X-646-73-153
PREPRINT

NASA TM X- 66260

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(NASA-TM-X-66260) DEPENDENCE OF FIELD-ALIGNED ELECTRON PRECIPITATION ON SEASON, ALTITUDE AND PITCH ANGLE (NASA) 30 p HC $3.50 CSCL 03B

N73-25868

Unclas
G3/30 05504

F. W. BERKO
R. A. HOFFMAN

MAY 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

DEPENDENCE OF FIELD-ALIGNED ELECTRON PRECIPITATION ON SEASON, ALTITUDE AND PITCH ANGLE

By

F. W. Berko

and

R. A. Hoffman

Laboratory for Space Physics
NASA-Goddard Space Flight Center
Greenbelt, Md. 20771

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ABSTRACT

An examination of factors affecting the occurrence of field-aligned 2.3 keV electron precipitation has been performed using data from more than 7500 orbits of the polar-orbiting satellite OGO-4. It was found that the frequency of occurrence of field-aligned precipitation was highest not at 0° pitch angle, but at actual pitch angles between 7° and 10°. Additionally, the probability of observing field-aligned fluxes was highest in the winter months at the highest satellite altitudes. Acceleration by a localized parallel electric field established by electrostatic charge layers is proposed to explain the particle observations.

INTRODUCTION

Field-aligned particles have been measured under a variety of magnetic conditions and at many different local times and altitudes. Observations of these phenomena at sounding rocket altitudes have been reported recently by Choy et al. (1971), Whalen and McDiarmid (1972), Bosqued et al (1973) and many others. Satellite observations have been reported by Hoffman and Evans (1968), Ackerson and Frank (1972), Paschmann et al (1972) and others at altitudes ranging up to 2500 km. Pitch angle distributions of electrons are of special interest because they not only can be related to electron precpitation mechanisms, but also they have often been interpreted as evidence for field-aligned electric fields.

Using data from the OGO-4 Auroral Particles Experiment (Hoffman and Evans, 1967), several studies have already been performed relating to field-aligned fluxes. The initial observations of such distributions were reported by Hoffman and Evans (1968). The spatial distribution, spectral characteristics, and relationships to visual aurora were recently determined by Berko (1973). High-latitude field-aligned 2.3 keV electron precipitation was found to occur primarily in a roughly oval-shaped region, with the greatest number of field-aligned events observed in the interval $67.5^{\circ} \leq \Lambda \leq 72.5^{\circ}$ and 22 hours ≤ MLT ≤ 01 hour. Finally, significant field-aligned currents measured by their magnetic signatures were found to occur primarily in the region of field aligned electron fluxes by Berko et al (1973). In this paper we investigate the universal time, seasonal, and altitude variations in the occurrence of field-aligned electrons at an energy of 2.3 kev, and consider the probability of finding field aligned fluxes as a function of exact pitch angle near 0°.

Electron precipitation data from OGO-4 are available for an 18-month period (July, 1967, through December, 1968) at satellite altitudes ranging from about 400 km to 925 km, at all magnetic local times (MLT), at invariant latitudes (Λ) primarily greater than 60°, and under all magnetic conditions. The angular distribution of electrons were obtained with four identical detectors, each comprised of a cylindrical electrostatic analyzer and channel electron multiplier, measuring electrons in a bandpass roughly ± 15% about an energy of 2.3 kev. The detectors were mounted 0°, 30°, 60° and 90° to the Z axis of the satellite, which was controlled to remain parallel to the radius vector from the earth. Thus, while the 0° detector measured near 0° pitch angle particles at high latitudes, the range of actual measurements was from 0° to ~ 18°.

In this study data were used primarily from the 0° and 60° detectors. Field-aligned events are defined as one-second periods of electron precipitation satisfying the following criteria: (1) the average flux of electrons at 2.3 kev with near 0° pitch angle was at least 2×10^7 electrons/cm^2-sec-ster-keV, and (2) the ratio of the fluxes at 2.3 kev with pitch angles near 0° to near 60° was greater than $1 + \Delta$, where Δ, the combined statistical uncertainty in the ratio, is a function of the particle counting rates at near 0° and 60° pitch angles (N_0 and N_{60}):

$$\Delta = (1/\sqrt{N_0} + 1 / \sqrt{N_{60}}) / \sqrt{2}.$$

In previous work (Berko, 1973), only events with $\Delta \geq 0.53$ were considered to have met the criteria; in this study, periods with Δ as low as 0.1 have been included. Such data periods were statistically meaningful and greatly increased the quantity of data being considered.

UNIVERSAL TIME AND SEASONAL EFFECTS

Universal time and season may effect the probability of occurrence of field-aligned events because these parameters determine the tilt of the dipole to the earth-sun line. The tilt angle, in turn, modifies the magnetospheric configuration (see Forbes and Speiser, 1971, for example, for model modifications of the field topology, and Burch, 1972, for the location of the cusp as a function of tilt angle), and also changes drastically the solar radiation incident on the high latitude ionosphere. The dipole (north pole) is tilted toward the sun at about 19½ hours U.T., and, of course, at the summer equinox, and away from the sun at about 7½ hours U.T.

We first look for any universal time (U.T.) effects on the occurrence of field-aligned electrons, using the entire set of OGO-4 data in the northern hemisphere (all Λ's, MLT's and altitudes). Plotted in Figure 1 is the percentage of field aligned events which occur in a one hour interval of U.T., normalized for uneven sampling in U.T. (The area under the curve adds to 100%.) There is an apparent peak in the probability of encountering field-aligned events at 9 to 10 hours, but the percent of events fluctuates too much from hour to hour to make this peak meaningful. If one considers only precipitation in the interval $67.5^{\circ} \leq \Lambda \leq 75^{\circ}$ and 22 hours ≤ MLT ≤ 1 hour, the region of highest probability for encountering field-aligned events (Berko, 1973), the percent of field-aligned events appears to be peaked in three UT intervals: 9-10, 12-14, and 20-21 hours. In both cases the most obvious feature is the minimum probabilities in the early hours of U.T.

Next we separate the parameter of season from a consideration of U.T. dependence on the occurrence of field aligned events. The seasons are defined as equal time intervals around the equinoxes and solstices. After again normalizing the percent of field-aligned events within each season to account for uneven seasonal sampling of precipitation, a definite winter peak appears around noon, as shown in Figure 2. For all hours of U.T., the maximum probability for encountering field-aligned events is during winter, with a minimum probability in autumn, as tabulated in Table 1.

Thus there is no clear relationship between the probability of occurrence of field-aligned events and dipole tilt angle.

VARIATIONS WITH ALTITUDE AND SEASON

The next parameter to investigate is the effect of altitude on the probability of field-aligned events. The physical parameters which might be associated with altitude are anomalous resistivity (Kindel and Kennel, 1971) and low altitude parallel electric fields.

