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K. W. OGILVIE
N. F. NESS

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K. W. Ogilvie
N. F. Ness
Laboratory for Space Sciences
NASA-Goddard Space Flight Center
Greenbelt, Maryland

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Abstract

Simultaneous measurements in cislunar space of the characteristics of the solar wind plasma as observed by Explorer 34, and the perturbed magnetic field in the lunar wake as detected by Explorer 35, were performed during July-October 1967. The plasma parameter β_i for the ions is found to be more important in determining the magnitude of the umbral positive and penumbral negative anomalies than the direction of the interplanetary magnetic field. A quantitative comparison of these observations with the lunar wake theory of Whang indicates that the solar wind electrons must contribute even move significantly than the ions to the effective β for the plasma. Using the lunar wake as a solar wind sock for the electrons yields $\beta_e \sim 2\beta_i$, so that on average the temperature of the electrons is indirectly determined to be $T_e/T_i \approx 2$ and the net effective β of the plasma is $\sim 3\beta_i$.

Introduction

Observations of the magnetic field close to the moon, at times when it was in the interplanetary medium, have been made by lunar Explorer 35 (Colburn et al., 1967; Ness et al., 1968a,b; and Taylor et al., 1968). The interplanetary magnetic field is found to be only slightly perturbed by the presence of the moon. In particular, a discontinuous jump in field magnitude by a factor of 2 to 4 times forming a boundary around a sheath region of relatively large amplitude rapidly fluctuating fields was not detected. This makes it very unlikely that a bow shock is formed as the solar wind flows past the moon, or that a shock wave trails the moon, as suggested by Michel (1967).

The major effect of the moon on the interplanetary medium is to create a cavity behind it from which plasma has been removed (Lyon et al., 1967), since most electrons and ions impacting the moon's surface are absorbed by it. The cavity is closed as one moves away from the moon down stream by the pressure of the surrounding plasma. A small increase in plasma flux simultaneous with a field magnitude increase in the exterior penumbral regions has been interpreted as providing evidence of the deflection of plasma from the limbs of the moon (Siscoe et al., 1968).

In the core of the lunar wake, magnetic observations characteristically show an increase of the interplanetary magnetic field $\lesssim$ 50% of the unperturbed value. In the penumbral regions, around this core both positive and negative perturbations of the interplanetary field strength are often observed (Ness et al.,1968b; Taylor et al., 1968).

The magnitude and geometry of the perturbations vary with conditions in the undisturbed solar wind.

In this paper we describe further observations which support the view summarized above, and investigate the quantitative relationship between the magnitudes of the umbral and penumbral anomalies and the properties of the solar wind. For this purpose we use simultaneous observations made by the satellites Explorers 34 and 35.

Although the observations of the properties of the interplanetary magnetic field are performed on Explorer 35 in lunar orbit, the determination of the plasma properties is made from observations by Explorer 34 which is in earth orbit. It is assumed that on an hourly average time scale these plasma characteristics are valid representations of those in the immediate vicinity of the moon. Direct comparisons of simultaneous magnetic field observations by Explorers 33 and 35 (Taylor et al., 1968) support this viewpoint. Comparisons of magnetic field data from IMP-3 with plasma data from the Vela 3 satellite show a correlation also justifying this assumption (Hundhausen, Bame and Ness, 1967). Finally, comparisons of plasma properties measured on Explorer 34 with those obtained with Mariner 5 have been performed, confirming the validity of this equivalence assumption, (Lazarus, Chao and Bridge, 1968).

The relationship observed between the magnitude of the magnetic field anomaly and the plasma parameter β_i is qualitatively consistent with the predictions of a theoretical treatment by Whang (1968a, 1968b). There, the effects of magnetization, gradient drift, and curvature drift currents are calculated for a guiding center plasma flowing past the moon which absorbs all particles whose trajectories intersect it. However, a large and variable effect is observed, and ascribed to the electron component of the plasma. It is possible to determine an average value of the ratio of electron to ion temperature from the discrepancy between theory a l observations.

