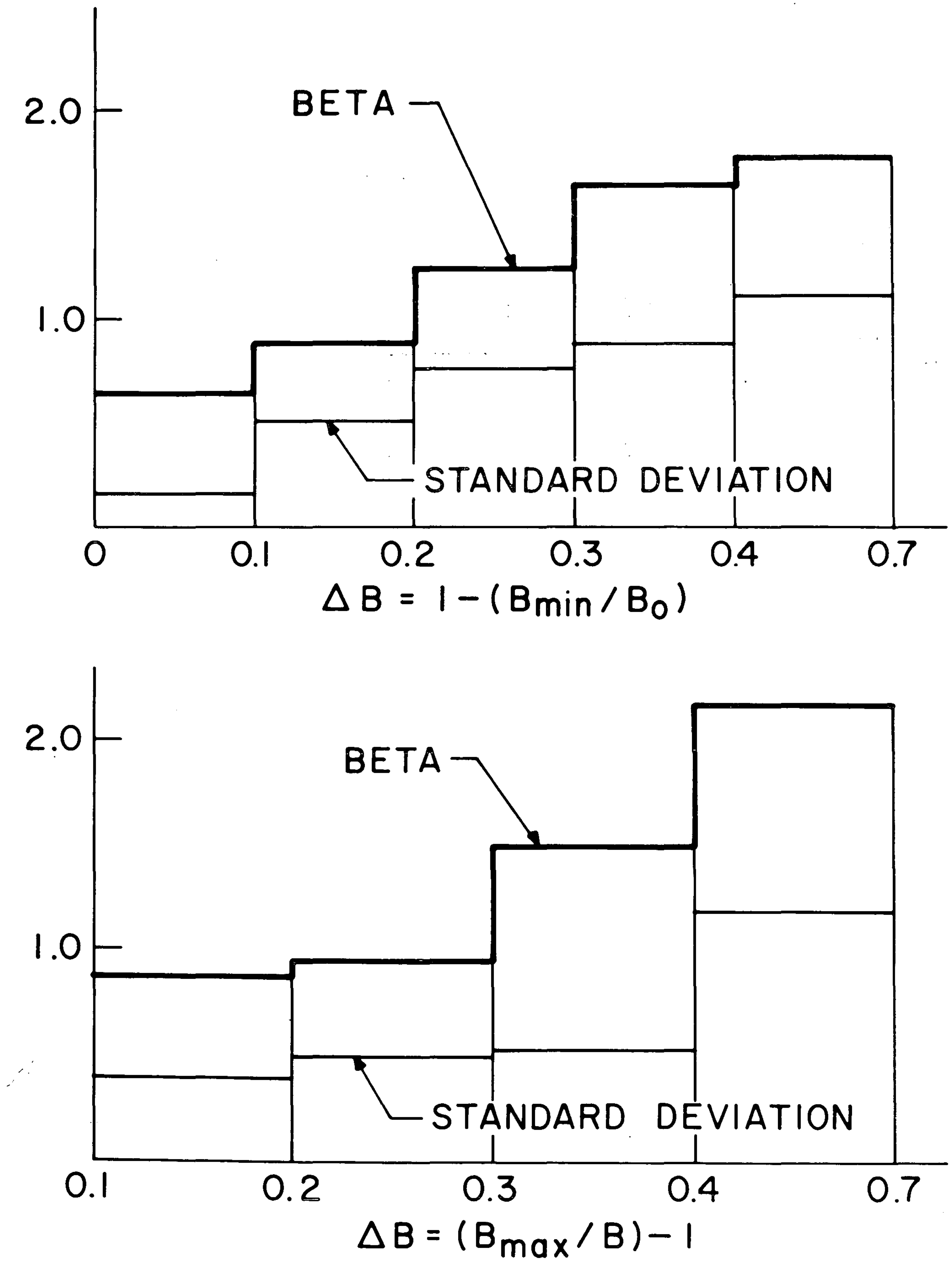

2.0
1.0
BETA
STANDARD DEVIATION
0
0.1
0.2
0.3
0.4
0.7
ΔB = 1 − (Bmin / Bo)
2.0
1.0
BETA
STANDARD DEVIATION
0.1
0.2
0.3
0.4
0.7
ΔB = (Bmax / B) − 1

