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ON THE NATURE AND ORIGIN OF DIRECTIONAL DISCONTINUITIES

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Abstract

Less than 25% of the "directional discontinuities" (directional changes $> 30^o$ in less than 30 sec) identified by Burlaga in the interplanetary magnetic field data of Ness from Pioneer 6 are Alfven shocks ($\equiv$ rotational discontinuities). Thus, most of these directional discontinuities are tangential. The Pioneer 6 magnetic field and plasma data are not consistent with the hypothesis that directional discontinuities originate primarily by the collision of fast streams with slower plasma, since the rate of occurance of discontinuities in regions of increasing bulk speed is only a little higher than the rate elsewhere. The rate at which discontinuities are seen at .82 AU, is somewhat lower than at 1 AU, but the difference may be due to the lower data quality and increase in the number of data gaps when the spacecraft is far from the earth. The distributions of the change in direction of the field across the discontinuity and of the "normals" ($\underset{\sim}{B}_1 x \underset{\sim}{B}_2 / \underset{\sim}{B}_1 x \underset{\sim}{B}_2$) are essentially the same at $\approx$.8, $\approx$.9 and $\approx$1.0 AU. This suggests that most discontinuities originate within .8 AU and do not evolve appreciably between .8 and 1.0 AU.

INTRODUCTION

Discontinuities in the interplanetary magnetic field on a scale of .01 AU were discovered by Ness et al. (1966). Statistical studies by Siscoe et al. (1968) and Burlaga (1969a) showed that these discontinuities pass a spacecraft at the rate of ≈ 1/hr. Since fast or slow shocks occur much less frequently, and since contact discontinuities show no change in $\underline{B}$, the discontinuities found by Ness must be predominantly tangential discontinuities, Alfven shocks, or a mixture of both (see Colburn and Sonett (1966) for a discussion of the types of hydromagnetic discontinuities). Burlaga (1968) and Burlaga and Ness (1969) used magnetic field and plasma data to show that some of the discontinuities are tangential. Siscoe et al. (1968) suggested that, in fact, essentially all interplanetary discontinuities are tangential discontinuities. On the other hand, Smith et al. (1970), Belcher and Davis (private communication), and Turner and Siscoe (1970) suggested that most "discontinuities" are Alfven shocks. Thus, the relative number of tangential discontinuities and Alfven shocks is controversial.

In view of the great complexity of interplanetary magnetic field changes, and noting the possibility that the discontinuities found by Ness might be a mixture of 2 types, Burlaga (1969a) introduced the term "directional discontinuity" to denote a discontinuity in which the magnetic field direction, ω, changes by $>30^{\circ}$ in ≤ 30 sec. Most of the discontinuities identified by Ness et al. (1966) and Siscoe et al. (1968) are directional discontinuities. It is not clear whether or not the discontinuities referred to be Smith et al., Belcher and Davis, and Turner and Siscoe are directional discontinuities.

This paper has two aims: 1) to determine the ratio of Alfven shocks to tangential discontinuities in the set of directional discontinuities obtained by Burlaga (1969a) from Ness's Pioneer 6 magnetic field data for the period Dec. 16, 1965 to Jan. 5, 1966; and 2) to discuss some hypotheses concerning the origin of these discontinuities, a problem that has not been studied experimentally until now.

II. Nature of Directional Discontinuities

There are a few ways to distinguish between a tangential discontinuity and an Alfven shock, but only one could be applied to the data under consideration. If a discontinuity is an Alfven shock, then

$$\underset{\sim}{V}_1 - \underset{\sim}{V}_2 = \pm \left(\frac{\underset{\sim}{B}_1}{\rho_1} - \frac{\underset{\sim}{B}_2}{\rho_2}\right) \left(\frac{\rho_1}{4\pi}\right)^{\frac{1}{2}} x A \tag{1}$$

here

$$A \equiv \left(1 - \frac{P_{\parallel 1} - P_{\perp 1}}{B^2/(4\pi)}\right)^{\frac{1}{2}} , \tag{2}$$

is a measure of the anisotropy of the velocity distribution, $\underset{\sim}{V}$ is the bulk velocity, $\underset{\sim}{B}$ is the magnetic field, ρ is the plasma density, and $P_{\parallel}$ and $P_{\perp}$ are the total thermal pressure (ions plus electrons) parallel to or perpendicular to $\underset{\sim}{B}$. In general, $|B_1| \neq |B_2|$ in which case $P_{\parallel 1} \neq P_{\perp 1}$ (Hudson, 1970).