Magnetic Field Observations - Explorer 35

The details of the instrument, telemetry system, spacecraft and orbit have already been fully described by Ness et al., (1968). For the present work, information from the period 27 July to 4 Oct. 1967 was used, during which time the moon and satellite were in the interplanetary medium for 45 days (Behannon, Fairfield and Ness, 1968). A plot of the variation of the magnitude of the magnetic field during several traversals of the satellite behind the moon is shown in Figure 1. From this it will be seen that observations of the anomalies $(\frac{\Delta B}{B})_k$, k = 1, 2, 3 could readily be made. The errors in this procedure will be discussed below when the results are presented.

In selecting orbits for measurement, periods of intense fluctuation in magnetic field were avoided, due to the difficulty of establishing representative mean levels. It has been shown (Burlaga, Ogilvie and Fairfield, 1969), that such periods tend to be associated with high β $(=nkT/{B^2/8\pi})$ in the plasma. This results in the present work in a concentration upon values of β less than about 0.7. It also means that the results tend to be less certain for the largest anomalies. Periods that are magnetically very quiet tend to be associated with small β values; such records are relatively easy to analyze accurately.

Plasma Observations - Explorer 34

The plasma parameters, to be compared with the magnetic field observations, were measured by the GSFC - University of Maryland experiment on Explorer 34, (Ogilvie, McIlwraith and Wilkerson, 1968). The magnetic field observations on Explorer 34 were conducted by Ness and Fairfield (Fairfield, 1968).

The principal plasma quantity of interest is β, the ratio of the kinetic pressure in the frame of reference moving with the average solar wind velocity to the magnetic pressure,

$$\beta = n_p k T_p / B^2 / 8\pi$$

The experiment separates protons from other species by the use of a velocity selector, so that the temperature used to calculate β is the average proton temperature, T_p. This is obtained from the differential measurements of ion counting rate as a function of velocity by fitting them to a theoretical convected maxwellian velocity distribution function. The velocity moments of this approximation are then computed using the equations

$$\langle V_n \rangle = \int_o^\infty V^n \frac{df}{dv}\, dv,$$

$$n_p = \langle V_o \rangle \ , \quad T_p = \frac{m}{k} \ \frac{\langle V_2 \rangle - \langle V_1 \rangle^2}{\langle V_o \rangle}$$

where $\langle V_n \rangle$ is the nth velocity moment. Hourly averages of these parameters are used in subsequent comparisons.

The principal uncertainty in this process comes from the fact that the plasma is anisotropic. This anisotropy cannot be observed by the present instrument, which has insufficient angular resolution to distinguish the excess of ions which approach it parallel to the direction of the magnetic field.

In comparing temperatures measured at different times, therefore, there is an unknown effect of anisotropy to be taken into account. This is particularly true when computing β since it is $\beta_{\perp}=n_p kT_{\perp}/\beta^2/8\pi$ which determines the magnitudes of the anomalies. On the average $T_{\parallel}/T_{\perp} \simeq 1.5$ (Hundhausen et al., 1968), so that the errors in β can amount at most to a factor of 1.5, but will normally be considerably less than this in magnitude. We shall therefore use β calculated using T_p for comparison with the calculations.

Other errors in the temperature have been minimized by rejecting from consideration time intervals when less than three non-zero values of counting rate were observed in the proton velocity spectra. This also ensures that the errors in determining the proton density, n_p, will be reduced to less than $\pm$ 20%.

Results

Ninety orbits of Explorer 35 were found when the moon, accompanied by the satellite, was in the interplanetary medium, and when Explorer 34 provided simultaneous interplanetary observations. Plots of the magnitude of B, similar in form to Figure 1, were used to measure $(\Delta B/B)_k$. The initial level was estimated by drawing a base line as shown, and values of ΔB scaled from the plots. Since periods of large magnetic field fluctuation were eliminated, this procedure was accurate to better than ± 10%.

