SUDDEN COMMENCEMENT ASSOCIATED DISCONTINUITIES IN THE INTERPLANETARY MAGNETIC FIELD OBSERVED BY IMP 3

by

Harold E. Taylor*

Goddard Space Flight Center

National Aeronautics and Space Administration

Greenbelt, Maryland 20771

June, 1968

*NAS/NRC Resident Research Associate

Extraterrestrial Physics Branch Preprint Series

ABSTRACT

The magnetic field measurements made by the magnetic field experiment on the IMP 3 (Explorer 28) spacecraft have been examined at the time of geomagnetic s.s.c. events. 36 such events occurred while IMP-3 was in the interplanetary medium during 1965, 66 and 67 and have been analysed. Of these events 8 must have been tangential discontinuities, 2 are either tangential discontinuities or rotational discontinuities and 26 are possible shock waves. (2 of these 26 events have been shown by other authors to be shocks.) These 26 possible shocks have similar magnetic signatures: an increase of 20% or more in the magnetic field magnitude and a relatively small (always less than 90°) change in direction. The larger s.s.c. events were more likely to be caused by possible shocks while the smaller events were often associated with tangential discontinuities. The orientation of the discontinuity surfaces of the 26 possible shocks shows a preference to be aligned somewhere between a direction perpendicular to the sun-earth line and a direction tangent to the local spiral angle of the magnetic field. It was possible to associate solar flares with 14 of the 26 possible shock events. Of these 14 a reliable orientation was deduced for 8 events. By considering the orientation of these 8 events in relation to the position of the parent flares on the solar disk it is suggested that a typical shock front propagating out from the sun has a radius of curvature less than but of the order of 1 a.u.

INTRODUCTION

A number of authors have considered discontinuities in the solar wind associated with geomagnetic disturbances (Gold, 1955 ; Sonett et al., 1964 ; Hirshberg, 1965 ; Colburn and Sonett 1966 ; Gosling et al., 1967a, 1967b, 1968 ; Van Allen and Ness, 1967 ; Ogilvie et al., 1968). It is agreed that geomagnetic sudden commencement (s.s.c.) events are caused by a discontinuous increase in the plasma pressure on the magnetosphere. Satellite studies of these magnetohydrodynamic discontinuities have revealed that some are shock waves (Sonett et al., 1964 ; Gosling et al., 1967a; 1968 .) and some are tangential discontinuities (Gosling et al., 1967b).

These s.s.c.-associated discontinuities are thought to be the boundary between plasma ejected from the sun in a solar flare and the quiet, pre-flare solar wind. The propagation of the flare plasma out from the sun has been considered by various authors (Gold, 1959 ; Parker, 1963 ; Hirshberg, 1968) and various models have been suggested. The measurement of the magnetic field associated with this type of s.s.c. related event gives information about the local orientation of the discontinuities and thus can help to determine the large scale structure of these features. In this paper a number of sudden commencement-associated events have been studied with the magnetometer on the IMP 3 (Explorer 28) spacecraft. Two findings of this study can be summarized as follows.

1. Both shock waves and tangential discontinuities are capable of causing an s.s.c. event. The larger events are more likely caused by shock waves.
2. When it passes the earth a typical shock front caused by the flare-associated outburst appears to have a radius of curvature of less than, but of the order of, 1 a.u.

The measurements from 36 different s.s.c.-associated events which occurred while the IMP 3 spacecraft was in the interplanetary medium between June, 1965 and January, 1967 will be presented and discussed.

THE EXPERIMENT

The IMP 3 spacecraft was launched on May 29, 1965 into a highly eliptical orbit. Initially its apogee was 41.9 Re (Re=6378 km) and decreased to 36.3 Re during the spacecraft's lifetime of approximately two years. The perigee varied from only slightly more than 1 Re (a few hundred km altitude) at launch to as high as 6.5 Re late in its lifetime. The initial sun-earth-apogee angle was 121 degrees. The orbital period was initially 140.6 hours or 5.86 days and remained within 1.5 hours of this value during the lifetime of the satellite.

During the months of June through January of each year the spacecraft spent at least some time in the interplanetary medium, upstream from the bow shock. During the months of February, March, April and May IMP 3 never crossed the bow shock and therefore did not sample the interplanetary medium directly.

The magnetic field experiment on IMP 3 was identical to that used on IMPs 1 and 2. It consisted of two monoaxial spinning fluxgate magnetometers. The instrument has been described previously in detail by Ness et al. (1964) and by Fairfield and Ness (1967).

Unfortunately one of the magnetometers failed during the launch sequence boom erection so that measurements are obtained only half as frequently, that is every 41 seconds instead of every 20.5 seconds as on the earlier IMP 1 and 2 spacecraft.