The variation in the probability of field-aligned events with the altitude of the observation is an effect which appears to be closely associated with season. Figure 3 contains the percent probabilities in 100 km altitude intervals from 400 km to 900 km, normalized for uneven sampling in season and altitude intervals. Data are taken only for the local time interval 22 hours to 01 hour and from latitudes greater than

60°. The percent probability means, for example, that given a pass during summer in the altitude range 600 to 700 km, there is a 17% probability of encountering field-aligned electron precipitation at 2.3 kev in each second of data during the pass. For spring the probabilities are quite independent of altitude, with an indication of a higher probability at the maximum altitude. Summer shows the opposite effect and autumn has very low probabilities at all altitudes sampled. The winter season has the largest variation, with a very high probability (31%) at the highest altitude, almost twice as high as any other probability.

ACTUAL PITCH ANGLE MEASURED

There is one final, more subtle, parameter to investigate to determine if it could bias the preceding studies: the actual pitch angle measured by the 0° detector.

At high latitudes where these data were obtained, the near-0° pitch angle detectors, mounted to point radially away from the earth, measured precipitation at actual pitch angles ranging from 0° to about 18°. Because of operational contraints on both the experiment and spacecraft, data were acquired in the high latitude region usually during two periods of each day over two different longitude ranges. Thus, passes were usually either high magnetic latitude or low magnetic latitude passes. The magnetic latitude and local time of a pass determined the inclination of the magnetic field, so one group of passes oriented the 0° detector more or less parallel to the magnetic field than the other group. As a result an actual range of pitch angles were sampled, but not all near-0° pitch angles were sampled with equal frequency at different altitudes in each season; in fact, there were strong biases in the actual pitch angles sampled as a function of season and altitude.

Figure 4 shows the probability of measuring field-aligned electron fluxes at 2.3 kev for each second of data in the magnetic local time interval 22 hours to 01 hour for the four seasons as a function of actual pitch angle measured by the 0^o detector. The data displays the surprising result that the maximum probability of measuring field-aligned fluxes was not when the 0^o detector was aligned with the magnetic field, but when it was at an angle of 7^o to 10^o to the magnetic field. In fact this situation held for all seasons, but is most predominant for the winter.

There are several factors that still could bias the probability distributions in Figure 4. We have already mentioned the uneven distribution of pitch angle sampling witn season and altitude. In addition, it has been demonstrated previously (Berko, 1973; Hoffman and Burch, 1973) that the occurrence of field-aligned events is especially high during substorms. We have treated here each second of data as statistically independent, whereas, if a particular second of data has the field-aligned characteristic, there is a very high probability that the next second of data will also. Thus with the uneven sampling of pitch angles a single pass could make a large contribution to the field-aligned statistics in a particular altitude range if there were only a few other passes with the same altitude and angle parameters.

To investigate this problem in detail we plot all the data used in this study in Figure 5. In the upper panel under each season, the location in altitude-pitch angle space of each second of data is plotted as a data point. The center panel contains each data point which is field-aligned. The bottom panel contains the actual ratio of 0^o to 60^o fluxes at 2.3 kev as a function of pitch angle, independent of altitude.

The following features should be noted in the figures:

i) For summer there is fairly good sampling from 4^o to 14^o and up to 800 km. There does not appear to be any striking concentration of field aligned events in any altitude range or pitch angle. Thus one has some confidence that the probabilities shown in Figures 3 and 4 up to 800 km are trustworthy, but the point in Figure 3 from 800 to 900 km should not be treated with equal weight.

ii) The data in autumn is especially significant because of the high density of measurements over the entire pitch angle range from 0^o to 16^o up to 800 km. However, a very small fraction of these data points were field aligned, especially in the case of small angle samples. In fact the lower panel shows that most field-aligned events occurred between 6^o to 10^o. Therefore, the low probabilities at altitudes up to 800 km and especially at small pitch angles shown in Figures 3 and 4 are significant.

iii) The winter distribution is extensively biased towards high altitude sampling, especially above 800 km, and at low altitudes at small pitch angles. Note that only the first group has field-aligned events. Thus the very high probability for winter for 800 to 900 km in Figure 3 is significant.

iv) Data from the spring season is especially useful because of the sampling at the larger pitch angles at all altitudes. Compared to the number of samples, very few are field-aligned for angles above 12^o. Thus in Figure 4 the decrease in probability as a function of pitch angle for the larger pitch angles is significant. Also note the reasonable number of samples above 800 km which are field-aligned. The rise in probability from 800 to 900 km in Figure 3 is probably real.

v) The largest ratios of 0^o to 60^o fluxes seem to lie between 6^o and 12^o actual pitch angle.

ANALYSIS CONCLUSIONS

We draw the following conclusions from this study:

1. The actual pitch angle of the 0^o detector was the most significant parameter in determing the probability of encountering field-aligned fluxes at 2.3 kev. The maximum of this probability occurred when the detector was oriented 8^o to 10^o to the magnetic field, and was independent of season.
2. The highest probabilities occurred when the measurements were made at altitudes above 800 km.
3. In this high altitude range, the electron precipitation was more likely to be field-aligned during winter than any other season.

The descending order of confidence in the conclusions is in the order stated.

DISCUSSION

The conclusions reached in this work are based upon a statistical study of a fairly large volume of data acquired over a period of about one and one-half years. It utilizes the output of only two detectors, one aligned with the radius vector from the earth, the other mounted at an angle of 60° to this direction, and both measuring electrons in a narrow bandpass about the energy of 2.3 kev. It has been demonstrated that there are strong biases in the acquisition of data with respect to the parameters altitude, season, and actual pitch angle measured by the 0° detector. A field-aligned event is identified by the ratio of the measurement at a single pitch angle near 0° to the measurement at about 60°, thus the actual distribution at a given instant is never fully measured.

However, the measurements at the two angles are made absolutely simultaneously. There are no biases or possible misidentifications of field-aligned events due to the necessity of identifying such events by means of scanning pitch angles through the roll of the satellite. The importance of this fact cannot be overstressed, because it has been shown (Berko, 1973) that there is a strong correlation between the existence of field-aligned events and substorm breakup. Under these conditions the bursts of field-aligned electrons have short durations, from a few tenths of a second (Berko et al, 1973) to a few seconds (Berko, 1973) of data acquisition time (or a km to a few tens of km in distance, if the bursts are spatial), and during these short periods the fluxes are rapidly changing.

It is with cognizance of these limitations and advantages of the data that we proceed to some consequences based upon the conclusions.

Conclusion 1, that the most probable angles for the occurrence of field-aligned electron fluxes at 2.3 kev is 8° to 10°, places some stringent requirements upon any mechanism which accelerates the electrons or modifies an electron beam to produce the field-aligned distribution, and possibly also reflects some information about the source of such electrons.

We are not aware of any type of mechanism which operates on a probability basis in interacting with the electrons on a line of force (for example, wave-particle interactions) which could result in effects appearing in highly selected pitch angles for precipitation. Thus we are led to investigate the consequences of electric fields parallel to the magnetic field, as many other authors have done. (See references cited in Introduction.)