The flow of plasma around the moon may be analyzed with respect to a coordinate system which moves with the moon. The origin is located at its center; the X axis is parallel to the velocity vector $\bar{U}_o$. The acute angle α between the velocity vector $\bar{U}_o$ and the magnetic field $\bar{B}$ is an important parameter in determining the flow geometry

$$\text{Cos } \alpha = \bar{U}_o \cdot \bar{B} / |U_o||B|$$

We have assumed the plasma flow to be radially outwards from the sun, $\bar{U} = -U \hat{x}_{SE}$, so we can write

$$\text{Cos } \alpha = \text{Cos } \theta \text{ Cos } \varphi,$$

and we have neglected the 3^o-5^o aberation of the solar wind flow due to heliocentric motion of the Earth-Moon system. Here θ and φ are the lattitude and longitude angles of $\bar{B}$ in a solar ecliptic system. The angle α was calculated from the hourly average values of θ and φ tabulated from the observations by Explorer 34. The combined errors in the determination due to variations in direction of the plasma flow, and to variation in direction of the magnetic field were of order $\pm 15^o$.

The data was organized into three classes each for the anomalies $(\Delta B/_B)_{1,3}$ and $(\Delta B/_B)_2$ respectively. Class I contained observations made when $0 \leq \alpha \leq 29^o$, Class II observations made when $30^o \leq \alpha \leq 59^o$ and Class III observations made when $60^o \leq \alpha \leq 90^o$. In this way the dependence of $(\Delta B/_B)_k$ upon α and β could be exhibited independently.

The theory of Whang (1968a,b) considers explicitly the motion of ions, electrons only entering his treatment implicitly in order to render the gas electrically neutral. He finds the magnitude of the anomaly $(\Delta B/_B)_2$ to be a function of β, $T_{\parallel}/T_{\perp}$, S, the angle α, and R the distance of the satellite from the center of the moon when it crosses the X axis. Here $T_{\parallel}$ and $T_{\perp}$ are the ion temperatures parallel and perpendicular to the direction of the magnetic field. We are unable, as discussed above, to resolve this anisotropy. S, the speed ratio, is defined as $U_o/(2k\ T_{\parallel}/m_i)^{\frac{1}{2}}$, and for typical plasma observed in the solar wind, S is approximately 10 or less. The magnitude of the anomalies is found to be much less sensitive to variations in S than to variations in α and β. The values of R for which we have data range from 1.5 to 4.3; since the umbra persists to distances of about 5-10 lunar radii, the maximum magnitude of the anomaly $(\Delta B/_B)_2$ would not be expected to vary appreciably for distances between 1.5 and 4.3 lunar radii (R_m). The theoretical variation of $(\Delta B/_B)_2$ for different values of α and S show small effects in the distance range 1.5 - 4.3 R_m.

Thus we might expect to be able to observe systematic variations in $(\Delta B/_B)_2$ as a function of the parameters β and α, with the first of these being the more important. There is at present no theoretical treatment for the anomaly $(\Delta B/_B)_{1,3}$, so observations of the penumbral anomaly will be presented in the same way as those of $(\Delta B/_B)_2$.

In Figure 2 we see a plot of $(\Delta B/_B)_2$ as a function of β with points from the three angular classes appropriately indicated. The observed magnitudes of the anomaly are of the same order as those predicted by the theory. Although there is a large spread in the magnitude for a given value of β, the result both of errors in the determinations of the quantities and of fluctuations during the measurement interval, it is clear that agreement with the dashed lines is as good as can be expected from the data. These dashed lines, referring to the upper abscissa scale, are plots of $(\Delta B/_B)_2$ as a function of β', derived from Whangs theory.

The total β for the plasma, which we identify with β' is

$\beta' = \sum_j n_j kT_j \,/\, B^2/8\pi$, where the sum is taken over the species of particles making up the plasma, whereas β is calculated from the parameters of the ions alone. Thus the difference between β' and β, a factor of 3, represents the contribution of the other species. Neglecting the presence of helium, which can only make a negligiable contribution, since it usually constitutes less than 5% by number, the other important species must be the electron component of the plasma. In this way we arrive at an average value of the ratio $(T_{\perp}e/_{T_{\perp}}i)$ of 2, in fair agreement with that obtained by direct measurement (Montgomery et. al., 1968).