Figure 4

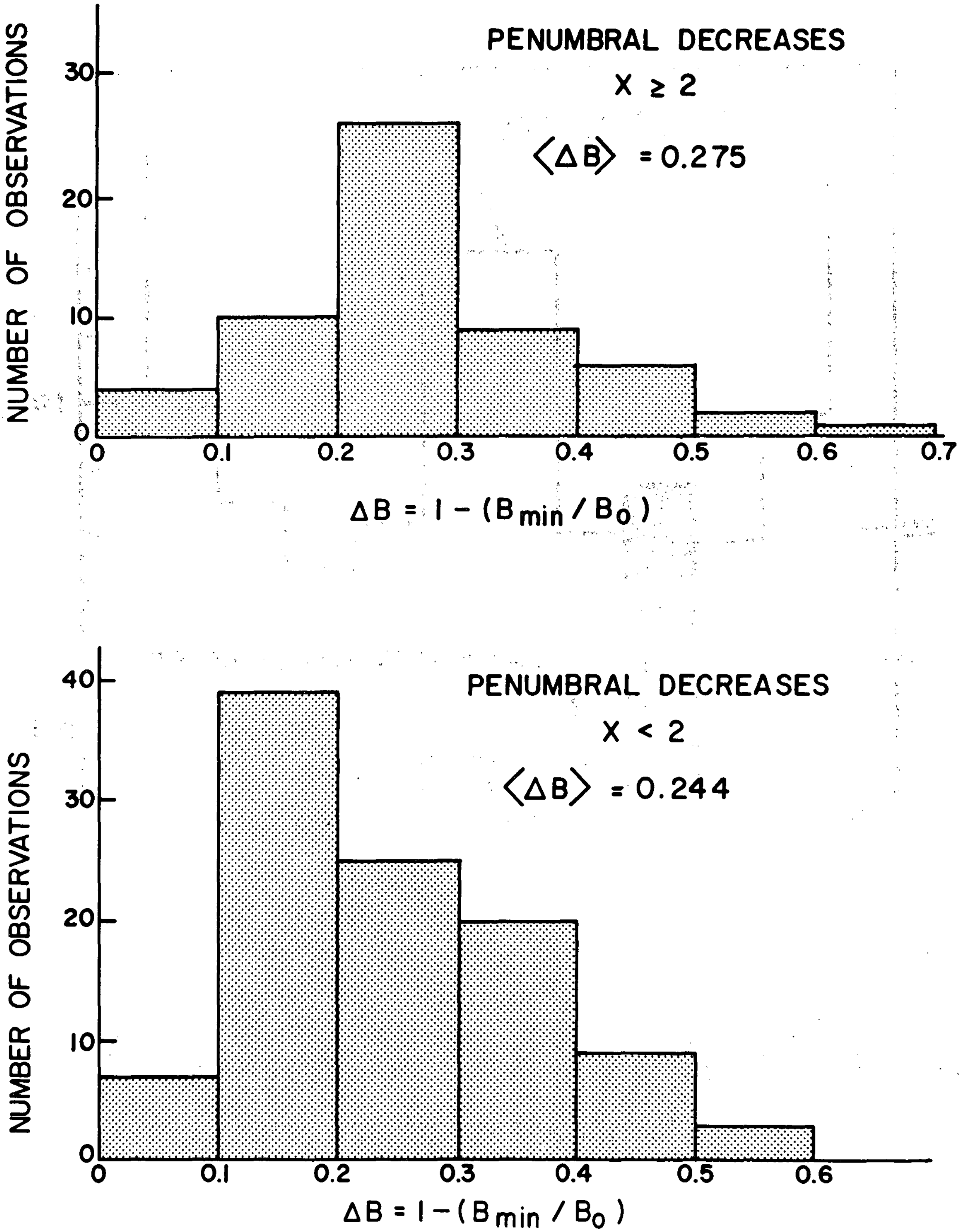
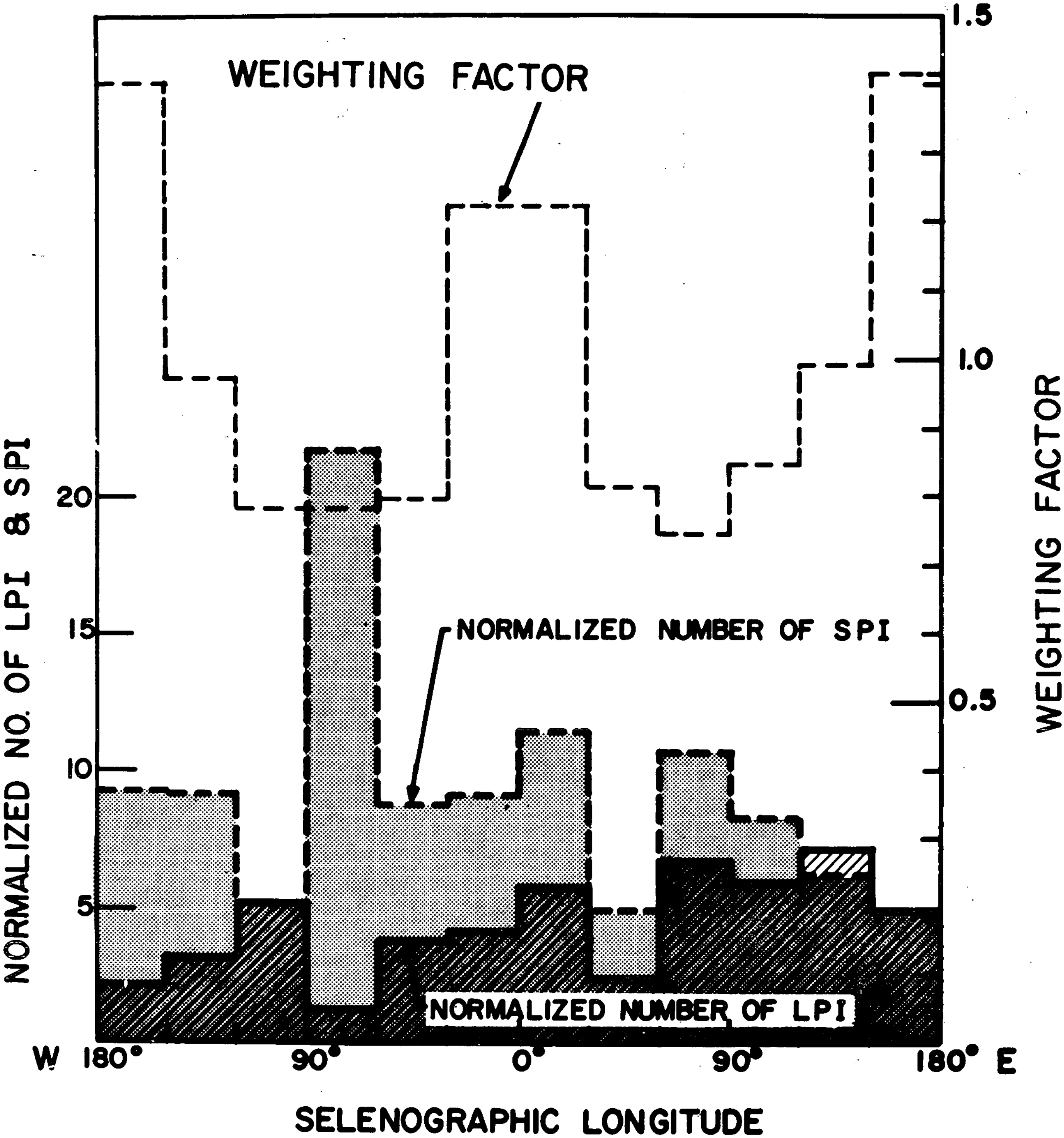

PENUMBRAL DECREASES
X ≥ 2
⟨ΔB⟩ = 0.275
NUMBER OF OBSERVATIONS
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ΔB = 1 − (B min / B0)
PENUMBRAL DECREASES
X < 2
⟨ΔB⟩ = 0.244
NUMBER OF OBSERVATIONS
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
ΔB = 1 − (B min / B0)

Figure 5



WEIGHTING FACTOR
NORMALIZED NUMBER OF SPI
NORMALIZED NUMBER OF LPI
NORMALIZED NO. OF LPI & SPI
WEIGHTING FACTOR
20
15
10
5
1.5
1.0
0.5
W 180°
90°
0°
90°
180° E
SELENOGRAPHIC LONGITUDE

Figure 6