The effect of electric field acceleration on the angular distribution of electrons is usually described by the following considerations:

Using the subscripts "i" and "f" for initial conditions and for final conditions at the point of measurement, and from the conservation of energy

$$W_f = W_i + \Phi \qquad (1)$$

where Φ is the energy gained by the electrons from the electric field, conservation of the first invariant

$$\sin^2 \alpha_f = \frac{B_f/B_i}{W_f/W_i} \sin^2 \alpha_i , \qquad (2)$$

and Liouville's theorem

$$\frac{J_i(W_i, \alpha_i)}{W_i} = \frac{J_f(W_f, \alpha_f)}{W_f} \tag{3}$$

where J refers to flux distribution in energy and pitch angle, we obtain for the flux at the point of measurement

$$J_f = \frac{W_f}{W_f - \Phi} \; J_i \; [W_f - \Phi; \; \sin^{-1} (P \sin \alpha_f)], \tag{4}$$

where

$$P = \left(\frac{W_f/W_i}{B_f/B_i} \right)^{\frac{1}{2}} .$$

If we simplify the situation by assuming the initial particle spectrum is separable into independent energy and pitch angle terms, and the latter is given by $\sin^n \alpha_i$ (or any function which can produce either isotropic or pancake distributions by a variation in a parameter), then

$$J_f = \frac{W_f}{W_f - \Phi} \; f(W_f - \Phi) \sin^n [\sin^{-1} (P \sin \alpha_f)]. \tag{5}$$

Choosing a particular Φ then defines all the energy dependent parts of J_f, since $W_f = 2.3$ kev in our case, so that the shape of J_f as a function of α_f is just

$$J_f'(\alpha_f) = \sin^n [\sin^{-1} (P \sin \alpha_f)] \quad . \tag{6}$$

We now assume that the electric field is sufficiently strong so that the particle energy changes faster than the magnetic field increases, so that $P > 1$. Since $P \sin \alpha_f$ cannot exceed 1, $\alpha_f < 90^\circ$, thus giving a cut-off to the measured pitch angle distribution on the large pitch angle side at some $\alpha_{f(\max)}$. For $\alpha_{f(\max)} \simeq 15^{\circ}$, $P \simeq 4$ or $W_f/W_i \simeq 16\, B_f/B_i$. Thus, unless W_i is of the order of thermal energies, it is necessary to restrict the region of the field-aligned electric field so as to keep B_f not much different than B_i. Thus we are limited to low altitude electric fields.

We can also find a cause as to why the particle flux may not reach small pitch angles at the point of measurement by a further consideration of equation 6. For an isotropic distribution (n=0), the flux at "f" will be isotropic over the angle range from 0° to $\alpha_{f(\max)}$, as illustrated in Figure 6. However, as n increases, the flux at very small pitch angles will decrease, with the effect becoming larger with increasing n. For $P = 4$, we show in Figure 6 the cases for n = 1, 2, 3, and 4. Note that n need not be large to produce a hole in the distribution near 0°.

Therefore, for an initial pancake distribution of electrons, independent of the energy spectrum, the flux distribution at 2.3 kev can have a maximum at non-zero pitch angle after the electrons have been accelerated by an electric field parallel to the magnetic field.

The above does not explain the isotropic fluxes, or the fact that electron fluxes exist at 60° during a highly field-aligned event. There have been two suggestions for producing this "background". The first, by Hoffman and Evans (1968), required a two temperature gas, the low temperature component producing the small pitch angle maximum, the weaker high energy component the large pitch angle fluxes. But unless the high energy component is isotropic at the initial location, it could not produce the isotropic background to fill the void at very small pitch angles left by the effects of a large n. It would seem unreasonable for the high energy component to be isotropic, while the low energy component is concentrated near 90^{o} at the initial location.

More reasonable is the suggestion by Paschmann et al (1972) that the background arises from the same group of particles producing the peak in the angular distribution by being scattered in pitch angle, probably from backscatter out of the atmosphere.

Conclusion 2, that the highest probabilities occurred when the measurements were made at altitudes above 800 km, implies that the field-aligned portion of the electron beam becomes destroyed as it passes to lower altitudes.

Quite obviously the convergence of the magnetic field over the altitude range being considered, from 800 to 400 km, is trivial, so the beam cannot be defocused by convergence.

Pitch angle scattering of a beam of 2.3 kev field-aligned electrons in this altitude range is also insignificant. Densities perhaps approaching 10^{5} oxygen ions/cm^{3} at 400 to 800 km altitudes in this latitude region have been reported (J. H. Hoffman, private communication, 1973) as opposed to H^{+} ion densities of the order of $10^{4}/cm^{3}$ (Taylor et al, 1971), making O^{+} the dominant ion. Using the empirical relation given by Fermi (1950) for the angular spreading of a beam by scattering, we compute a value of only about 1 x 10^{-5} degrees for passage of the electrons from 800 to 400 km.

A third possibility for destroying a focused beam of electrons involves the location and topology of charge layers which could produce the focusing in the first place. Block (1972b) has recently reviewed the conditions under which ionsopheric double layers (charge layers) are formed. Generally, sheath thicknesses (in altitude) seem to be smaller than their cross sections in the latitude direction, (Block, 1972a; Carlqvist and Bostrom, 1970), which in our case is up to a few tens of km. Thus parallel electric fields as large as a volt/meter would be required to produce the particle anisotropies with the $\alpha_{f(max)}$ measured and fringing fields, or fields above and below the charge layers would be minimal (approaching the infinite parallel plane case).

If a double layer could be produced with its altitude extent large compared to its width, the resulting potential distribution would approach that of two infinitely long charged wires: $\Phi = (\lambda/2\pi\ \varepsilon_0)\ \ln \frac{R_1}{R_2}$, where λ is charge per unit length and the R's are the distances from the wires. This potential distribution is illustrated in Figure 7 in the vertical direction. Such a distribution would first focus the electron beam through downward acceleration above the top wire, followed by a deceleration and return to initial conditions half way between the wires. At the height of the positively charged top layer, electrons having the energy of the angular measurements, 2.3 kev, would be maximally field-aligned, and therefore would most likely be measured as a field-aligned distribution. While a single charge layer would accomplish the same thing, the double layer configuration has the property that the deceleration distance is much shorter than the acceleration region, and therefore the focused condition of the electrons would be rapidly destroyed. For such a charge layer configuration our probability curves as a function of height in Figure 3 merely reflect the probability as a function of height of the location of the double layer; that is, double layers are more likely to appear at 900 km than at 500 km. This would also explain why Paschmann et al (1972) report that the occurrence frequency of field-aligned anisotropies is very low; their satellite reached an altitude of only 590 km.

Conclusion 3, that the winter time high altitude region has the highest probability for observing field-aligned fluxes, could then be explained by a seasonal dependence on the altitude of double layers.