Because of their high thermal speed relative to their bulk speed, the speed ratio for the electrons is very much less than for the solar wind ions. Thus the dependence of the wake characteristics upon the angle α should be very much weaker in fact than that predicted by

Whangs theory.

It will be seen from Figure 2 that the expected variation of $(\Delta B/_B)_2$ with α for fixed β does not even show up as a trend in the observations. The three dashed lines are calculated from Whangs theory for $\alpha=15^o$, 45^o, and 75^o, and the points identified as shown. This behavior is to be expected if the dominant agent in producing $(\Delta B/_B)_2$ is the electrons.

Figure 3 shows observed values of $(\Delta B/_B)_{1,3}$ plotted againts $(\Delta B/_B)_2$ for the same hour. We see that the two anomalies, umbral and penumbral, are approximately equal in size for the same β.

In these studies we have not considered the variable position of the satellite in the lunar wake relative to the plane of symmetry (Whang, 1968b), or the fact that the wake will in general not be cylindrically symmentrical because of this. We do not believe these to be important omissions at the present time.

Conclusions

From a quantitative study of magnetic field observations from 90 orbits of Explorer 35, and simultaneous plasma observations on Explorer 34, we have deduced that:

1). The lunar wake umbral and penumbral anomalies in magnetic field magnitude are approximately equal for the same value of β of the plasma.

2). The size of these anomalies is most strongly determined by the β of the plasma, being approximately linearly proportional to it, $(\Delta B/_B)_k = k\beta$

3). Our observations do not clearly show the influence of the angle α, the acute angle between magnetic field and flow direction, because,

4). The influence of the electron component is very important in determining the size of these anomalies. We find that $T_e \approx 2\ T_i$, in agreement with direct observations (Montgomery et al., 1968). This indirect method of estimating electron temperatures also agrees well with the indirect method of Burlaga (1968). The present work represents an approximation to an average value of T_{e/T_i} over a period of two months.

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FIGURES

Figure 1 Representative magnetic field data obtained in passages through the lunar wake in 1967. The corresponding β and $(\Delta B/_B)_i$ values are indicated.

Figure 2 The magnitude of the anomaly $(\Delta B/_B)_2$, the umbral anomaly, plotted as a function of β. Theoretical results, using Whangs theory, are plotted as a function of β', upper abscissa scale.

Figure 3 The magnitude of the anomaly $(\Delta B/_B)_{1,3}$, the penumbral anomaly, plotted as a function of $(\Delta B/_B)_2$, the umbral anomaly, for times when the two observations took place in the same hour.