If a discontinuity is tangential, then $\Delta\underset{\sim}{V} \equiv \underset{\sim}{V}_2 - \underset{\sim}{V}_1$ can have any value and is independent of $\underset{\sim}{B}$ (but very large $\Delta\underset{\sim}{V}$ may give rise to the Kelvin-Helmholtz instability; Parker (1963), Burlaga (1969b)). Thus, one way to set an upper limit on the number of Alfven shocks is to determine the number of discontinuities which satisfy (1). This givs an upper limit because some tangential discontinuities might also satisfy (1) by coincidence.

There is one complication with the method just described: The anistropy was not measured for the discontinuities under consideration, so A cannot be determined for each discontinuity. However, the value can be reliably estimated as follows. From Hundhausen et. al. (1970), (T_{max}/T_{min}) median = 1.9; since the thermal anisotropy is field aligned, this is $T_{\parallel}/T_{\perp}$ for the protons. Measurements for the electrons are not clearcut, but Montgomery et al. (1968) find that nearly always $(T^e_{max}/T^e_{min}) < 1.2$. Thus, we shall take $T^e_{\parallel}/T^e_{\perp} \simeq 1.1$. Hundhausen et al. (1970) give 6.9×10^4°K and $6.6\ cm^{-3}$ for the median proton temperature and density, respectively, and the electron temperature is $\approx 1.5 \times 10^5$°K (see Montgomery et. al. (1968), and the brief summary in Burlaga and Ogilvie (1970)). The magnetic field intensity is typically ~6γ. With these numbers, one finds that A =(.9 ± .1).

We shall consider a subset of the discontinuities listed in Burlaga (1969a),those for which accurate plasma data are available from the MIT plasma instrument on Pioneer 6. The subset consists of 200 directional discontinuities in the period Dec. 17, 1965 to Jan. 4, 1966. $\underset{\sim}{B}_1$ and $\underset{\sim}{B}_2$ were obtained as described in Burlaga (1969a). The parameters n_1, $\underset{\sim}{V}_1$, n_2 and $\underset{\sim}{V}_2$ were obtained from the spectra just before and after the discontinuity, except when the discontinuity might have occured while a spectrum was being recorded, in which case the preceding (or following) spectrum was used. A discussion of the plasma instrument may be found in Lazarus et al. (1966). The vectors $\underset{\sim}{B}$ and $\underset{\sim}{V}$ were resolved in RTN components, where $\hat{R}$ is radial away from the sun, $\hat{T}$ is in the ecliptic plane and points in the direction of the earth's motion, and $\hat{N}$ is perpendicular to the ecliptic. The most accurately measured velocity component is V_R, the least accurate is V_N. In these coordinates, (1) may be written

$$\frac{(V_{1i} - V_{2i})}{Q_i} = \pm A, \quad i = R,T,N, \qquad (3)$$

where

$$Q_i \equiv 21.8 \left(\frac{B_{1i}}{n_1} - \frac{B_{2i}}{n_2}\right)\left(\frac{n_1}{4\pi}\right)^{1/2} \qquad (4)$$

and n is the number density.

All of the quantities on the LHS of (3) are known. The question at issue may now be stated as follows: "What fraction of the directional discontinuities satisfy (3) with $A \approx .9 \pm .1$?"

Figure 1 shows the distribution of $\Delta V_i/Q_i$ for the 200 directional discontinuities. If the discontinuities were mostly Alfven shocks the distributions would be peaked at +.9 or -.9. The observations in Figure 1 are not distributed in this way. Rather, the distributions are all peaked at zero, as one might expect for tangential discontinuities. Clearly, then, most of the directional discontinuities are not Alfven shocks, and are thus probably tangential discontinuities.

A quantitative upper limit on the fraction of Alfven shocks may be obtained as follows. Figure 2 shows ΔV versus Q_R. If the discontinuities were all Alfven shocks, the points would scatter about the line $\Delta V = .9$. Suppose that all of the points above the line $|\Delta V| = .9Q$ in Figure 2 are rotational discontinuities and that an equal number (26) of the points below the line are rotational discontinuities. Since there are 200 directional discontinuities in the sample, this implies that <u>$\leq 25\%$ of the directional discontinuities are rotational</u>. This is clearly an upper limit, since some of the points above the line in the region $Q<10$ are are almost certainly tangential discontinuities.

