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GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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Abstract

The analysis of detailed measurements at 5.11 second intervals by the NASA-GSFC magnetic field experiment on Lunar Explorer 35 in the vicinity of the moon has revealed the presence of rapid fluctuations up to the instrument bandpass of 5 Hz with amplitudes of several gammas. These disturbances are transmitted both up and downstream from the penumbra into regions of space directly connected to the penumbra by the magnetic field. Similar fluctuations are not observed in the center of the lunar wake, the solar wind plasma umbra, where no plasma is present. Power spectral analyses made in a field aligned coordinate system reveal that these fluctuations have approximately the same amplitude both parallel and transverse to the average field direction. Statistical studies are presented of the frequency of occurrence of the disturbances as a function of the distance to the point of observation from the lunar wake and of the fluctuation amplitude, and correlation with field magnitude. These observations suggest that the fluctuations have their source where the solar wind proton and electron distribution functions are disturbed by the removal of particles by absorption by the moon. Instabilities induced by this disturbance of the electron distribution function are postulated as the source of the fluctuations, and their propagation with the electron velocity, which is greater than the bulk speed of the solar wind, allows the upstream solar wind to be affected by the wake of the moon.

Introduction

Results from experiments on the lunar orbiting spacecraft Explorer 35 have reported no evidence for a shock wave in the vicinity of the moon, although a regular pattern of small perturbations is frequently observed in the magnitude of the interplanetary magnetic field in the solar wind umbra created by the absorption of plasma by the moon (see review by Ness, 1969).

This paper will discuss observations by the NASA-GSFC magnetic field experiment which show a direct effect of the lunar wake upon the interplanetary medium in the immediate vicinity of the moon. The present analysis extends over the time interval from launch on July 18, 1967 through July 31, 1968 and hence because of the heliocentric motion of the Earth-Moon system the orbital line of apsides changes at a uniform rate by 370^{o} relative to the moon-sun line. This 12 month interval provides a complete sweep of the orbit about the moon so that the region from spacecraft periselene ($1.4\ R_M$; $R_M = 1738$ Km) to aposelene ($5.4\ R_M$) is sampled throughout an azimuthal range of more than 360^{o} relative to the moon-sun line. The orbital plane is inclined less than 11^{o} to the ecliptic plane. The plane of symmetry of the lunar wake is defined by the solar wind velocity and the interplanetary magnetic field direction. Because of the variability of the magnetic field direction, especially the solar ecliptic latitude, the inclination or aspect of the orbital plane varies considerably with respect to the symmetry plane. Thus there will be an effective three-dimensional spatial sampling of the lunar environment with respect to solar plasma flow in spite of the relatively fixed inclination of the orbital plane.

The data reveals the presence of rapid fluctuations of the interplanetary magnetic field with amplitudes up to several gammas. A schematic representation illustrating the solar wind plasma umbral and penumbral regions behind the moon and the regions where these rapid fluctuations have been observed in the interplanetary magnetic field is shown in Figure 1. These fluctuations are not observed in the solar wind umbral core of the lunar shadow but appear to exist both upstream and downstream of the penumbral shadow of the moon. Simultaneous plasma data was not available for correlative analysis and it is assumed that the magnetic field magnitude anomalies (Colburn et al., 1969; Ness et al., 1969, Ness et al., 1968 and Taylor et al., 1968) indicate the location of the solar plasma umbra and penumbra.

One condition necessary for the observation of these fluctuations is that the magnetic field line passing through the spacecraft must also pass through the lunar penumbral region. The spatial extent, relative amplitude, direction and solar wind properties that favor the occurrence and observation of these fluctuations will be presented.

Experimental Observations

Simultaneous observations of the interplanetary magnetic field on March 26, 1968 by Explorers 33 and 35 are shown in Figure 2. While Explorer 33 is measuring the interplanetary magnetic field, Explorer 35 is in loose orbit about the moon. Observations on Explorer 33 measure a rather steady field with magnitude 6γ. The observations by Explorer 35 reveal the presence of an umbral increase in field magnitude and detectable decreases in the penumbral region identified respectively by + and - signs on the magnitude plot.
The average direction of the interplanetary magnetic field, the spacecraft orbit and the direction to the earth are shown in the upper left hand corner. At this time the satellite Explorer 33 is located at $X_{SE} = 27.3\ R_E$, $Y_{SE} = 7.5\ R_E$, $Z_{SE} = -4.5\ R_E$ while Explorer 35 is located at $X_{SE} = 56.5\ R_E$, $Y_{SE} = -24.3\ R_E$, $Z_{SE} = -3.4\ R_E$ so that a separation of 43.2 R_E between the two spacecraft exists. These simultaneous data illustrate an important feature of cislunar space, namely: that on average the interplanetary magnetic field is relatively uniform over this distance scale for time scales of 30 minutes or more.

In Figure 3 are presented simultaneous observations of magnitude measurements at 5.11 second intervals obtained by both spacecraft during the March 26, 1968 pass illustrated previously in Figure 2.

Identified on the Explorer 35 data are noisy and quiet regions of the magnetic field. The presence of a quasi-sinusoidal variation in the field magnitude on Explorer 35 is spurious and associated with the aliased spin period of the spacecraft and the incomplete removal of spin modulation associated with zero level and gain uncertainty of the two sensors transverse to the spin axis of the spacecraft. Note that in the lunar shadow region this aliased spin modulation is nearly a pure sinusoid representing a very steady ambient magnetic field. The presence of small amplitude (less than 0.20γ) noise would destroy the waveform of the spin modulation and lead to data similar to that taken after the lunar shadow.

The simultaneous data taken by Explorer 33 do not reveal the presence of the noise which is observed, in this case, only as Explorer 35 approaches the lunar wake and not readily identifiable as the spacecraft leaves the lunar wake. The region identified as noisy, observed prior to the wake anomaly, represents the rapid fluctuations of interest to this paper. It is seen that the amplitude of these fluctuations peak-to-peak is approximately 2γ. These fluctuations might be related to the earth's bow shock since the position of the spacecraft and the field line as indicated in Figure 2 are at times such that the field line which passes through the satellite also intersects the earth's bow shock.

This possibility can be excluded by noting that the rapid fluctuations persist only in the region near the plasma penumbra and are not observed in the lunar plasma umbra. A study of several hundred passes of Explorer 35 through the lunar wake has indicated that rapid fluctuations will be observed only if the spacecraft is in close proximity to the penumbra and if the field line passing through the spacecraft also passes through the plasma penumbra.

In order to study this criterion more precisely, several parameters relevant to field line threading the wake have been computed and studied both by detailed comparisons with individual orbital passes and also statistically for those passes which show measureable rapid fluctuations. Figure 4 illustrates those parameters concerning the field line wake threading calculations which will be discussed in this paper.

The penumbra is approximated by a cylinder tangent to the limb of the moon parallel to the moon-sun axis and extending infinitely behind the moon. This simplified model does not take into account the real geometry since it is known that the solar wind velocity varies as much as $\pm 10^{\circ}$ from the earth-sun line (or moon-sun line equivalently) nor that the plasma penumbra while cylindrical close to the moon may become elliptical downstream with the major axis increasing to beyond 2 lunar radii (Whang, 1968a; 1968b). For this initial study these higher approximations to the lunar wake geometry will be neglected. On average, this should not be a serious problem as the spacecraft is generally a few lunar radii from the moon and wake deviations from cylindrical geometry become appreciable only beyond about 5 lunar radii.

As shown in Figure 4 the position of the spacecraft is given in selenocentric solar ecliptic coordinates. The magnetic field line observed threading through the spacecraft is rectilinearly extended in a fashion similar to that used by Van Allen and Ness (1968) in studying the shadowing of energetic particles by the moon. The relevant parameters to field lines threading the wake are as follows:

XC is the X_{SSE} coordinate of the position ($\vec{X}_c$) along the extended field line which is Closest to the X_{SSE} axis.

DFA is the Distance to the extended field line From the X_{SSE} Axis.

DCA is the Distance along the field line from the spacecraft to the point of Closest Approach to the axis of the wake ($\overrightarrow{DCA} = \vec{X}_{SC} - \vec{X}_c$)

XW is the X_{SSE} coordinate of the position along the field line where the intersection with the theoretical lunar Wake occurs

DW is the Distance along the field linefrom the spacecraft to the lunar Wake surface intersection XW. Values of this quantity greater than 0 are defined to indicate that the spacecraft is upstream from the position where the field line crosses the wake ($X_{SC} > XW$) and conversely a negative value is indicative of a spacecraft position which is downstream from the lunar wake intersect position ($XW < X_{SC}$).

The above parameters will be used in the following discussions of detailed passes and statistical analysis of the spatial occurrence of rapid fluctuations. All distances will be in units of lunar radii.

Figure 5 shows a series of three additional passes through the lunar wake in which observations of rapid field fluctuations were made by Explorer 35. Universal time and spacecraft position in selenocentric coordinates are tabulated along each abscissa. In addition the shaded regions indicate those times when the field line which passes through the spacecraft also threads the lunar wake as defined by the criterion DFA is less than 1 and XC is less than 0. The numbers in Figure 5 listed above the shaded areas indicate the value of DCA.