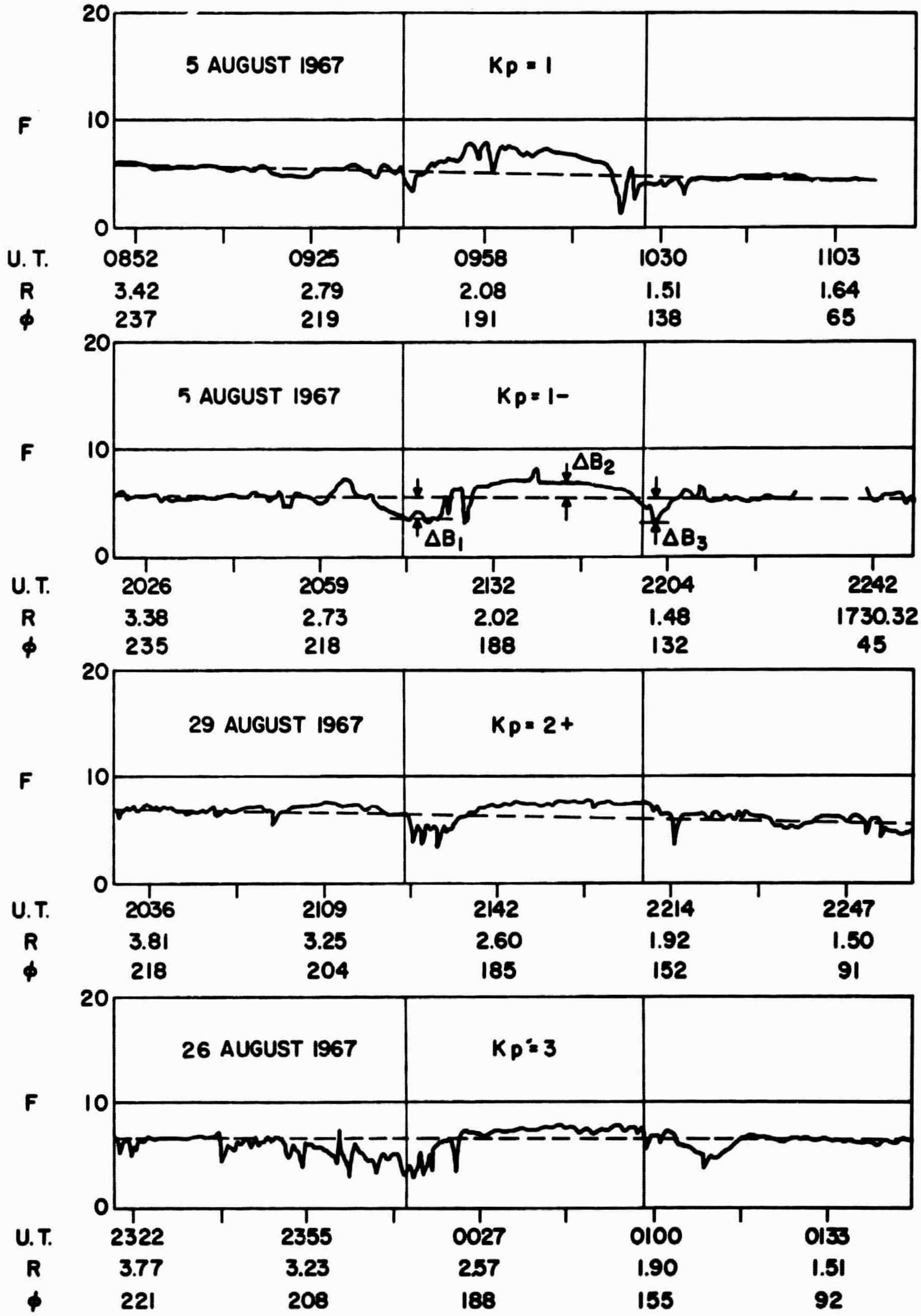
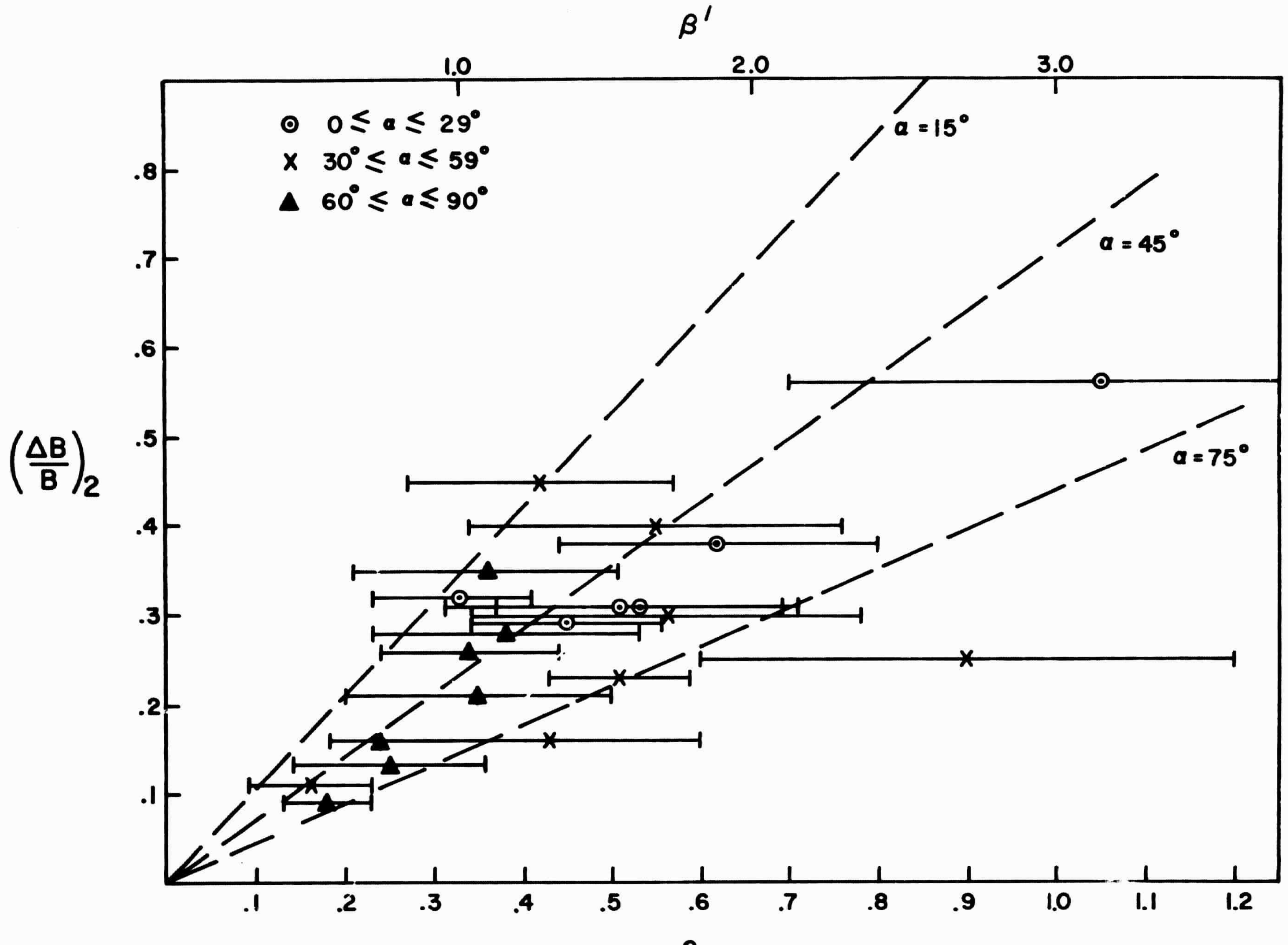