In spite of the large number of observations of field-aligned particle fluxes which have been performed to date, the complete distribution function has never been measured as a function of height. The total measurement is required to test the functional dependence of the anisotropy with energy [$\alpha_{f(max)}(E)$]. It would also give the initial energy spectrum. Of special importance is the distibution at very small pitch angles, for this determines the angular distribution of particles at the source (n in $\sin^n \alpha_i$)

ACKNOWLEDGMENTS

We wish to thank Drs. J. L. Burch, K. Maeda, and T. G. Northrop for many helpful suggestions. Special thanks are extended to Dr. S. E. DeForest for suggesting the detailed analysis of the actual pitch angle measured.

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FIGURE CAPTIONS

Figure 1. Percent of all field-aligned events per hour UT considering events at all local times and invariant latitudes (light line); considering only events in the interval $67.5^\circ \leq \Lambda \leq 75^\circ$ and 22 hours ≤ MLT ≤ 01 hours (heavy line).

Figure 2. Percent of all field-aligned events per 3 hours UT for the winter months (solid line) and summer months (dashed line).

Figure 3. Probability of precipitation being field-aligned as a function of altitude for each season, considering data collected in the 22 hours to 01 hour MLT interval.

Figure 4. Probability of 2.3 keV electron precipitation being field-aligned for the four seasons as a function of pitch angle in the MLT interval 22 hours to 01 hour.

Figure 5. For data in the MLT interval 22 hours to 01 hour: top- distribution of all the data points in altitude and pitch angle; center - distribution of field-aligned data in altitude and pitch angle; bottom - ratio of 0° flux to 60° flux at 2.3 keV for each data point as a function of pitch angle. a: Winter and spring. b: Summer and autumn.

Figure 6. Flux as a function of pitch angle as given by Equation 6, with $P = 4$ and $n = 0, 1, 2, 3$ and 4. The ranges of pitch angles sampled by the 0° and 60° detectors are indicated at the top of the figure.

Figure 7. The potential distribution as a function of altitude (arbitrary units) for two infinitely long, oppositely charged wires separated in the vertical direction.

SEASON	PERCENT OF ALL FIELD-ALIGNED EVENTS NORMALIZED TO EVEN SEASONAL SAMPLING
WINTER	40.3
SPRING	21.5
SUMMER	30.2
AUTUMN	8.0

table 1

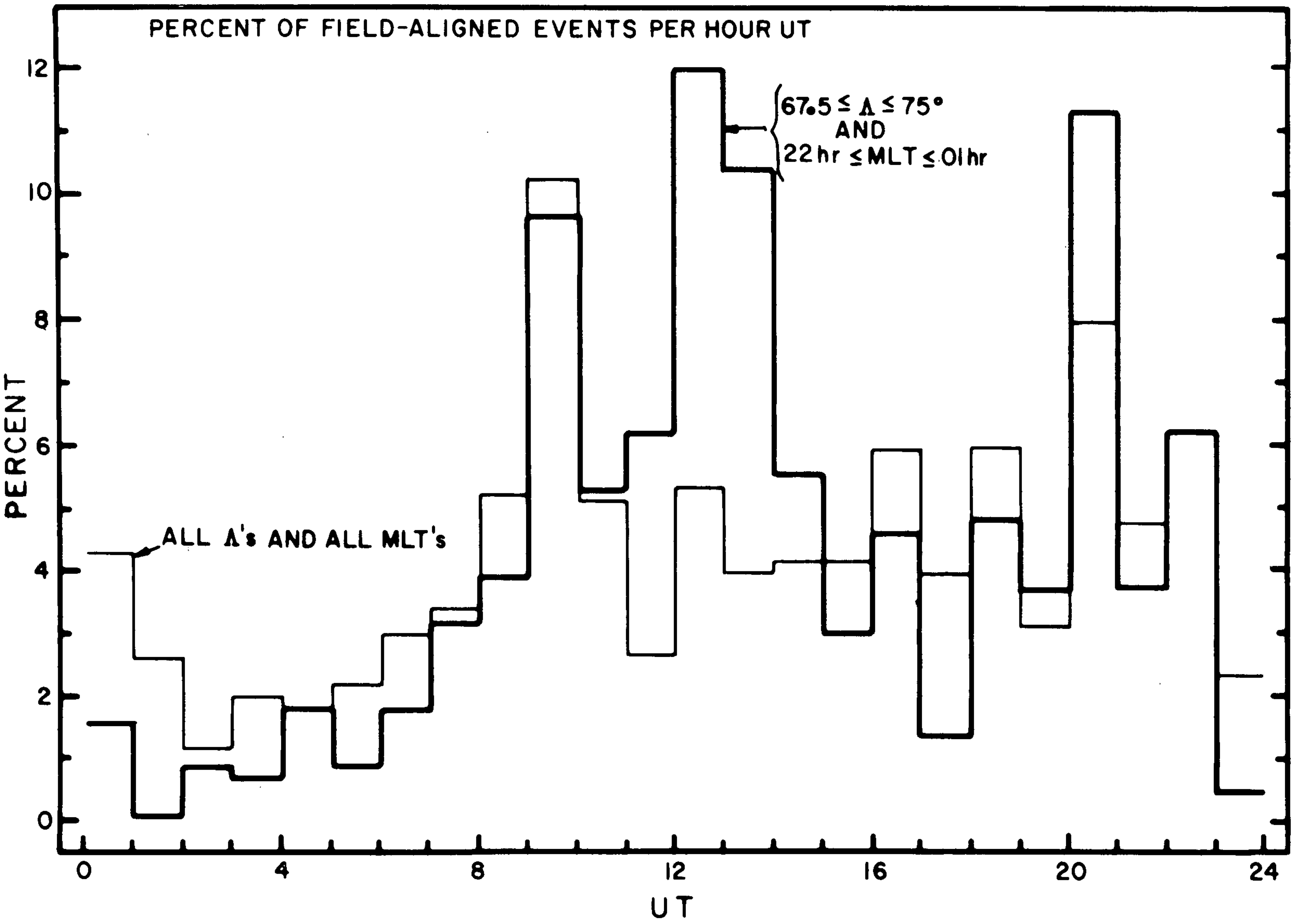
PERCENT OF FIELD-ALIGNED EVENTS PER HOUR UT
PERCENT
0
2
4
6
8
10
12
UT
0
4
8
12
16
20
24
$67.5 \leq \Lambda \leq 75°$ AND 22 hr ≤ MLT ≤ 01 hr
ALL Λ's AND ALL MLT's