The April 27, 1968 orbit of Explorer 35, shown in the bottom panel, illustrates that noise is closely associated with the field line threading criterion. At approximately 0300 UT the field line which passes through the spacecraft also threads the penumbra region of the lunar wake and rapid fluctuations are detected in the field magnitude. At this time values for DCA are between 2-5. At approximately 0330 UT the field line no longer threads the penumbral region and although the spacecraft motion brings it closer to the wake region the noise is no longer observed. In the umbral region at approximately 0430 UT, the field line threads the wake but no noise is detected. As the spacecraft emerges from the wake region, the field line continues to thread the wake and noise is once again observed. Finally after the field line ceases to thread the wake, the noise again disappears. Similar interpretations of the April 25 and 26 data can be made illustrating the close association between the field line threading parameters and the observation of rapid fluctuations of the magnitude. In general, values of DCA extending from 1 through 4 are seen to favor the occurrence of rapid fluctuations. Hence the noise is observed upstream in the solar wind a substantial distance from the lunar penumbra.

A computation of the power spectra associated with three separate regions in the vicinity of the moon are shown in Figure 6. The three regions are identified as undisturbed interplanetary, noisy interplanetary, and umbral regions and are taken from the April 26, 1968 pass shown in Figure 5. Computation of the power spectra is effected in a special coordinate system in which the Z axis is parallel to the average magnetic field direction during the interval computations are made, while X and Y refer to directions orthogonal to this. This special field coordinate system permits a direct separation of longitudinal and transverse perturbations of the interplanetary magnetic field by inspection of the separate XYZ results.

The first column, referring to undisturbed interplanetary space, reveals the presence of principally transverse disturbances since the X and Y components are approximately equal and almost an order of magnitude larger than the Z component. Note the presence of spectral peaks in both the Z and magnitude spectra. These are associated with the incomplete removal of the zero level and gain uncertainties of the sensors transverse to the spin axis.

These spectra were computed from the 5.11 second data obtained by the NASA-GSFC magnetic field experiment. The frequency bandpass of the instrument extends to 5 Hz where the 3dB attenuation point occurs and attenuation of higher frequencies occurs at a rate of 20dB per octave. Thus fluctuations of the magnetic field which occur with a frequency between 0.098 to ~ 5 Hz are aliased in these spectral computations. Depending upon the shape of the spectrum such aliasing may or may not be a serious problem in the interpretation of such spectra. It is known that the spectra of fluctuations in interplanetary space decrease rapidly with increasing frequency (Siscoe et al., 1968; Sari and Ness, 1969). Thus aliasing will not lead to a misinterpretation of the data since the fraction of total energy aliased is small.

Returning to Figure 6, inspection of the noise region in the middle column indicates that the fluctuations have approximately the same amplitude both parallel and transverse to the average field direction. However, a slight preference towards transverse fluctuations can be noted since the X and Y components have spectral densities approximately 2 to 3 times that of the Z component. In this panel only the second harmonic of the spin period is detectable in the magnitude spectrum. The third column presents the spectra for the umbral region where the interplanetary magnetic field was observed to be extremely quiet. Here the X, Y and Z components are all reduced significantly compared with their previous levels both in the noise region and in the undisturbed region. Also the aliased spin period spectral peaks are readily evident in all three components as well as the magnitude. The very low power levels observed in this region indicate that it is extremely quiet, even relative to undisturbed interplanetary space.

Inspection of spectra from other passes of the satellite through the lunar wake region reveal similar results, namely: in interplanetary space undisturbed by the presence of the lunar wake the perturbations of the interplanetary field are typically small amplitude and transverse to the average field direction. The noise regions represent relatively large amplitude perturbations where magnitudes of the transverse perturbations in interplanetary space increase by a factor of 1.4-1.7, while the longitudinal component is increased by an order of magnitude. In the very quiet umbral core the transverse and longitudinal perturbations are reduced by an order of magnitude from the undistrubed interplanetary medium.

The spatial extent of rapid fluctuations observed by Explorer 35 from July 1967 through July 1968 is shown in Figure 7. The position of the spacecraft where the field fluctuations were observed has been rotated above the moon-sun axis into the selenocentric solar ecliptic plane. From this figure the extent of the fluctuating field region may be determined. It is seen that the disturbances are observed far from the moon both in the Y direction and also upstream of the wake. This indicates that the propagation velocity of these fluctuations has a component travelling perpendicular to the solar wind direction relatively fast as compared with the solar wind speed itself. The spatial extent of the disturbances does not possess any shock wave appearance indicative of a convective phenomenon associated with the solar wind flow past the moon.

Statistical Studies

Histograms of the occurrence of noise as a function of the parameters DFA and DCA are shown in Figure 8. The data used in this figure were obtained from sequence averages over an interval of 81.8 seconds. The histograms of noise occurrence as a function of DFA illustrate a generally flat appearance out to approximately 1 lunar radius and then a rapid decrease. This graph substantiates the hypothesis that the field fluctuations occur only on those field lines which pass through the spacecraft and the lunar plasma penumbra. In addition, there is only a slight increased occurrence of fluctuations with deeper umbral penetration by the field lines. This supports the hypothesis that the noise is associated with those field lines which intersect the penumbra and is not associated with the umbral core of the lunar wake.

An important parameter which should be studied is the plasma β value and other microscopic characteristics of the interplanetary medium, such as thermal anisotropy of the ions and the relative temperature of the electrons and ions. Since these data are not yet available, this important aspect of the study of occurrences of these fluctuations has not been possible.

The histogram of noise occurrence as a function of DCA suggests a value for the magnitude of DCA between 1 and 2 favoring the occurrence of noise. There appears to be an increase in the occurrence of noise for values of DCA greater than 0. This means that the noise appears more frequently upstream than downstream of the lunar wake. We believe that this is due to a combination of the spacecraft orbit as well as the preferential field line direction in interplanetary space.

A typical value of the amplitude of the peak-to-peak disturbance measured over a noise region is 1.5 γ. Less than 25% of the noise occurrences show peak-to-peak amplitudes greater than 2 γ.

The next series of figures will present a parametric study of the variations of noise dependent upon various field line threading parameters. The average field parameters to be computed are:

1. The RMS field magnitude variation given by

$$\delta F = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_i-\overline{F})^2}$$

and the RMS field component variation δC given by

$$\delta C = \sqrt{(\delta X)^2+(\delta Y)^2+(\delta Z)^2}$$

where δX, δY, and δZ represent the RMS deviations of the individual components. This δC parameter is invariant of the coordinate system used. It is employed to investigate component field variations as opposed to magnitude field variations. The first attempt to study variations of the noise regions with parameter values was based upon dividing each noise region into segments of 6 sequence lengths. Thus 96 individual observations at 5.11 second intervals were used for these periods. Shorter sequence intervals were also used and their results will be discussed.

Figure 9 presents a series of histograms of the number of observations versus the field magnitude RMS deviation, the field component deviation and these values normalized by the six sequence average field strength. The field component variation histogram is peaked at approximately 1 to 2γ, a value roughly 3 times the value of the peak of the field magnitude histogram, 0.50γ. This relationship gives an indication of the type of fluctuations under investigation. If the magnetic field disturbances were pure transverse waves (Alfvén waves) then the field magnitude variation to first order would be zero. In the case of longitudinal waves the field magnitude variation would equal the component variation. For small amplitude isotropic waves, the field magnitude variation would be 58% of the component variation. The observed variation of field magnitude is roughly 33% that of the component variation. Thus this places the waves intermediate between pure transverse and isotropically propagating waves. These statistical results confirm the spectral analysis previously given of the preference towards transverse disturbances in the noise regions.

A study of both disturbed and undisturbed interplanetary field magnitude distributions has shown no particular field magnitude enhances the probability of noise occurrence.

Histograms of the six sequence average values with respect to DFA and DW are shown in Figure 10. In the histograms with DW as abscissa, field lines with DFA greater than one were omitted as the field line in these cases does not thread the idealized wake and thus no value of DW can be computed. In addition when the spacecraft is located in the optical shadow of the moon, the value of DW is not included in this graph. The total number of data points deleted from this group comprises 19% of the entire data sample. Most of the cases deleted from this graph correspond to the case of DFA being greater than one.

The distribution expected from the variation of solid angle subtended by the wake, assuming an infinite cylinder, is shown as a solid line superimposed upon the observed noise histogram. In addition this theoretical curve assumes an isotropic distribution of the interplanetary field direction. There is rough agreement except that an asymmetry exists between positive and negative values of DW. This is likely a consequence of the actual wake extending only in the negative X direction and the anisotropic field line orientation in interplanetary space. This would result in a number of field lines with negative values of DW threading the infinite cylinder but missing the actual wake.

Two dimensional histograms of the field magnitude RMS deviation and the field component RMS deviation as a function of DW are shown in Figure 11. A dot or a number in a certain position indicates that one or that number of 6 sequence averages have the values associated with that point. A large triangle shows the median location for the column of points associated with the particular value of DW. No significant effect is seen in the field magnitude distribution although the component variation distribution shows a significant decrease in the amplitude of the noise with the absolute value DW. This shows that the noise has a smaller amplitude with increased distance from the wake region. A characteristic spatial distance at which approximately a 50% reduction in noise amplitude occurs is found to be 1.5 lunar radii.

A study of the effect of varying the number of sequences averaged appears to have a small effect on these distributions. Data for δF and δC histograms using 1 through 6 sequence averages were used. A slightly larger variation was found corresponding to a larger number of sequences averaged. This indicates that most but not all of the noise occurs at frequencies higher than that associated with the 81.8 second sequence period.