Our sample of discontinuities includes both a very quiet time ($V < 350$ km/sec) and a very disturbed period ($V < 600$ km/sec.) The distribution of the discontinuities on the most magnetically disturbed day in our sample (shown by the crosses in Figure 2) is not significantly different from the general distribution.

III. Origin of Directional Discontinuities.

We shall examine two hypotheses:

1). Discontinuities are caused by the impact of fast streams with slower plasma near 1 AU.

2). Discontinuities evolve by some process operating between .8 AU and 1 AU.

Impact Hypothesis. Figure 3 shows directional discontinuities for the period December 16, 1965, to January 5, 1966, as given by Burlaga (1969a), together with an indication of the times when the bulk speed was increasing for an hour or more (shaded areas). Cross hatched areas show times for which high bit-rate magnetic field data are not available, and the double-arrowed lines above the panels indicate times for which the plasma data were not available. Clearly, there is no strong tendency for directional discontinuities to cluster in regions where the bulk speed increases, so the faster streams cannot be the principal cause of directional discontinuities. However, the rate of occurance of discontinuities in the gradient regions, $(1.5\pm.2)$/hr, is possibly somewhat higher than outside these regions, $(1.0\pm.1)$/hr.

Evolution Hypothesis. This implies that the statistical properties should change with distance between .8 AU and 1 AU. We shall consider 3 distances, .82 AU (perigee), .91 AU,(where the trajectory crossed the earth-sun line) and .98 AU. The corresponding time intervals are 2000 UT April 29 through 1900 UT June 5, 1966, Feb. 25 through March 8, 1966, and Dec. 16, 1965 through Jan. 5, 1966, respectively.

The statistical properties that we shall consider are a) the rate at which discontinuities pass the spacecraft (this is a measure of their "density", since the solar wind speed does not change appreciably between

.8 and 1 AU), b) the distribution of ω, the change in the magnetic field direction across a discontinuity, and c) the distribution of "normals", $\hat{n} = \underset{\sim}{B}_1 x \underset{\sim}{B}_2$. The statistics are less accurate at .82 and .91 AU because of data gaps, lower telemetry rates and noise.

Subjectively selecting hours with "good" data for the periods of interest gives .7 discontinuities/hr at .82 AU, .8 at .91 AU, and 1.1 at .98 AU. The higher frequency of discontinuities near the earth is at least partly, and possibly entirely, due to the better and more continuous data near the earth. As a measure of the activity during these periods. we note that $\overline{K}_p$ was 12.0, 8.6 and 12.3 for Dec. 16-Jan. 5, Feb. 25-Mar. 8, and April 29-June 5, respectively. In view of the (weak) correlation between K_p and the density of discontinuities (Burlaga, 1969a), one might expect the first and last periods to be comparable, and the frequency of discontinuities for the intermediate period to be relatively low. We conclude that the density of directional discontinuities at .82 AU is possibly 35% less than at .98 AU, but the difference may be due mostly to the higher quality data near 1 AU.

The distributions of ω are shown in Figure 4. There is no significant difference between the 3 distributions, indicating little change in discontinuities as they move from .82 AU to 1 AU.

The distributions of "normals" ($\underset{\sim}{B}_1 x \underset{\sim}{B}_2$) are shown in Figure 5. These distributions were computed by putting all of the vectors in their proper orientations at the origin of a unit sphere and computing the density of the points which were determined by the intersections of these vectors with the unit spheres. The left side of Figure 5 shows the density integrated over ϕ, as a function of θ. (θ is the angle between the "normal" and its projection in the ecliptic plane, and ϕ is the angle between the projection and the earth-sun line). The right side of Figure 5 shows the density, integrated over Θ, as a function of ϕ. The radius of each sector is proportional to the number of normals per unit area on a unit sphere, for that ϕ interval. There is no significant difference between the Θ distributions for .82 AU, .91 AU, and .98 AU. The ϕ distributions at .82 and .91 AU are essentially the same, but appear to differ from that at .98 AU. The difference is probably not statistically significant, however, since there are only 25 to 30 discontinuities in the largest sectors.

<u>We conclude that most if not all directional discontinuities originate within .82 AU and do not change appreciably between .82 and .98 AU.</u>

FIGURE CAPTIONS

Figure 1 Distribution of $\Delta V_i/Q_i$. If the discontinuities were Alfven shocks the distribution would be peaked near $\pm.9$.