FIGURE 1

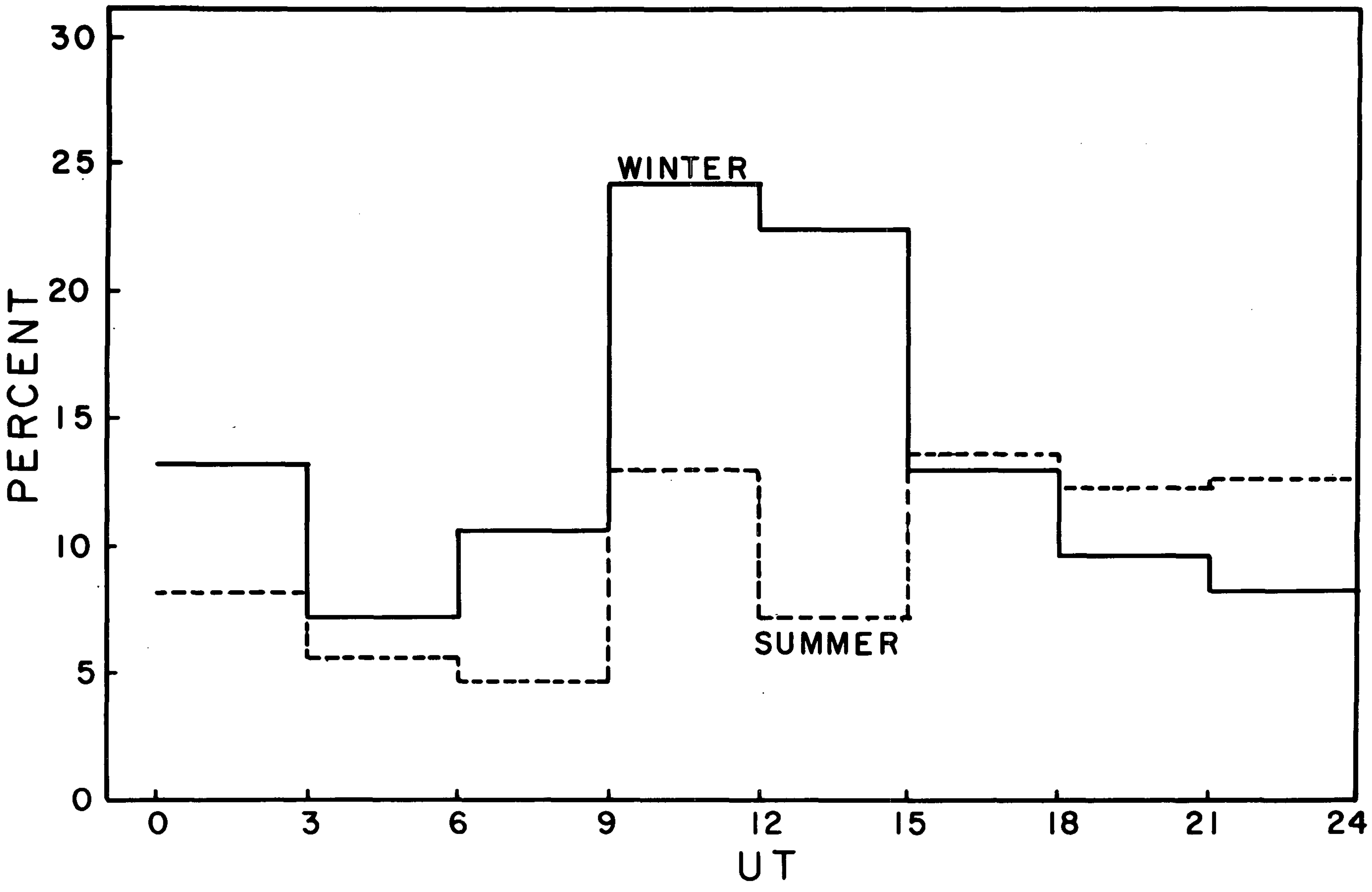

FIGURE 2

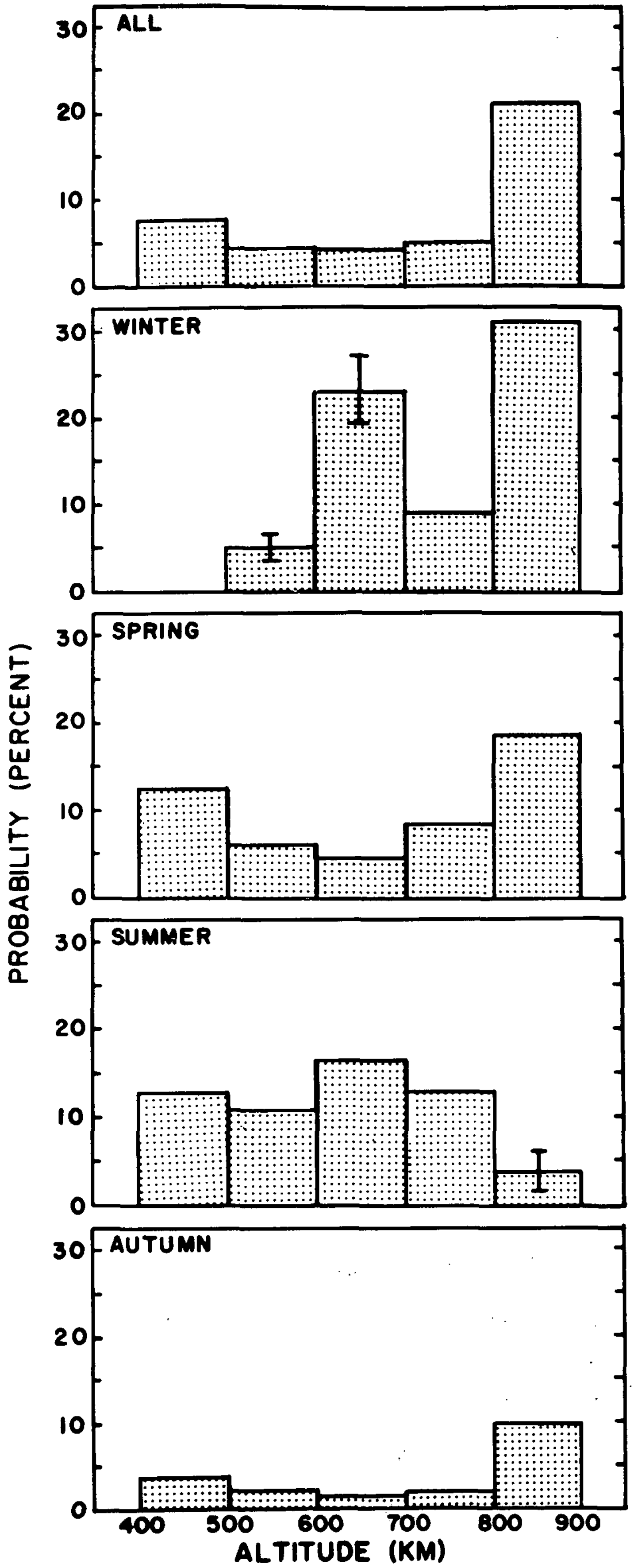
ALL
WINTER
SPRING
SUMMER
AUTUMN
PROBABILITY (PERCENT)
0
10
20
30
400
500
600
700
800
900
ALTITUDE (KM)