Conclusions and Discussions

From the experimental observations and statistical studies discussed previously, the following statements may be made with respect to characteristics of the rapid fluctuations of the interplanetary magnetic field in the immediate vicinity of the lunar wake:

1. The field fluctuations generally are observed within and outside the penumbral region associated with the lunar wake.
2. They are observed in regions of space in which the magnetic field line is directly connected to the lunar penumbra.
3. The field fluctuation region spatially extends from the penumbral region to a distance of several lunar radii along the field line away from the penumbra both upstream and downstream.
4. The field fluctuations are slightly more transverse than longitudinal, the amplitude ratio being approximately 1.5, when compared to an isotropic distribution of fluctuations.

5. The amplitude of the magnetic field component variation is inversely related to the field line parameter DW, the distance from the spacecraft to the wake along the field line. Representative values are $\delta\alpha$=1-2γ and δF=0.3-0.6γ
6. The observations of the frequency of the disturbances lie between .1 and 5 Hz. The upper passband of the instrument is the limiting factor and the low telemetry rate precludes unique waveform identification.
7. The mechanism that transports the disturbances moves with a velocity which has a component travelling upstream in the solar wind with a speed equal to or greater than the solar wind speed.
8. The noise occurrence is independent of field magnitude.

A consideration of the possible source of these disturbances suggests an origin where the proton and electron distribution functions of the solar wind are disturbed by the absorption of solar plasma by the lunar surface. Figure 12 presents a schematic diagram of these distribution functions as a function of the angle relative to the local magnetic field. A small asymmetry for the electrons along the flow direction is assumed and a large thermal anisotropy is shown for the ions. The distribution function of the protons in region A, the penumbral region in Figure 1, has a portion removed because protons are absorbed by the moon for a given range of directions. The electron distribution is also cutout as shown on the right side of Figure 12.

The bottom row shows the distribution function that would cause the observed high frequency field fluctuations observed in region B, a region upstream of the penumbra but connected to it by field lines. The ions are only disturbed slightly by the moon as a minute and insignificant portion of the distribution function is occulted by the lunar surface. The electrons move with velocities far in excess of the solar wind speed and thus in the absence of other forces would fill in the wake region. This would violate charge neutrality within the umbral region and consequently an electric field is set up to repel electrons from the umbral region as indicated in Figure 1. Since the Debye-radius is smaller than the distance over which the density changes appreciably, the charge shown would be smeared over the entire penumbral region. Thus electrons on the left of the distribution function in the bottom row are ordinary solar wind electrons whereas the ones on the right correspond to those which have been reflected by the electric field in the penumbral region and have travelled upstream. Thus they carry with them a memory of the disturbed conditions present there.

The distribution function will be effected severely by instabilities which will tend to flatten it. We interpret the presence of rapid fluctuations of the interplanetary magnetic field as a manifestation of these instabilities and in this way the upstream interplanetary medium can be affected by the lunar wake and indirectly by the moon itself. The companion paper of Krall and Tidman (1969) explains these fluctuations as a ballistic wake due to electrons recently arrived from regions of plasma turbulence.

It is interesting to speculate on the possibility that similar phenomena occur associated with other bodies in the solar system. This class of stimulated disturbances will be associated with the motion of a magnetized plasma past a moderately large body which possesses either an insufficient magnetic field or an insufficient atmosphere to deflect the plasma flow and hence absorbs the incident particle flux. Of the planets, Mercury would appear to be a prime candidate for occurrence of a wake region and the presence of similar stimulated waves. In the case of the planet Jupiter, the modulation of radio emission by its satellite Io has been an enigma for years since its initial identification. This present study of the waves stimulated as the solar wind flows past the moon suggests another mechanism to that of the unipolar inductor recently discussed by Goldreich and Lynden-Bell (1969).

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FIGURE CAPTIONS

Figure 1 Diagram of the umbral and penumbral regions formed due to the absorption of the solar wind by the moon. A sample orbit of Explorer 35 is shown, as are the regions of space where rapid fluctuations of the interplanetary magnetic field are observed. The direction of the electric field, necessary to maintain change neutrality, is also indicated.

Figure 2 Simultaneous observations of field magnitude and field direction in solar ecliptic coordinates observed on 26 March 1968 by Explorer 33 (solid lines) and 35 (dots). The position of Explorer 35 relative to the moon is shown projected on the ecliptic plane in the upper left hand corner.

Figure 3 Simultaneous detailed observations of the field magnitude observed by Explorers 33 and 35 from 2100 to 2400 UT on March 26, 1968. Noise detected by Explorer 35 is not observed by Explorer 33.

Figure 4 Schematic showing parameters calculated to determine if the field line which passes through the spacecraft also threads the wake. Idealized wake is represented as a cylinder of radius = radius of moon for $X_{SSE} \leq 0$. See text.

Figure 5 Observations of field magnitude by Explorer 35 for 3 passes during April 25-27, 1968. Universal time, selenocentric radius and ϕ angle are shown on the abscissa.

The shaded regions are indicative that the field line which passes by the spacecraft threads the lunar wake region. The numbers above the abscissa represent the distance DCA.

Figure 6 Relative spectral density of magnetic field components in interplanetary space, noise regions and umbral region of the lunar wake on April 26, 1968. The Z component refers to the direction along the field and the X and Y refer to orthogonal components.

Figure 7 Spacecraft positions, when rapid fluctuations were observed, rotated about the X_{SSE} axis into the X_{SSE} - Y_{SSE} plane.

Figure 8 Histograms of the occurrence of rapid fluctuations as a function of the parameters DFA and DCA.

Figure 9 Histograms of the field magnitude RMS deviation, δF, and field component RMS variation, δC, for six sequences averages. Also normalized values with respect to field magnitude are presented.

Figure 10 Histograms of occurrence of rapid fluctuations versus the field line parameters DFA and DW. The curve on the histogram with DW as the abscissa indicates the variation expected from an isotropic distribution of field lines threading an infinite cylindrical wake of one lunar radius.

Figure 11 Two dimensional histograms of the field magnitude RMS deviation and the field component RMS deviation versus DW.

Figure 12 The top diagram shows the two dimensional velocity vector distribution of the solar wind relative to the interplanetary magnetic field direction. Below this are a series of distribution functions for the protons and electrons as they might be affected by the lunar environment. The angle $\Delta\phi$ plotted on the abscissa refers to the top portion of the figure. Region A represents the lunar penumbra shown in Figure 1 and Region B is somewhat upstream of Region A along a field line. Electric fields and plasma instabilities may distort these distributions substantially.