Figure 2 The change in bulk speed across directional discontinuities versus the corresponding change in $Q=21.8\left|B_{1R}/n_1-B_{2R}/n_2\right|\left(\frac{n_1}{4\pi}\right)^{1/2}$ where B_R is the radial component of $\underset{\sim}{B}$. (See text.) If all directional discontinuities were Alfven shock, the points would scatter about the lines at $\pm.9$ in this figure.

Figure 3 Relation between directional discontinuities and increasing bulk speed. The discontinuities are shown by the vertical lines whose position gives the time they were observed at Pioneer 6 and whose height shows the angle through which $\underset{\sim}{B}$ changes across the discontinuity. The shaded regions indicate times when the bulk speed was increasing. There is no clear association between the shaded regions and discontinuities, indicating that fast streams are not the principal cause of directional discontinuities.

Figure 4 The distribution of ω for discontinuities observed at .98 AU, .91 AU, and .82 AU. No significant difference between the distributions can be seen, supporting the hypothesis that directional discontinuities do not evolve between .82 and .98 AU.

Figure 5 Distribution of the direction of the vectors $\underset{\sim}{B}_1 x \underset{\sim}{B}_2$ for the directional discontinuities at .82, .91, and .98 AU.

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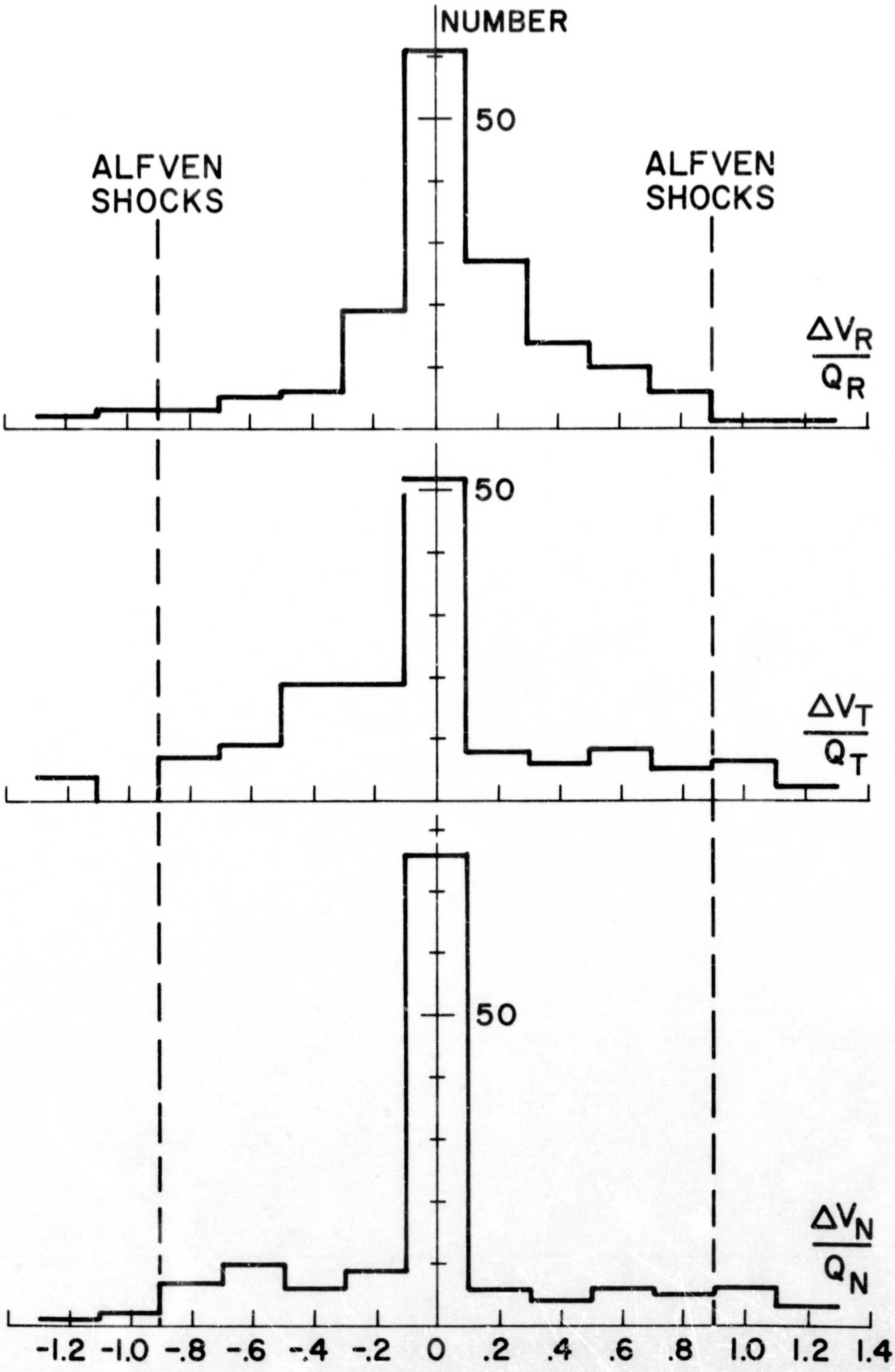
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50
ALFVEN SHOCKS
ALFVEN SHOCKS
$\frac{\Delta V_R}{Q_R}$
50
$\frac{\Delta V_T}{Q_T}$
50
$\frac{\Delta V_N}{Q_N}$
-1.2 -1.0 -.8 -.6 -.4 -.2 0 .2 .4 .6 .8 1.0 1.2 1.4