FIGURE 3

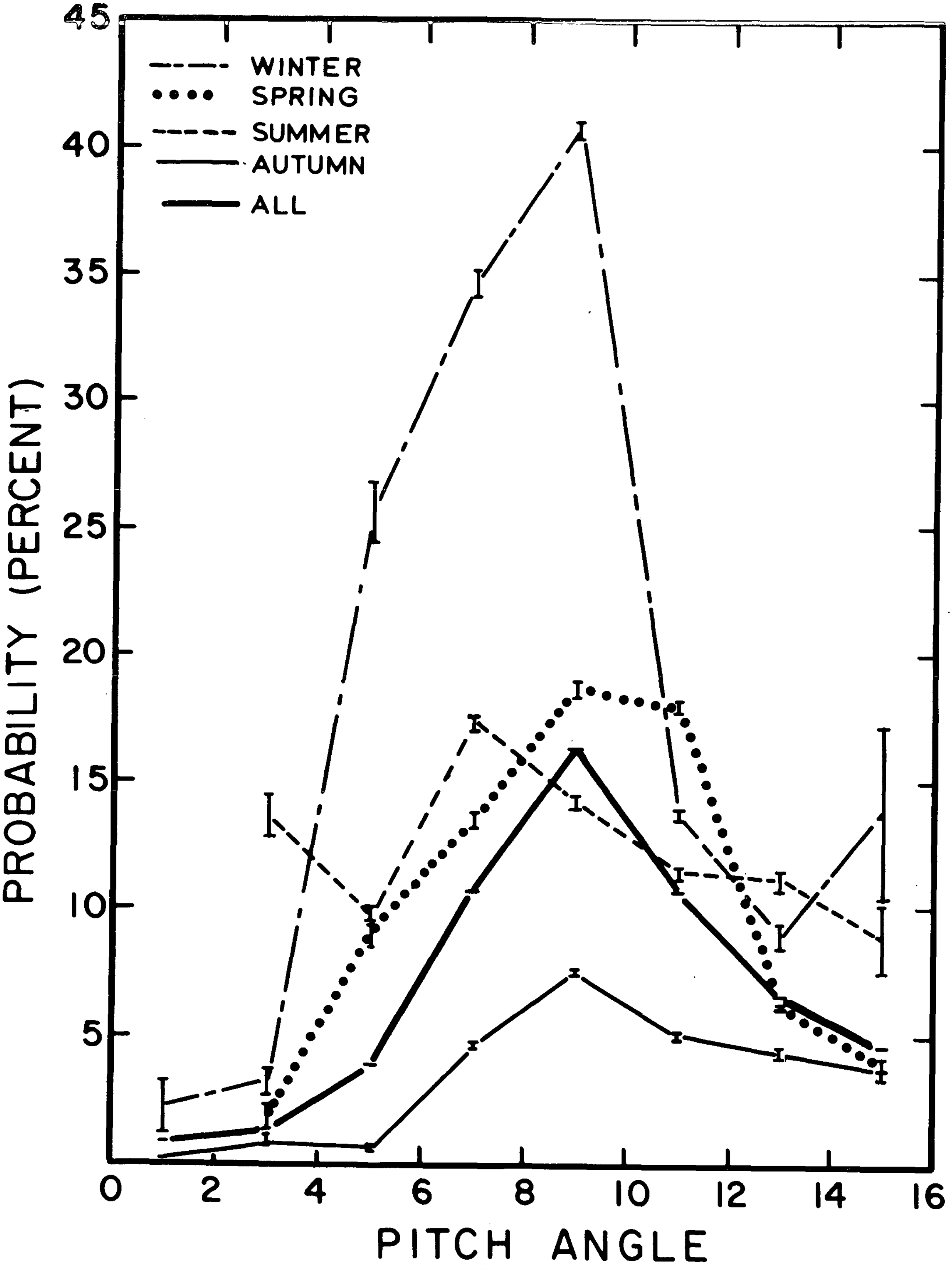
WINTER
SPRING
SUMMER
AUTUMN
ALL
PROBABILITY (PERCENT)
45
40
35
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
PITCH ANGLE

FIGURE 4

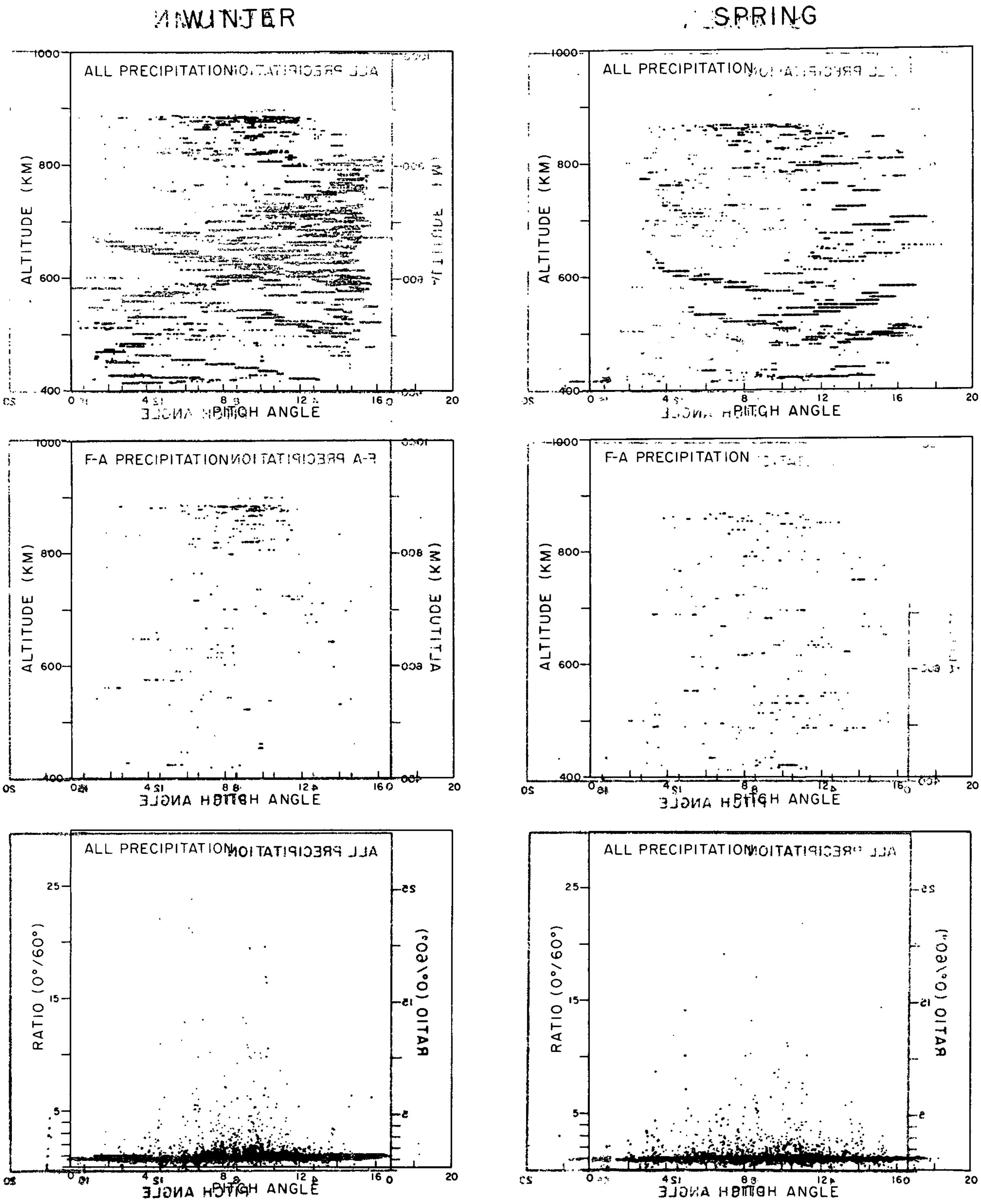
WINTER
SPRING
ALL PRECIPITATION
ALTITUDE (KM)
1000
800
600
400
PITCH ANGLE
0
4
8
12
16
20
F-A PRECIPITATION
ALL PRECIPITATION
RATIO (0°/60°)
25
15
5