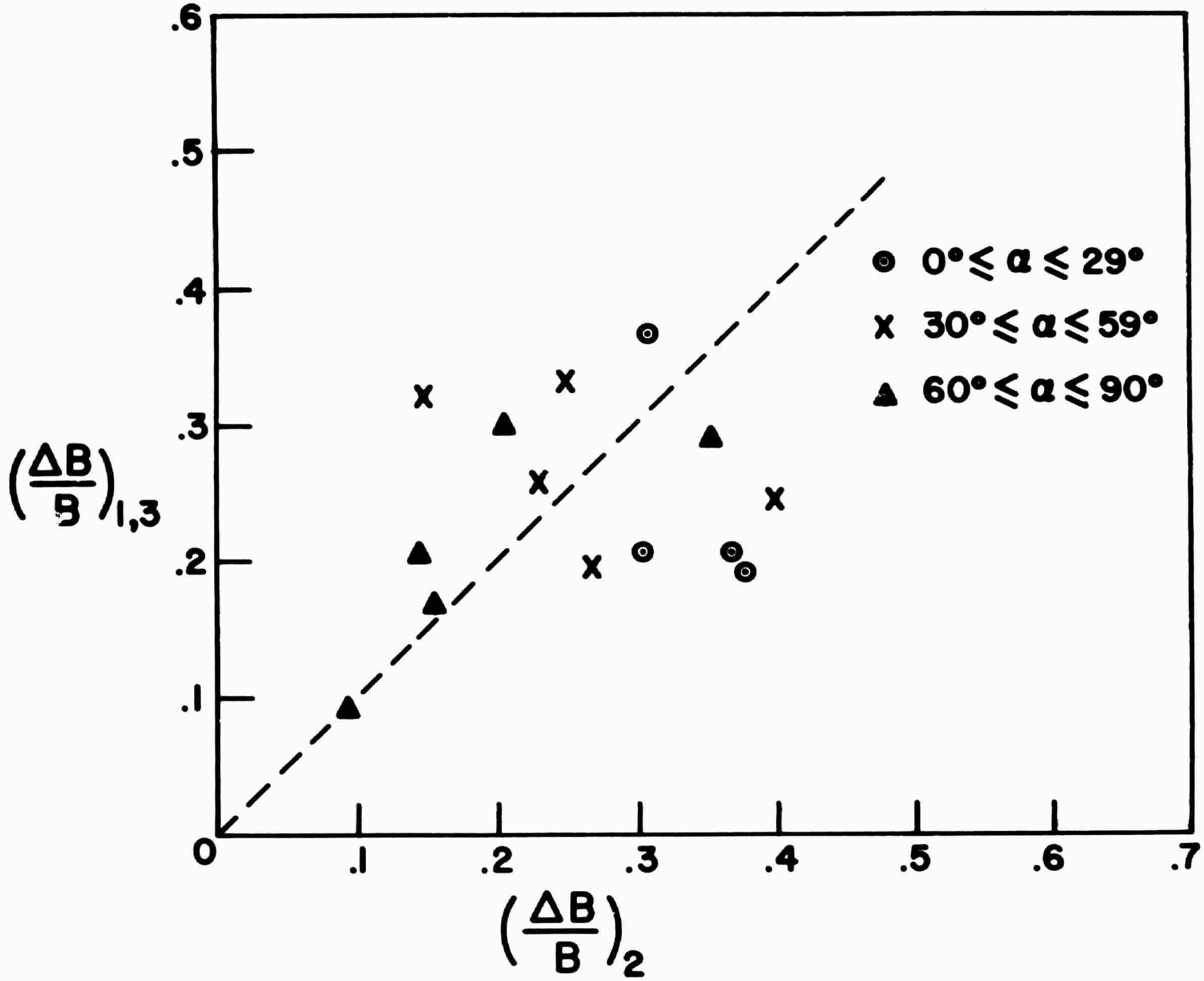