Figure 1

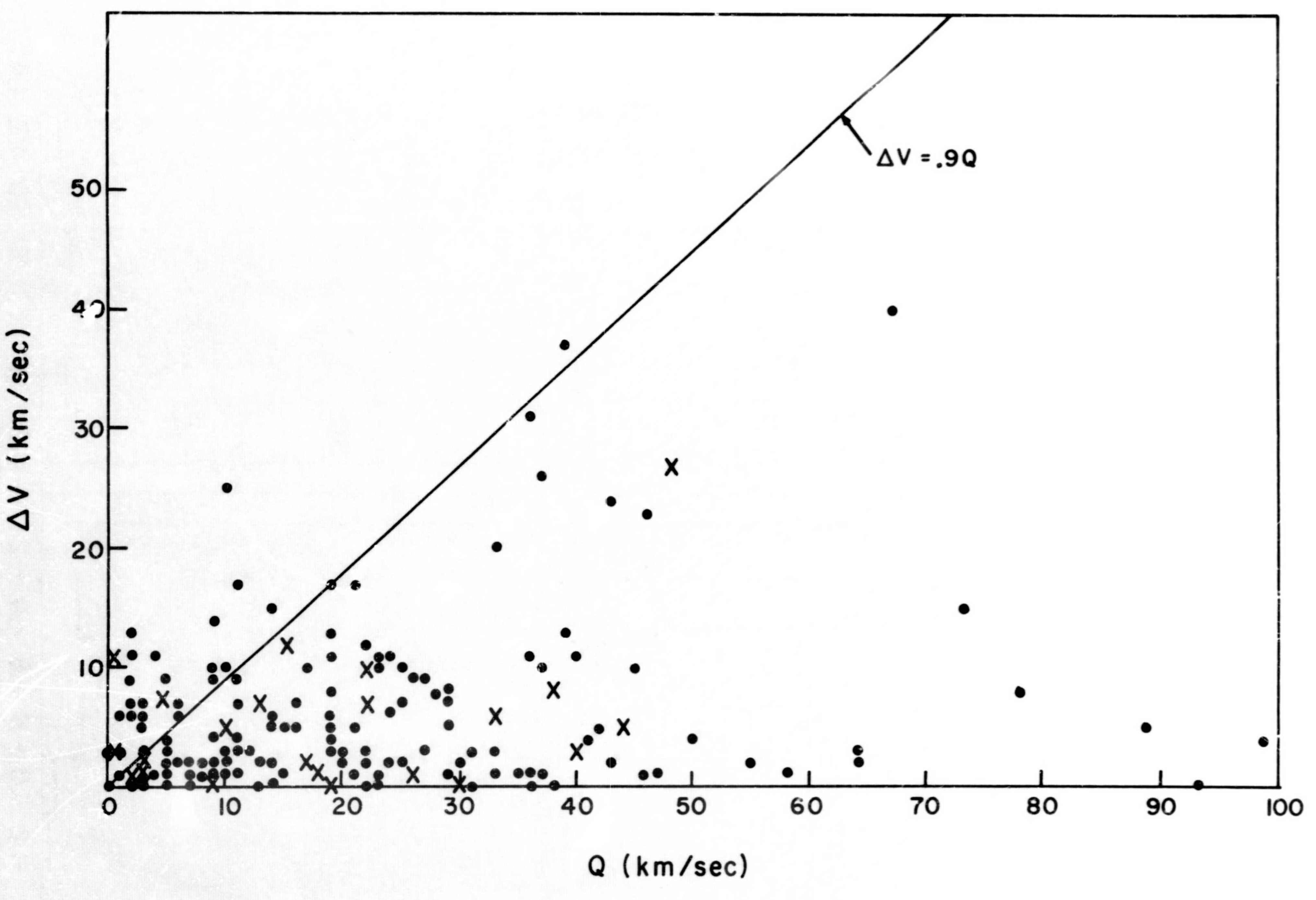

ΔV = .9Q
50
40
30
20
10
0
ΔV (km/sec)
0
10
20
30
40
50
60
70
80
90
100
Q (km/sec)