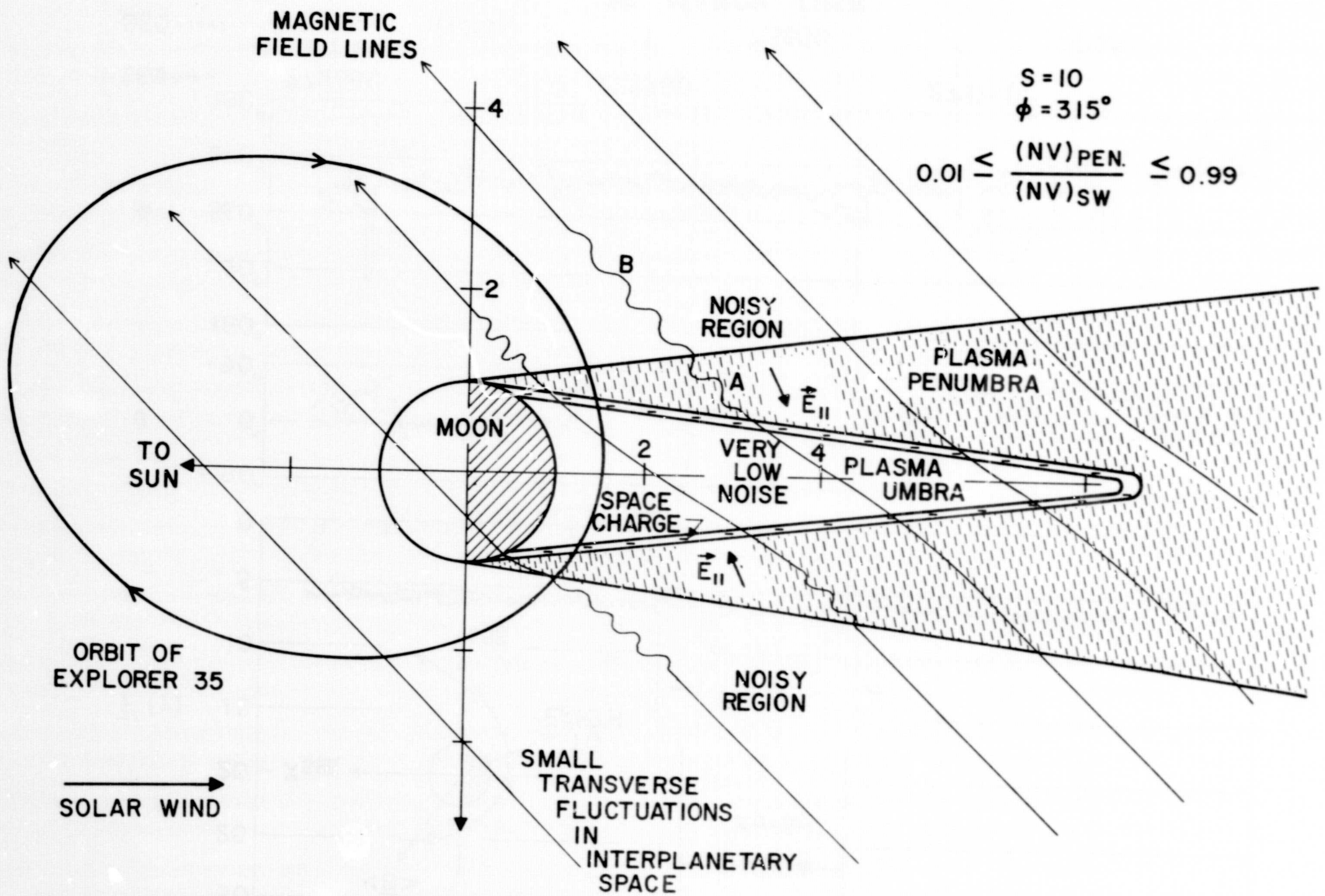
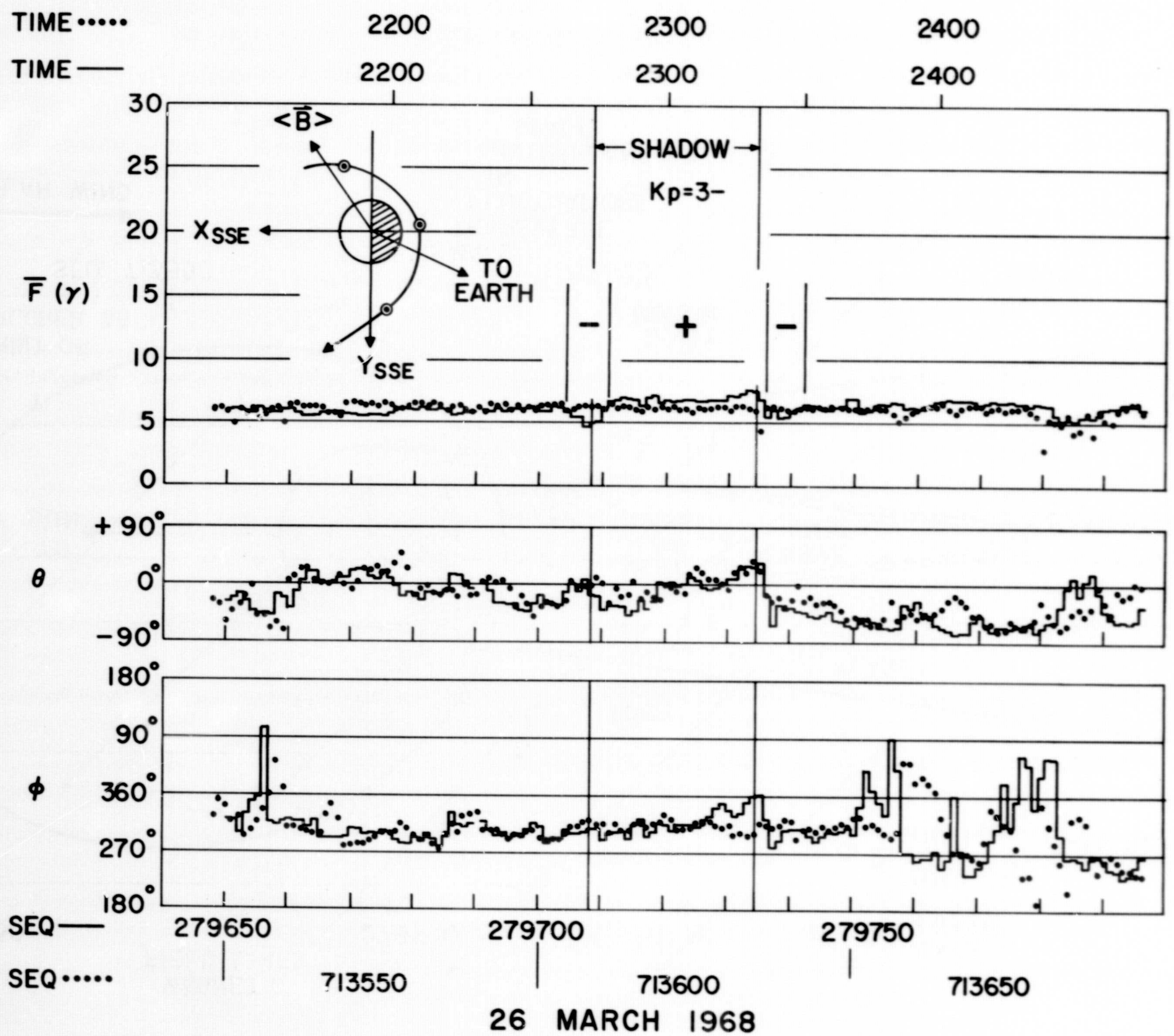

MAGNETIC FIELD LINES
S = 10
ϕ = 315°
$0.01 \leq \frac{(NV)_{PEN.}}{(NV)_{SW}} \leq 0.99$
B
NOISY REGION
A
PLASMA PENUMBRA
$\vec{E}_{II}$
MOON
TO SUN
VERY LOW NOISE
PLASMA UMBRA
SPACE CHARGE
$\vec{E}_{II}$
ORBIT OF EXPLORER 35
NOISY REGION
SMALL TRANSVERSE FLUCTUATIONS IN INTERPLANETARY SPACE
SOLAR WIND
4
2
2
4

FIGURE 1



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TIME ——
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2300
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30
25
20
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X_{SSE}
Y_{SSE}
TO EARTH
SHADOW
Kp=3-
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θ
+90°
0°
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φ
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90°
360°
270°
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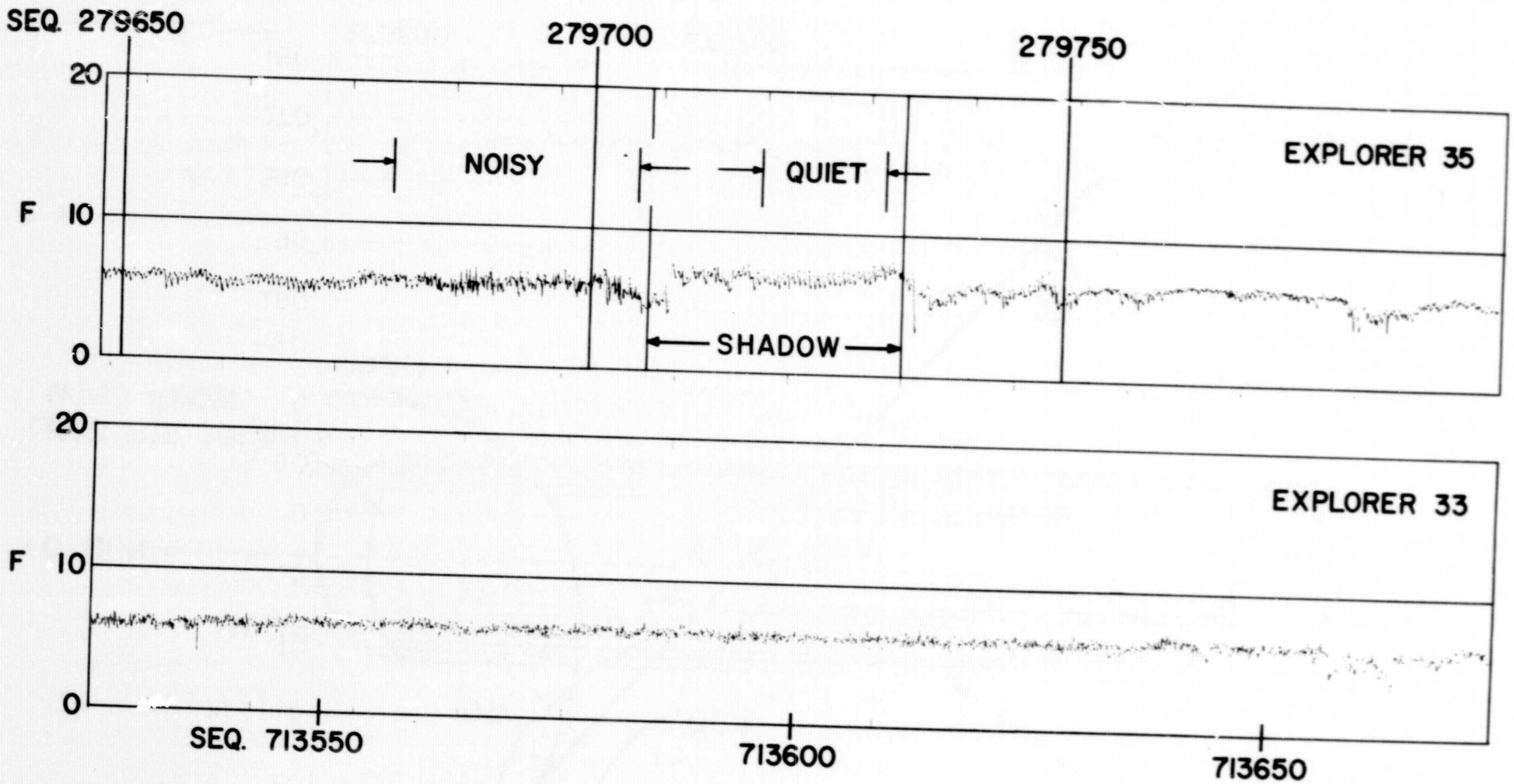
713650
26 MARCH 1968