FIGURE 5a

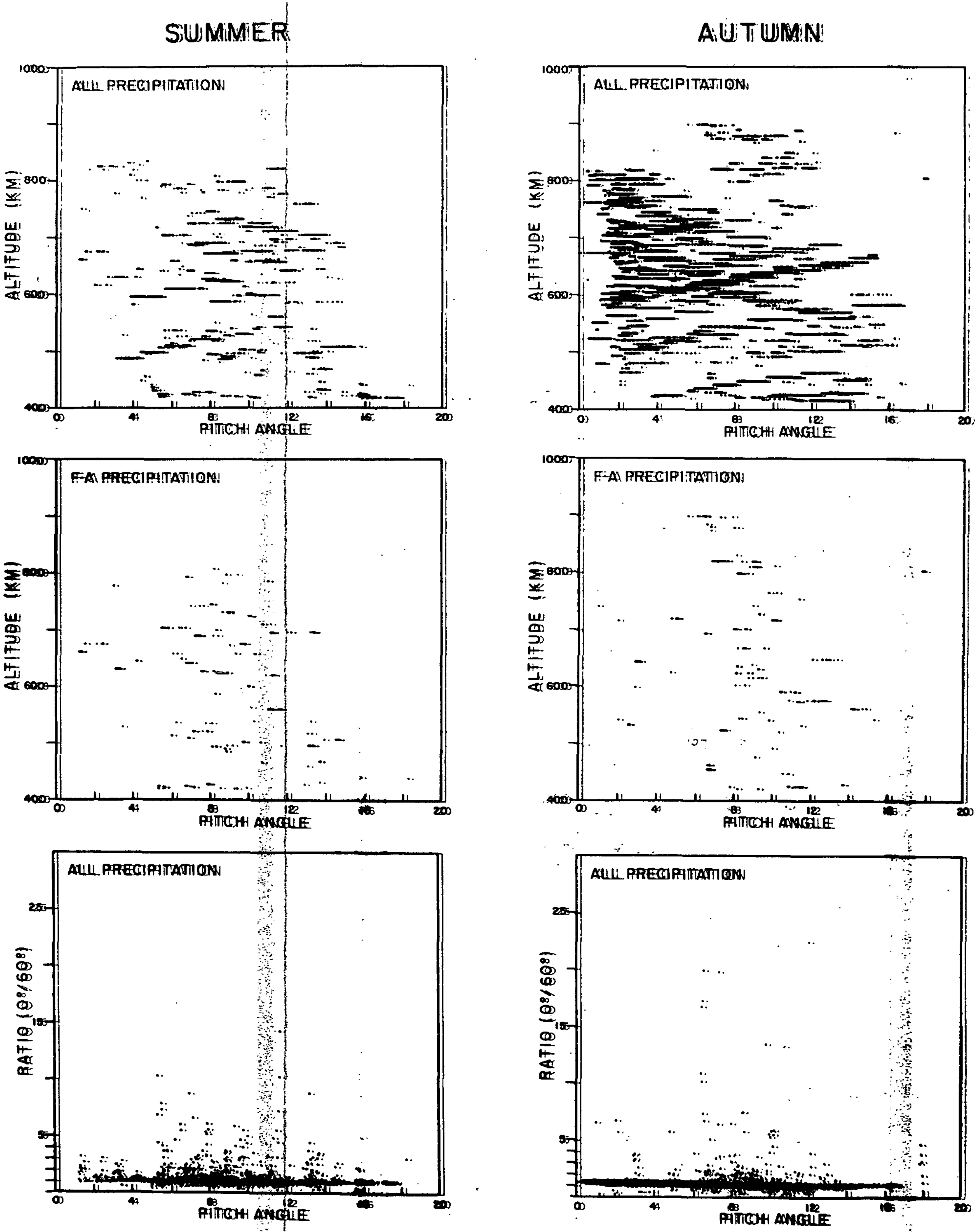
SUMMER
AUTUMN
ALL PRECIPITATION
F-A PRECIPITATION
ALL PRECIPITATION
ALTITUDE (KM)
RATIO (0°/60°)
PITCH ANGLE
1000
800
600
400
0
40
80
120
160
200
25
15
5