Figure 2

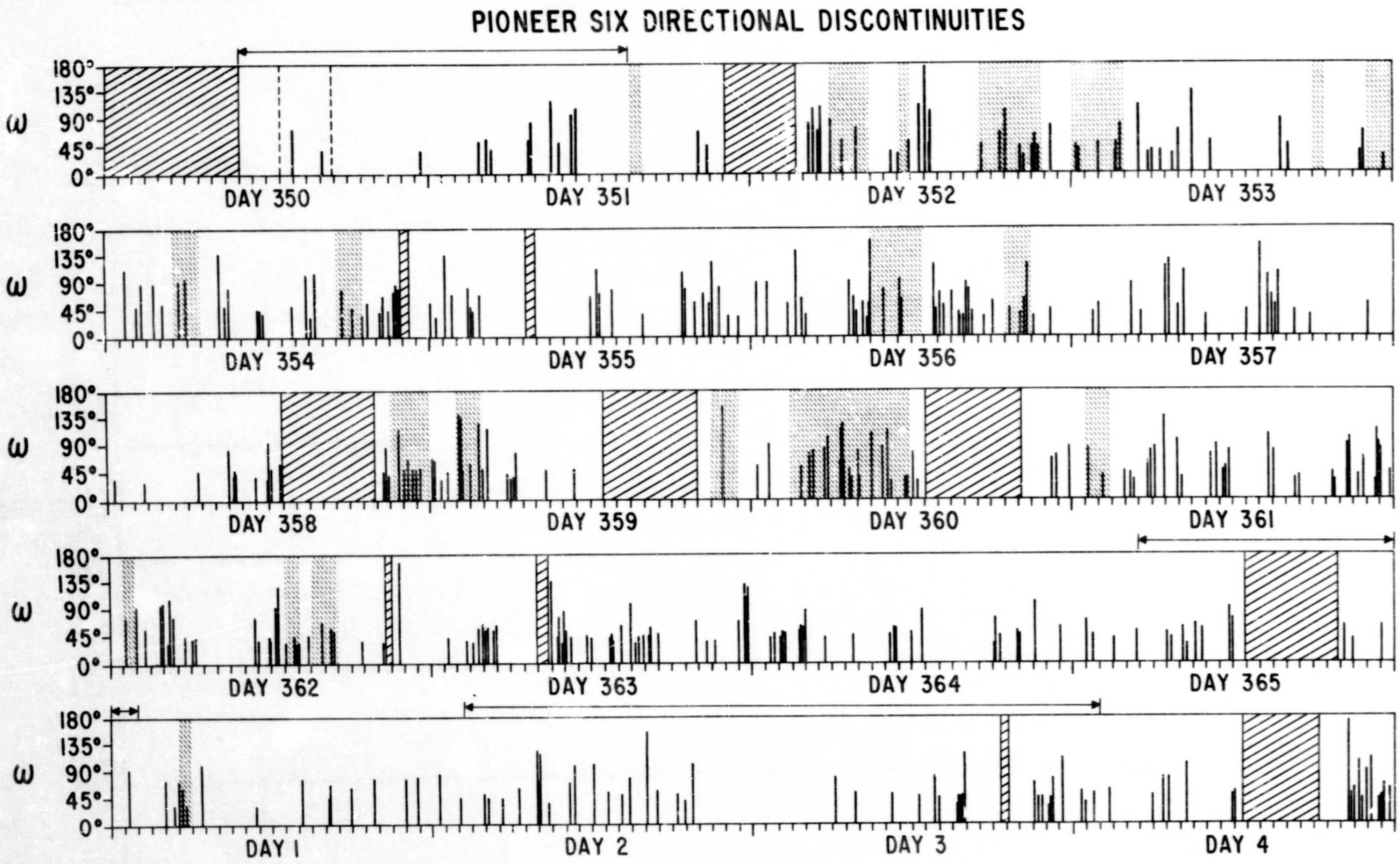

PIONEER SIX DIRECTIONAL DISCONTINUITIES
ω
180°
135°
90°
45°
0°
DAY 350
DAY 351
DAY 352
DAY 353
DAY 354
DAY 355
DAY 356
DAY 357
DAY 358
DAY 359
DAY 360
DAY 361
DAY 362
DAY 363
DAY 364
DAY 365
DAY 1
DAY 2
DAY 3
DAY 4