There is a gap of 123 seconds after every 6 data points when the rubidium magnetometer is read out. Each measurement is made in a period of 4.8 seconds by making a least squares fit of the spin modulated output of the detector to a sine wave. The root mean square (RMS) deviation of this fit is used as an indication of the goodness of the fit. Detailed analyses of the possible errors in this scheme have been published by Fredricks et al. (1967) and Fairfield and Ness (1967).

Direct comparisons with other spacecraft (Pioneer 6 and 7 and Explorer 33) throughout the IMP 3 lifetime give excellent agreement. Such comparisons indicate that the absolute error of the instrument is probably 1γ (γ=10^{-5} gauss) or less. The relative accuracy, important in this study of discontinuous changes in the field, is even better, especially over the short time periods of interest in this work (of the order of minutes).

ANALYSIS

Events were chosen for study by consulting the preliminary report of sudden commencements published quarterly in the *Journal of Geophysical Research* prior to 1966 and subsequently in Solar-Geophysical Data* at the same 3 month intervals. Geomagnetic impulses identified by 10 or more magnetic observatories as s.s.c. events ("Sudden commencements followed by a magnetic storm or a period of storminess") were selected for months of June, 1965 to January, 1966 and June, 1966 to January, 1967. Then the IMP 3 magnetometer records were examined near the time of each reported s.s.c. For the events which occurred while IMP 3 was in the interplanetary medium the associated discontinuity in the magnetic field was selected and a computer program used to calculate the average field on each side of the discontinuity. Periods of between 5 and 15 minutes were chosen over which to average, the interval length being chosen so that the field was reasonably steady throughout. This meant that the averages consisted of between 6 and 20 individual measurements.

In addition to the field averages B^1 and B^2 and the associated RMS deviations, various quantities were calculated including:

the vector change, $\vec{\Delta B} = \vec{B}^1 - \vec{B}^2$

the shock normal, $\hat{n} = (\vec{B}^1 \times \vec{B}^2) \times \vec{\Delta B} \; / \; |(\vec{B}^1 \times \vec{B}^2) \times \vec{\Delta B}|$

the normal component, $B_n = \vec{B}^1 \cdot \hat{n} = \vec{B}^2 \cdot \hat{n}$

the parallel components, $\vec{B}_t^1 = \vec{B}^1 - \hat{n} B_n$, and $\vec{B}_t^2 = \vec{B}^2 - \hat{n} B_n$; etc.

* Published monthly by the Environmental Science Services Administration of the U.S. Department of Commerce.

From these quantities it was determined whether or not the discontinuity might be a shock. The conditions for a fast shock (discussed by Colburn and Sonett, 1966) are the following: $B^2 > B^1$, $\rho^2 > \rho^1$, $T^2 > T^1$ and $\vec{B}_t^1 \cdot \vec{B}_t^2 \geq 0$. Because plasma data are not available on IMP 3 (the plasma experiment failed) the conditions on density, ρ, and temperature, T, cannot be checked, but the requirement on the fields was checked. The events with no clear increase in the field magnitude, B, or with $\vec{B}_t^1 \cdot B_t^2 < 0$ were identified as tangential discontinuities (or if $B^1 = B^2$ possibly a rotational discontinuity) and the other events as possible shocks.

The calculation of $\vec{\Delta B}$ and of $\hat{n}$ are used to give information on the orientation of the surface of the discontinuity. Ideally $\hat{n}$ is all that is needed, but if the discontinuity is not a shock, then $\hat{n}$ as calculated does not give the normal direction. In all cases, however, $\vec{\Delta B}$ must lie in the plane of the discontinuity since the flux across the surface of the discontinuity is conserved. In addition the calculation of $\hat{n}$ becomes inaccurate when $\vec{B}^1$ is nearly parallel to $\vec{B}^2$. Also the calculation of $\hat{n}$ is dependent on the instrumental zero levels while $\vec{\Delta B}$ is not. For these reasons it seemed useful to use the vector $\vec{\Delta B}$ as an indication of orientation of the discontinuity surface rather than the unit normal $\hat{n}$. If the normal to the surface is assumed to lie in the ecliptic plane then a knowledge of $\vec{\Delta B}$ is sufficient to determine the orientation uniquely.