FIGURE 2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713650
EXPLORER 33

FIGURE 3

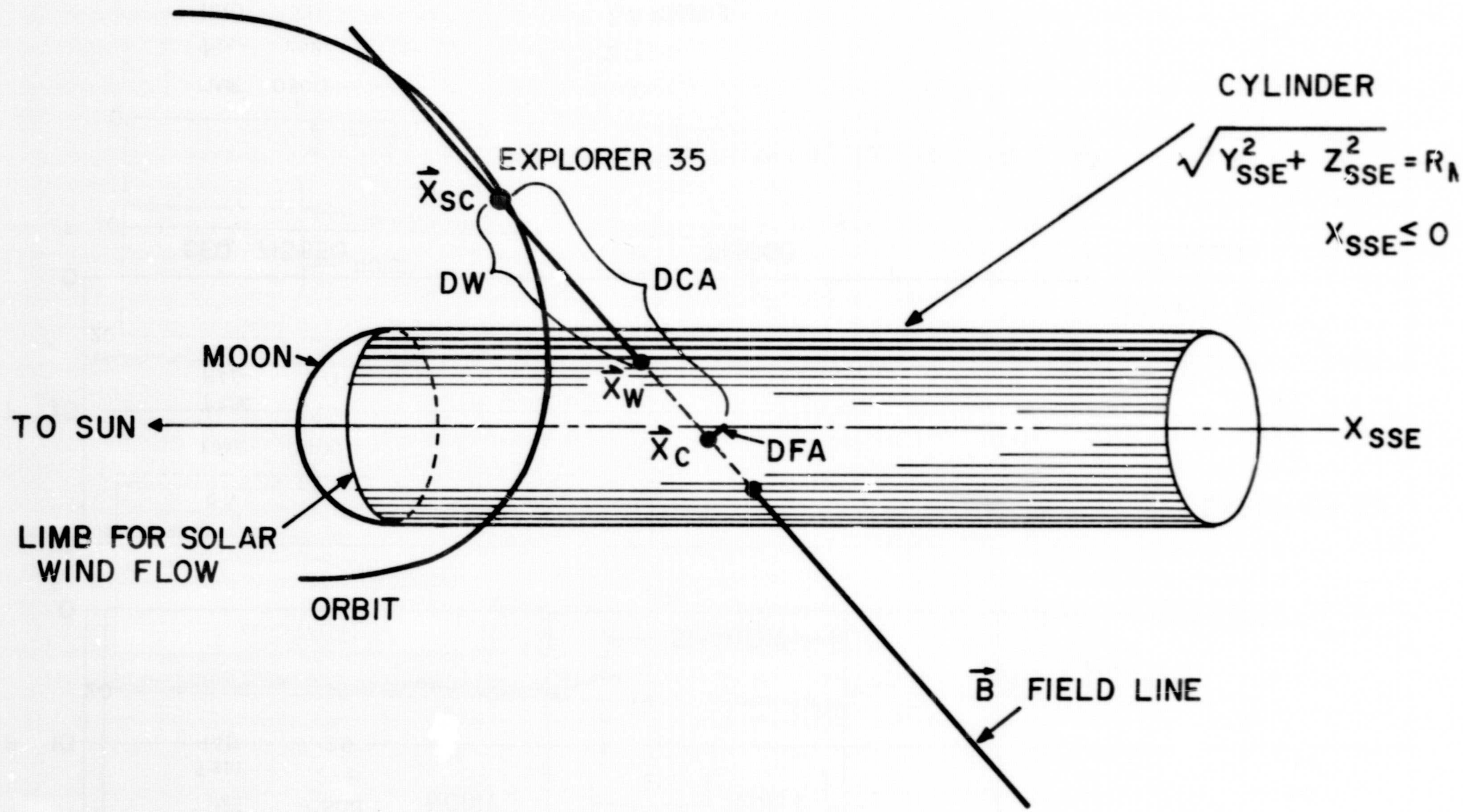
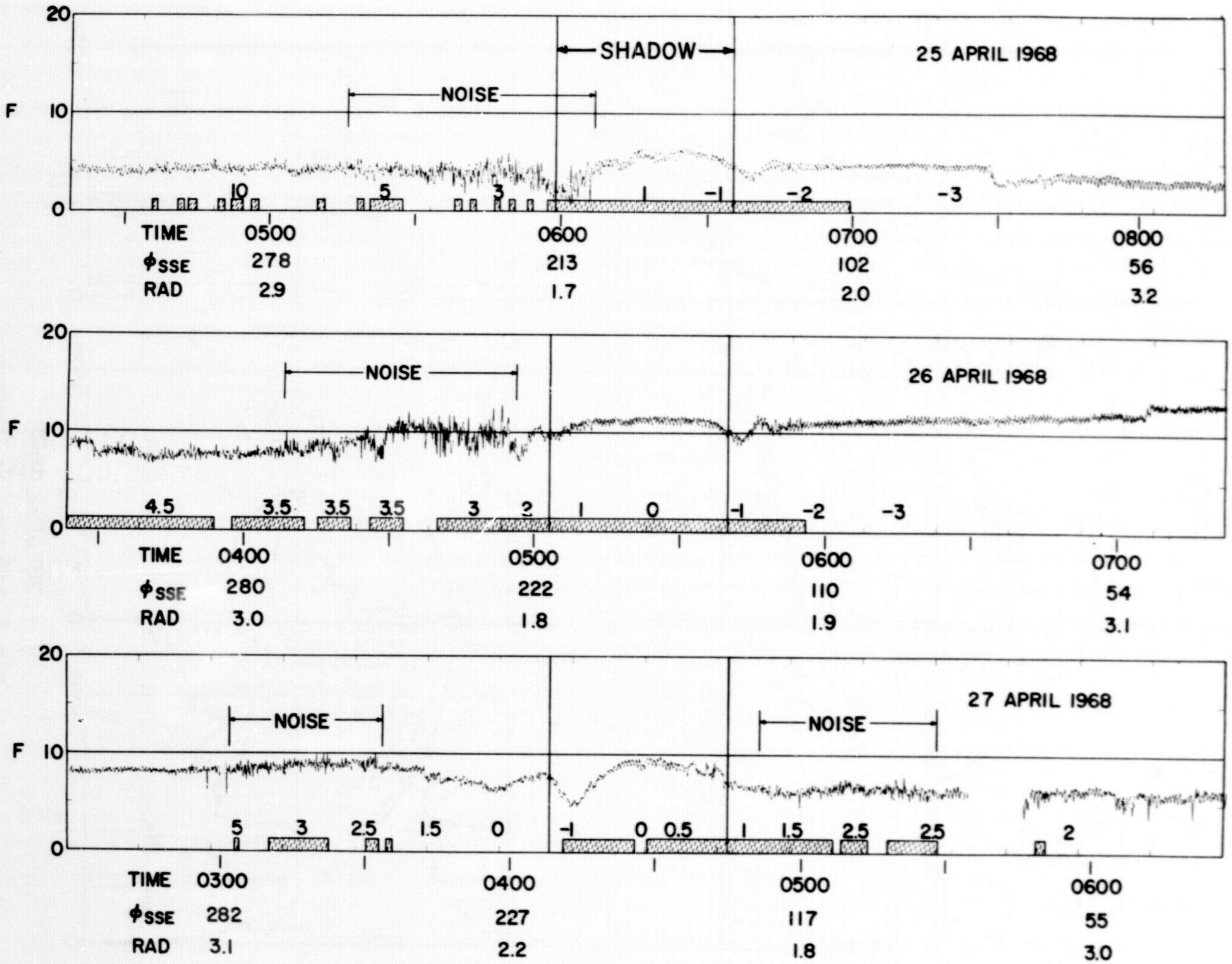
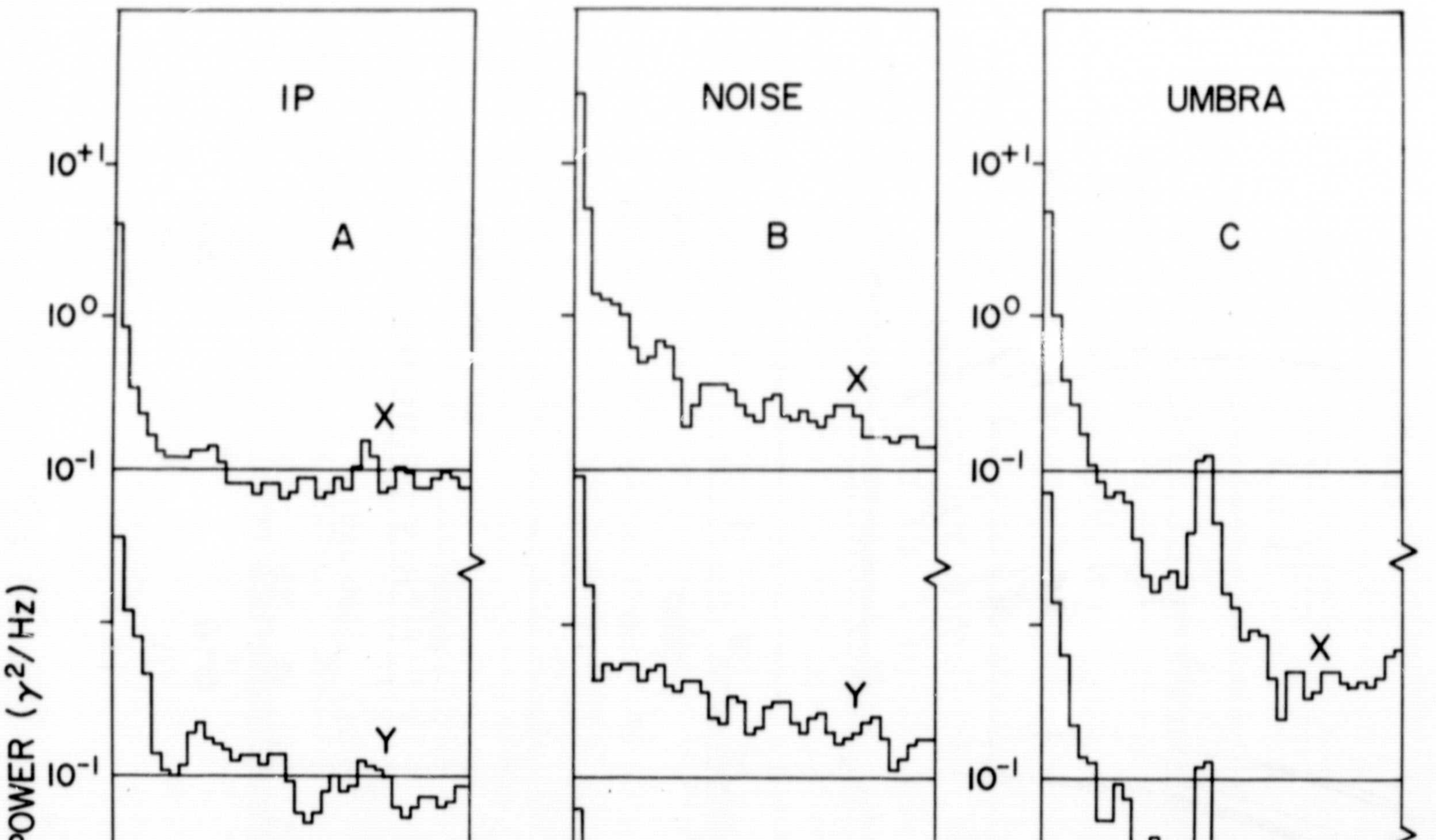