FIGURE 5b

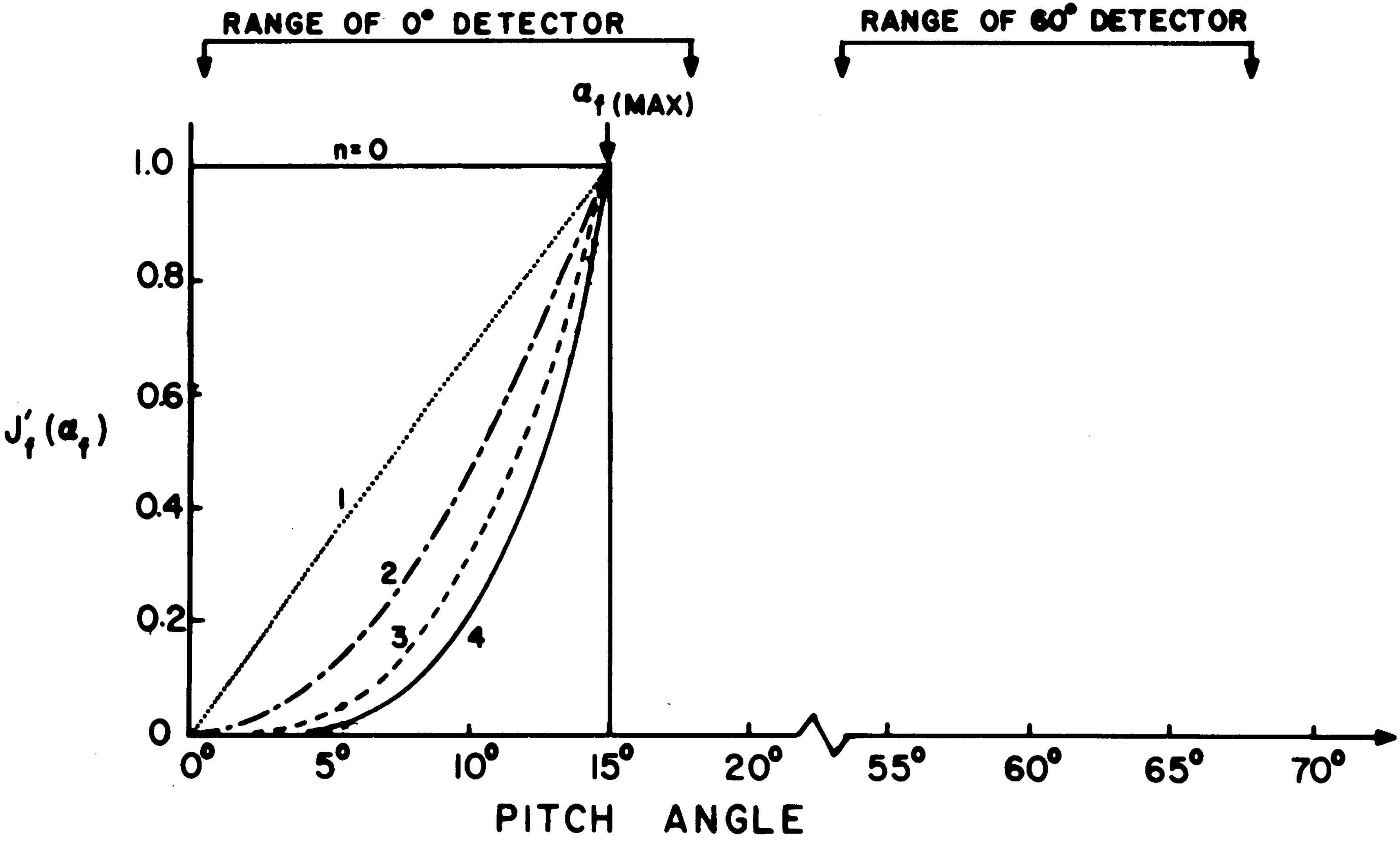
RANGE OF 0° DETECTOR
RANGE OF 60° DETECTOR
α_f (MAX)
n=0
1.0
0.8
0.6
0.4
0.2
0
J'_f (α_f)
1
2
3
4
0°
5°
10°
15°
20°
55°
60°
65°
70°
PITCH ANGLE

FIGURE 6

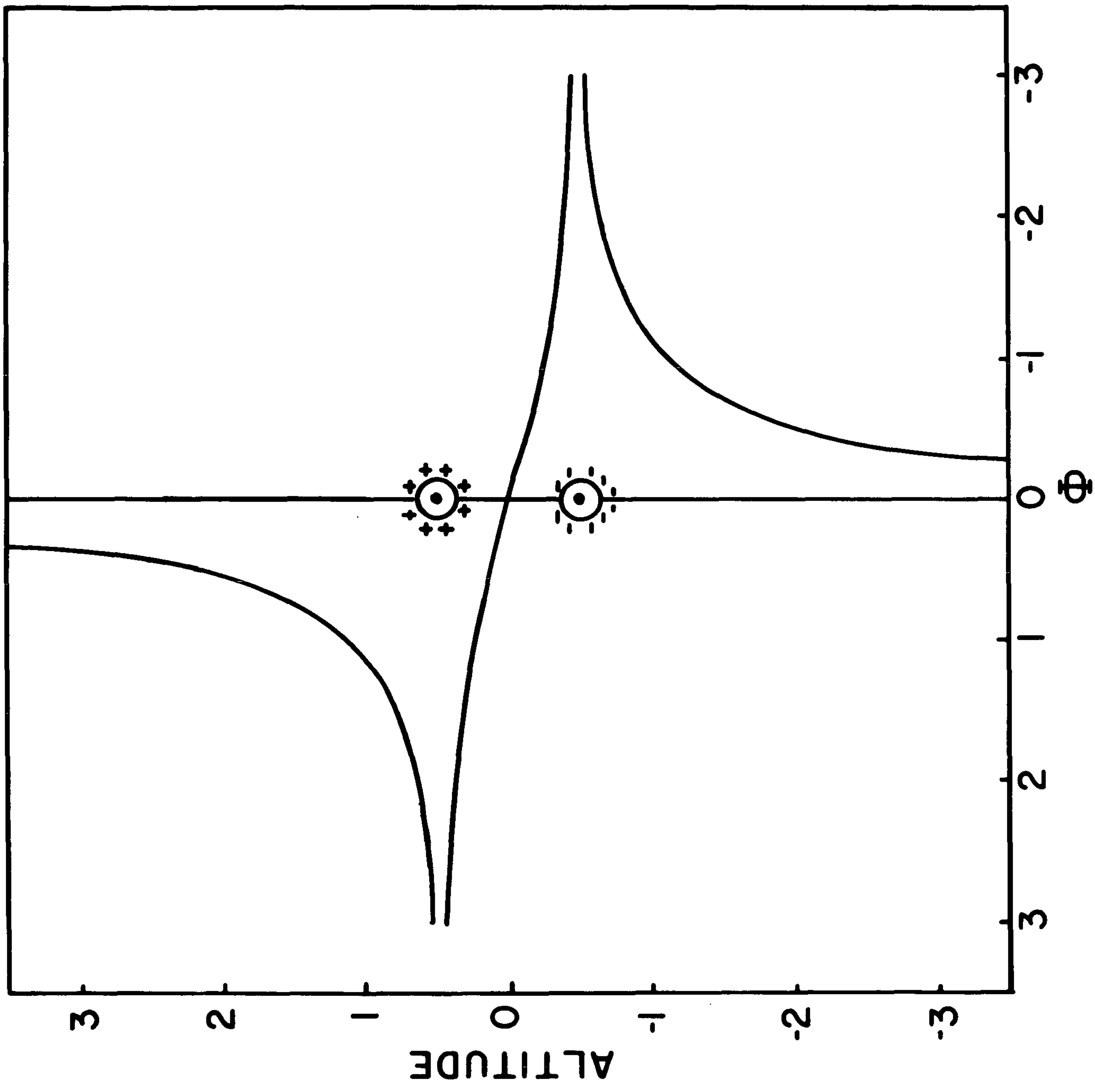

FIGURE 7