5 AUGUST 1967
Kp = 1
F
20
10
0
U. T. 0852 0925 0958 1030 1103
R 3.42 2.79 2.08 1.51 1.64
φ 237 219 191 138 65
5 AUGUST 1967
Kp = 1-
ΔB2
ΔB1
ΔB3
U. T. 2026 2059 2132 2204 2242
R 3.38 2.73 2.02 1.48 1730.32
φ 235 218 188 132 45
29 AUGUST 1967
Kp = 2+
U. T. 2036 2109 2142 2214 2247
R 3.81 3.25 2.60 1.92 1.50
φ 218 204 185 152 91
26 AUGUST 1967
Kp = 3
U. T. 2322 2355 0027 0100 0133
R 3.77 3.23 2.57 1.90 1.51
φ 221 208 188 155 92

Figure 1



β'
1.0
2.0
3.0
0 ≤ α ≤ 29°
30° ≤ α ≤ 59°
60° ≤ α ≤ 90°
α = 15°
α = 45°
α = 75°
(ΔB/B)₂
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
β

Figure 2



.6
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
.6
.7
$\left(\frac{\Delta B}{B}\right)_{1,3}$
$\left(\frac{\Delta B}{B}\right)_{2}$
0° ≤ α ≤ 29°
30° ≤ α ≤ 59°
60° ≤ α ≤ 90°

Figure 3