CYLINDER
$\sqrt{Y_{SSE}^2 + Z_{SSE}^2} = R_M$
$X_{SSE} \leq 0$
EXPLORER 35
$\vec{X}_{SC}$
DW
DCA
MOON
$\vec{X}_W$
TO SUN
$\vec{X}_C$
DFA
X_{SSE}
LIMB FOR SOLAR
WIND FLOW
ORBIT
$\vec{B}$ FIELD LINE

FIGURE 4



25 APRIL 1968
SHADOW
NOISE
F
20
10
0
10
5
3
1
-1
-2
-3
TIME 0500 0600 0700 0800
ϕSSE 278 213 102 56
RAD 2.9 1.7 2.0 3.2
26 APRIL 1968
NOISE
4.5
3.5
3.5
3.5
3
2
1
0
-1
-2
-3
TIME 0400 0500 0600 0700
ϕSSE 280 222 110 54
RAD 3.0 1.8 1.9 3.1
27 APRIL 1968
NOISE
NOISE
5
3
2.5
1.5
0
-1
0
0.5
1
1.5
2.5
2.5
2
TIME 0300 0400 0500 0600
ϕSSE 282 227 117 55
RAD 3.1 2.2 1.8 3.0

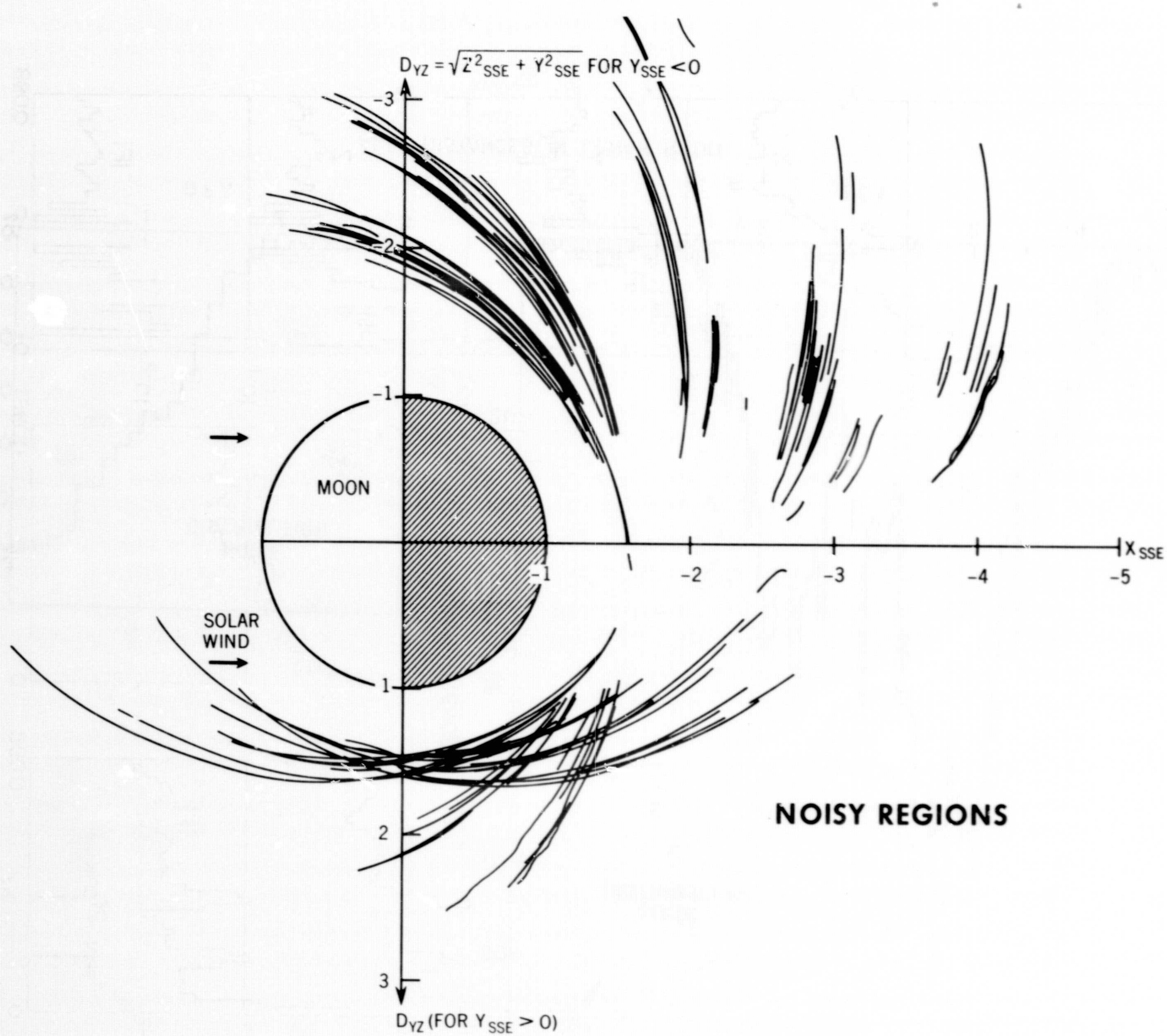
FIGURE 5



26 APRIL 1968

FIELD COORDINATE SPECTRA

FIGURE 6



$D_{YZ} = \sqrt{Z^2_{SSE} + Y^2_{SSE}}$ FOR $Y_{SSE} < 0$
-3
-2
-1
MOON
SOLAR WIND
1
2
3
D_{YZ} (FOR $Y_{SSE} > 0$)
-1
-2
-3
-4
-5
X_{SSE}
NOISY REGIONS