Figure 3

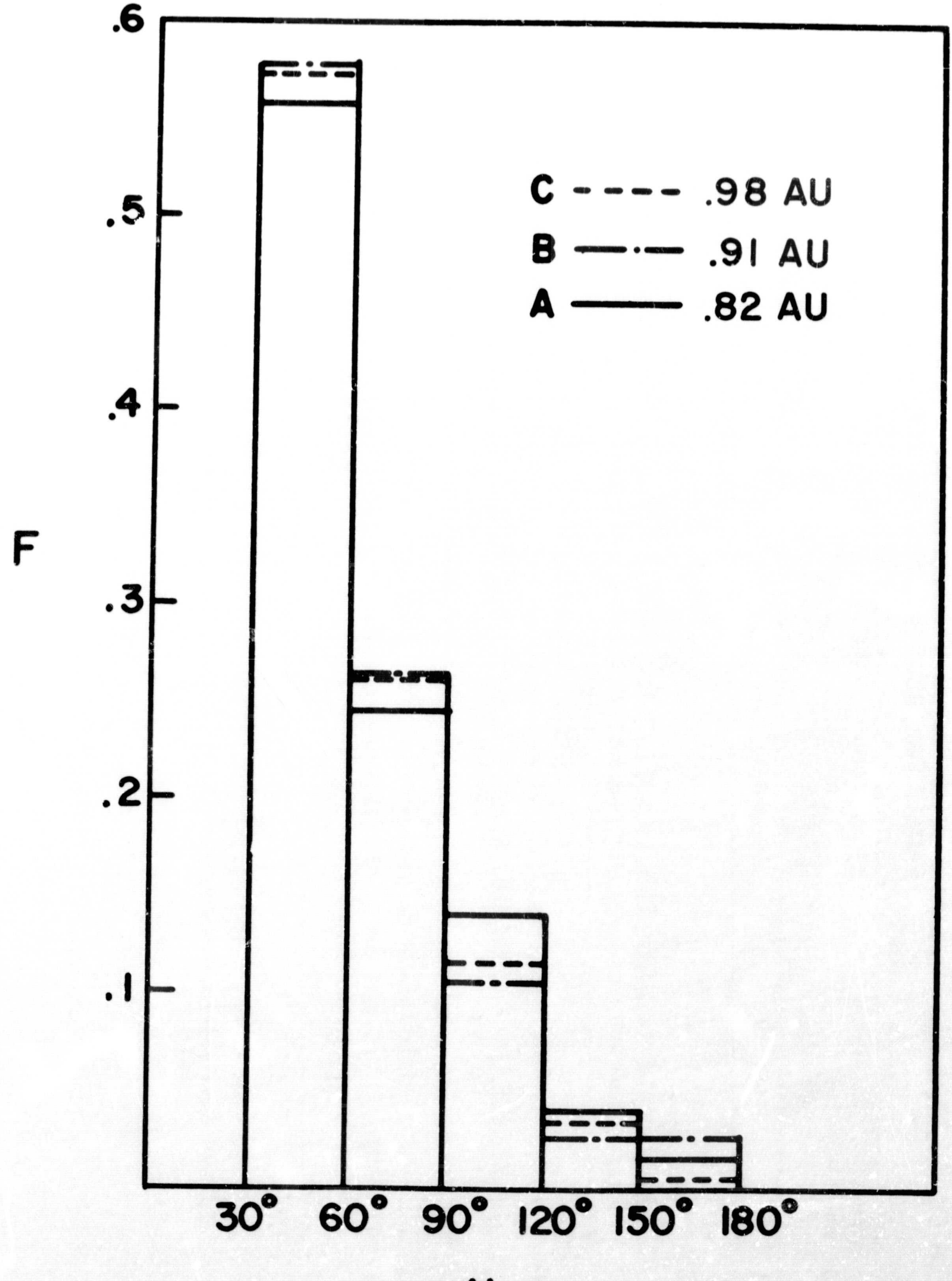
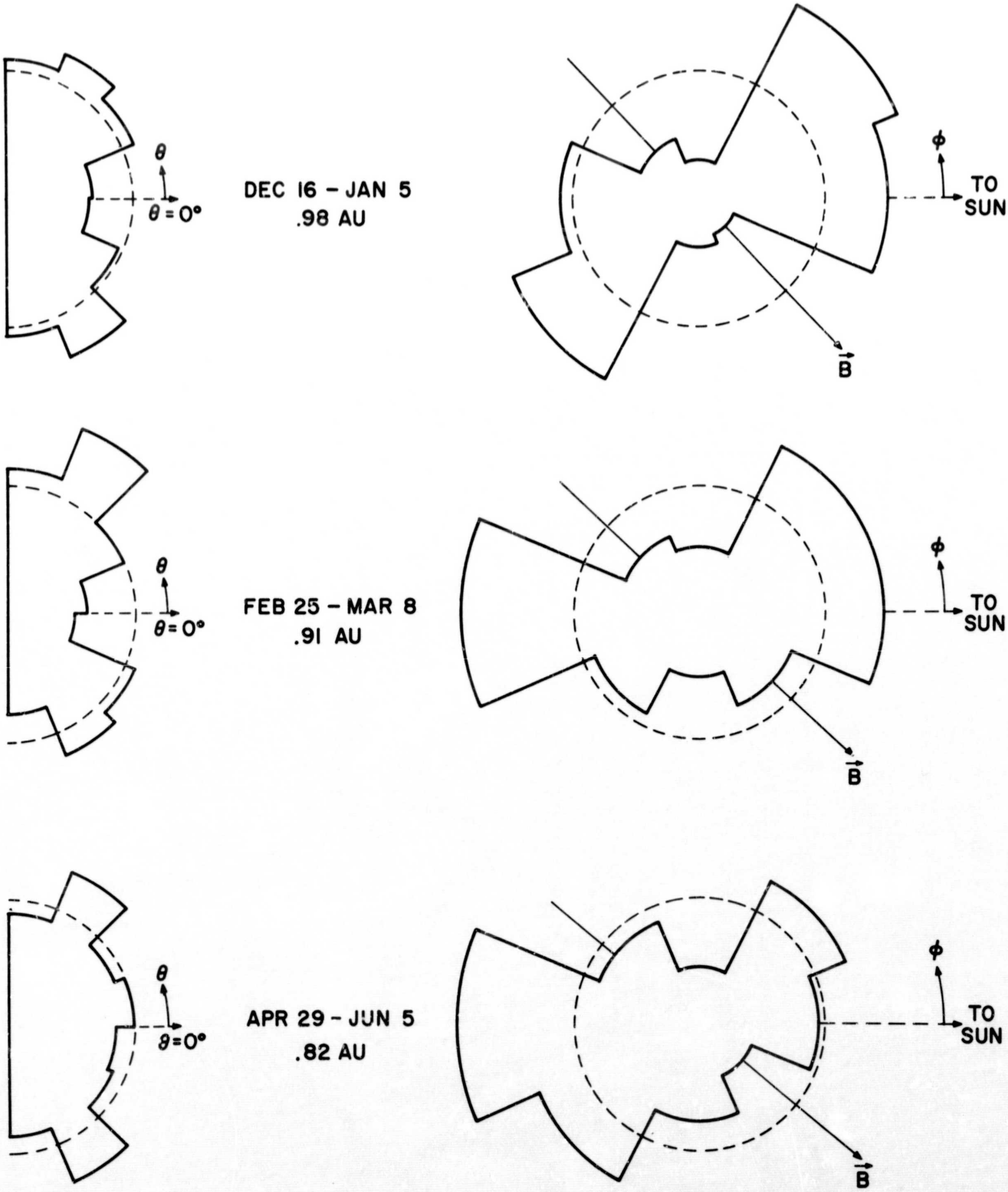


Figure 4



θ
θ = 0°
DEC 16 – JAN 5
.98 AU
φ
TO SUN
B
θ
θ = 0°
FEB 25 – MAR 8
.91 AU
φ
TO SUN
B
θ
θ = 0°
APR 29 – JUN 5
.82 AU
φ
TO SUN
B

Figure 5