FIGURE 7

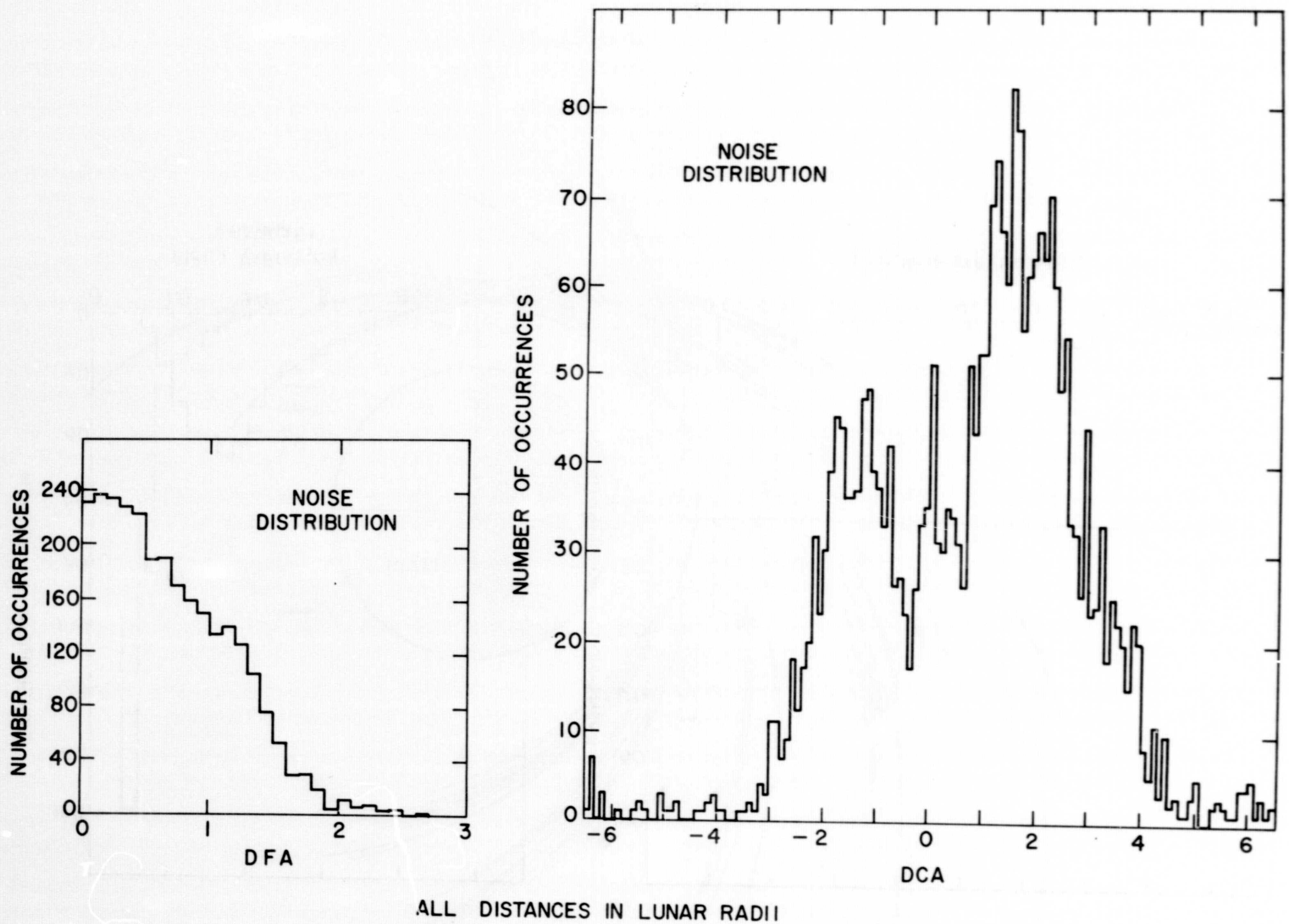
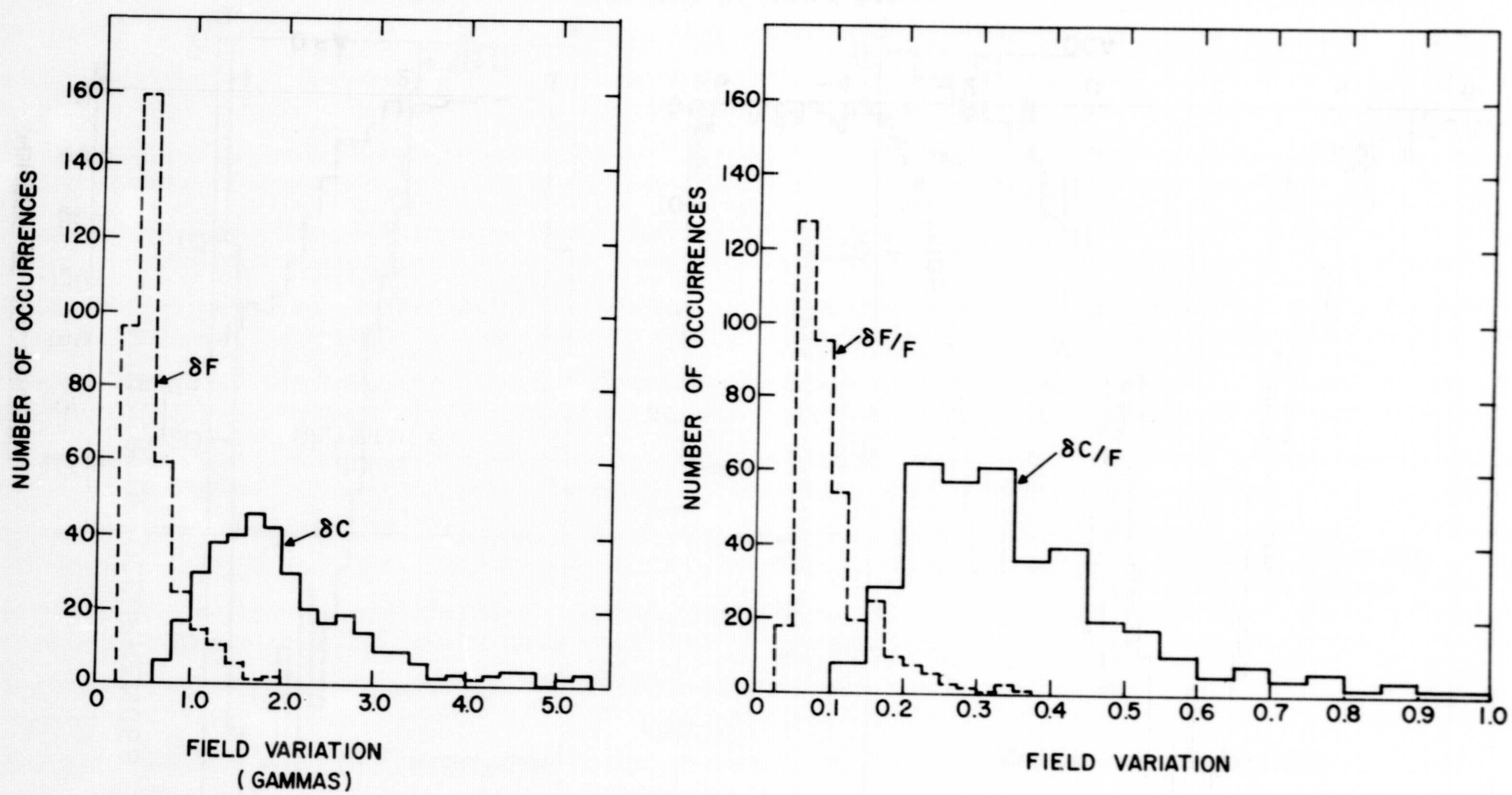

NUMBER OF OCCURRENCES
240
200
160
120
80
40
0
0
1
2
3
DFA
NOISE
DISTRIBUTION
NUMBER OF OCCURRENCES
80
70
60
50
40
30
20
10
0
-6
-4
-2
0
2
4
6
DCA
NOISE
DISTRIBUTION
ALL DISTANCES IN LUNAR RADII

FIGURE 8



NUMBER OF OCCURRENCES
0
20
40
60
80
100
120
140
160
δF
δC
0
1.0
2.0
3.0
4.0
5.0
FIELD VARIATION
(GAMMAS)
NUMBER OF OCCURRENCES
δF/F
δC/F
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
FIELD VARIATION

FIGURE 9

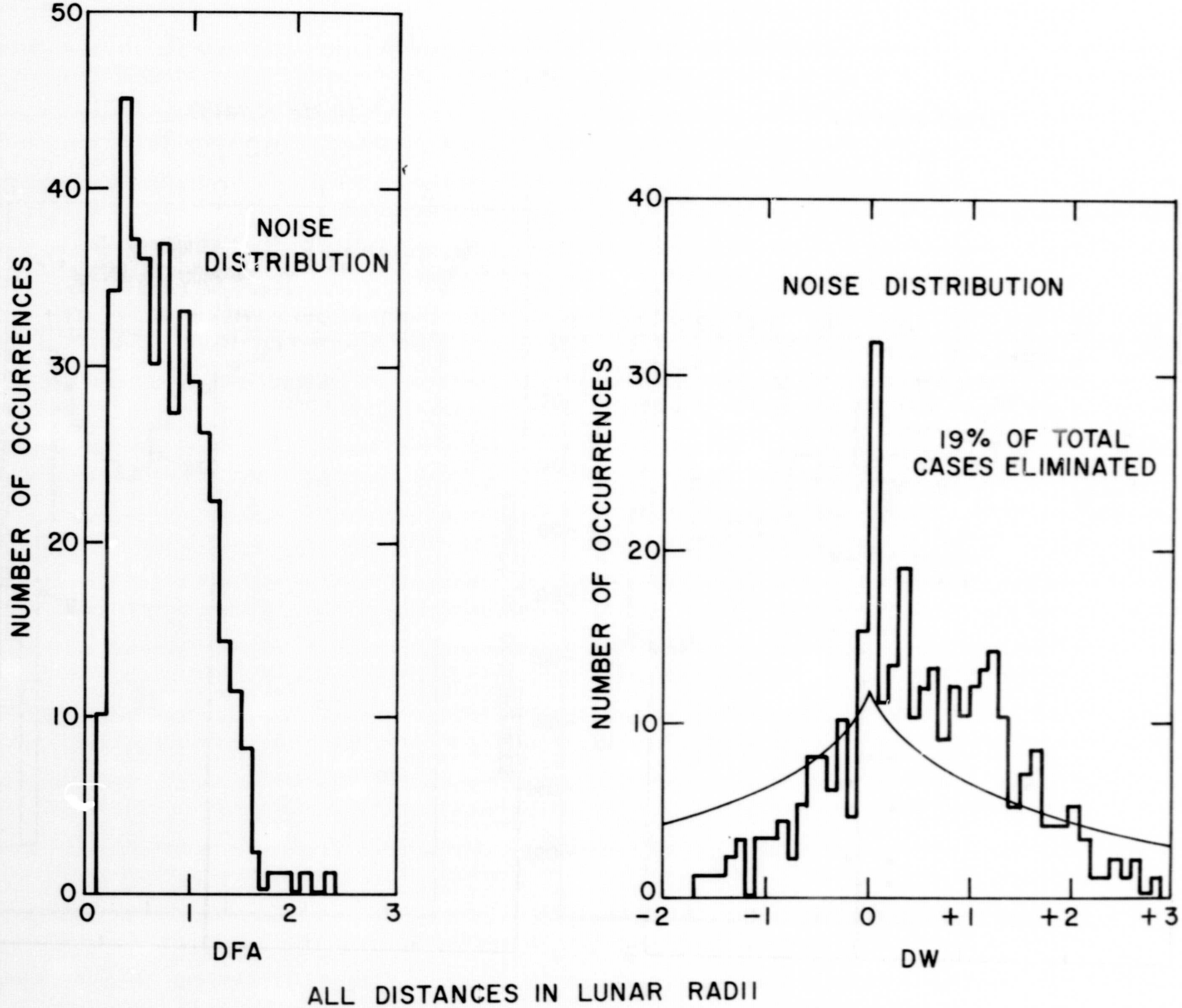

NUMBER OF OCCURRENCES
NOISE DISTRIBUTION
0
10
20
30
40
50
1
2
3
DFA
NUMBER OF OCCURRENCES
NOISE DISTRIBUTION
19% OF TOTAL CASES ELIMINATED
−2
−1
+1
+2
+3
DW
ALL DISTANCES IN LUNAR RADII

FIGURE 10

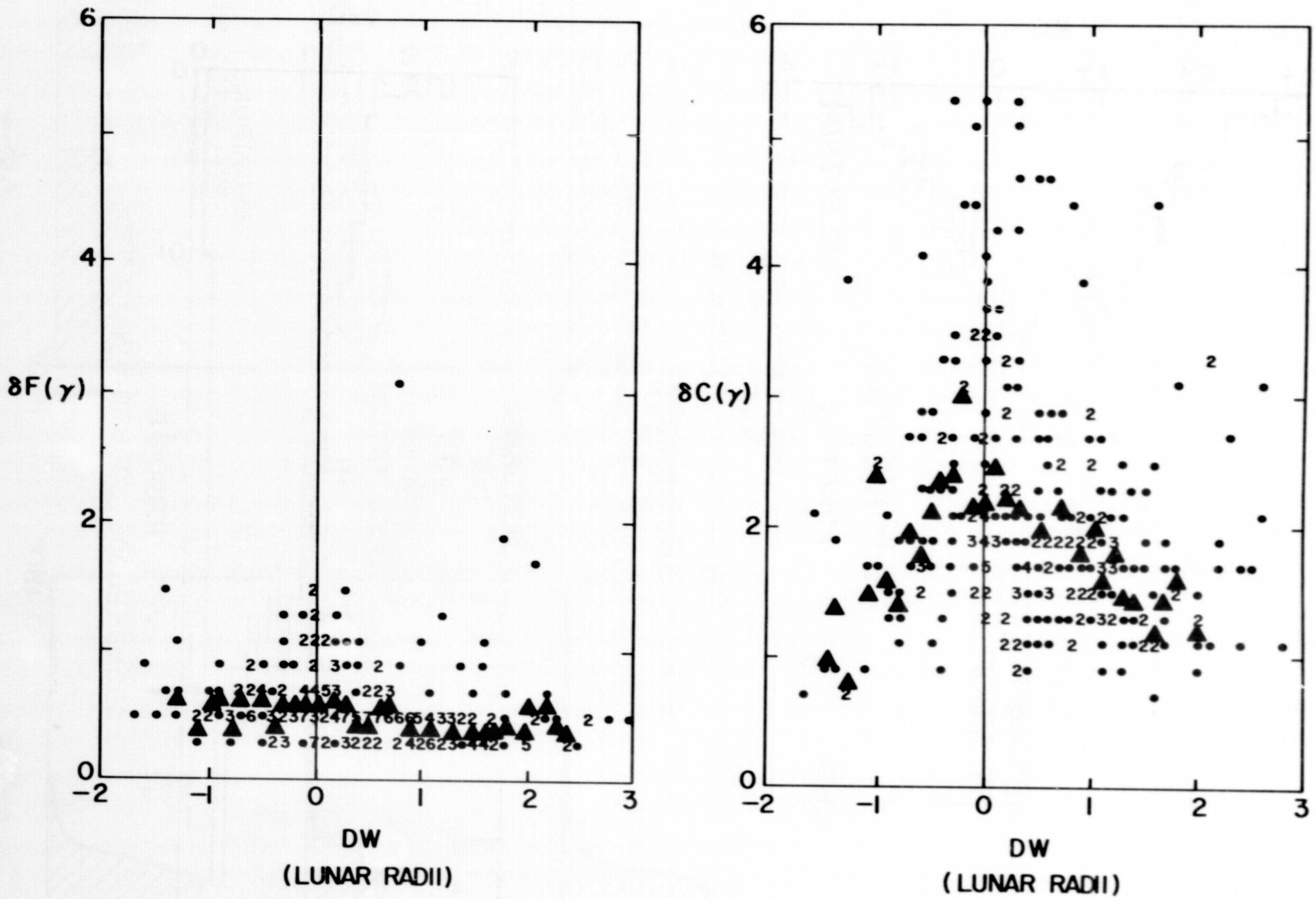
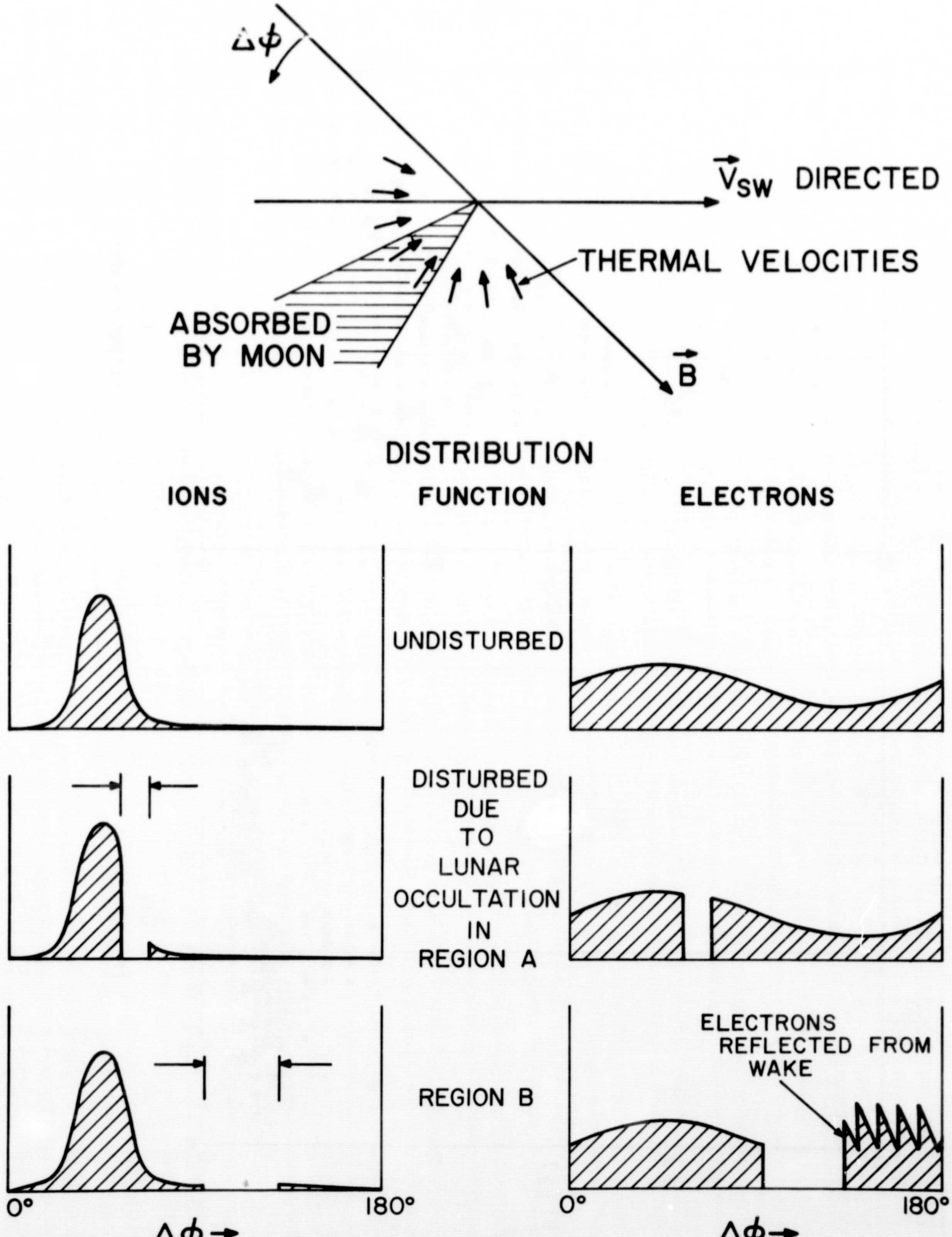


FIGURE 11



$\Delta\phi$
$\vec{V}_{SW}$ DIRECTED
THERMAL VELOCITIES
ABSORBED BY MOON
$\vec{B}$
DISTRIBUTION FUNCTION
IONS
ELECTRONS
UNDISTURBED
DISTURBED DUE TO LUNAR OCCULTATION IN REGION A
REGION B
ELECTRONS REFLECTED FROM WAKE
0°
180°
$\Delta\phi \rightarrow$

FIGURE 12