Another advantage of using $\vec{\Delta B}$ is that the RMS error in $\vec{\Delta B}$ is easily calculated. It can be shown to be given by the Pythagorean sum of the RMS errors in the individual components of $\vec{B^1}$ and $\vec{B^2}$. Thus it is a simple matter to estimate the accuracy of the measurement of $\vec{\Delta B}$ by considering the quantity $\sigma / \Delta B$, where σ is this RMS error in $\vec{\Delta B}$. If this quantity is greater than 1 then the measurement is rather poor and the uncertainty in the direction of $\vec{\Delta B}$ is large. On the other hand, if this quantity is less than 0.5 then the directional error in $\vec{\Delta B}$ is statistically expected to be less than $\pm 30^\circ$.

Another characteristic of the discontinuity, its velocity in the vicinity of the earth, can be calculated from the observations by dividing the perpendicular distance between the discontinuity surface and the earth by the delay time between the recording of the event at the spacecraft and its record at the earth. Unfortunately because of the different propagation characteristics of the magnetosheath and the magnetosphere the average velocity obtained in this way is not necessarily representative of the surface in the interplanetary medium. Alternatively this uncertainty may be viewed as an uncertainty in the time at which the surface passes the earth. A recent estimate of the propagation time within the magnetosphere yields values of the order of 90 seconds (Sugiura, 1965). The propagation time through the magnetosheath depends on the direction of arrival and is estimated to be of the same order as or slightly greater than this time of

90 seconds. Thus there is an uncertainty of 3 minutes or more in the time of arrival of the surface at the earth. For delay times that are long compared to 3 minutes this uncertainty would be unimportant, but for short delay times it introduces large inaccuracies. Because of this velocities were only calculated for those shocks with delay times greater than 6 minutes.

Finally, the relation of the s.s.c. events to solar flares was investigated. All flares of importance 1+ or greater occurring between 10 and 120 hours before the s.s.c. were considered and the largest disturbance (or the flare with associated Type II radio emission) was picked as the most likely parent flare. If there were several flares of comparable magnitude or no flares greater than importance 1 then no identification was made.

THE OBSERVATIONS

In all there were 52 s.s.c. events identified by 10 or more magnetic observatories during the months of June, 1965 to January, 1966 and June, 1966 to January, 1967. Of these, 36 occurred while IMP 3 was in the interplanetary medium. The magnetometer observations from IMP 3 for these 36 events are summarized in Table 1.

The first column of this table is simply a sequential numbering of the events. They are listed in chronological order. The next three columns show the date, universal time, and the number of magnetic observing stations reporting the event, respectively. The number of stations reporting the event is used as a statistical estimate of the significance of the event. Its usefulness is illustrated by the observation that each of the 9 events reported by more than 50 stations was found to be a possible shock, while of the 9 events reported by less than 20 stations only 4 were possible shocks.

The rest of the columns in the table relate to the IMP 3 measurements. The column headed ORB is the IMP 3 orbit number. When two or more events occurred during the same orbit the events are distinguished by a letter (e.g., the two events on orbit 7 are labelled 7a and 7b). These orbit number identifications will be used on subsequent figures for identification purposes. The column headed UT±Δt is the time of the passage of the discontinuity at IMP 3 along with the uncertainty in this time. In all but one case the uncertainty is just half the time between successive measurements -- that is, 20.5 seconds (about 0.4 minutes) if the jump occurred between 2 successive points 41 seconds apart or 61.5 seconds (about 1.0 minutes) when the jump occurred across the gap where the rubidium magnetometer is read out. In the one unusual case (event 9) the field underwent first a decrease and then 5 minutes later a sharp increase and it was unclear just what time should be selected, hence the large Δt.

The next three columns give the cartesian components of the spacecraft position vector in geocentric solar ecliptic coordinates. Xse is toward the sun, Zse toward the north ecliptic pole and Yse in the dusk meridian forming a right-handed system. The next 6 columns list the average magnetic field components along with the RMS deviation of the average. $\vec{B}^1$ is the field before the discontinuity and $\vec{B}^2$ is after. Again the coordinates are solar ecliptic. The next three columns give the components of the vector change in the field, $\vec{\Delta B}$. The column labelled $\sigma/\Delta B$ is the ratio of the RMS deviation of the vector change to the magnitude of the vector change and measures the reliability of the measurement. As mentioned in the preceding section, if this number is 0.5 or less the measurement is good. The last column, labelled S#, is a sequential numbering of the possible shocks. The events for which $B^2 \leq B^1$ or $\vec{B}_t^1 \cdot \vec{B}_t^2 < 0$ have no entry in this column. Thus it is seen that of the 36 s.s.c. events which occurred while IMP-3 was in the interplanetary medium, 26 of them were possible shocks.

Examples of the two types of events are shown in Figure 1. Figure 1a is event number 1 in Table 1. It occurred on June 8, 1965 and is a possible shock. The discontinuous increase in the field magnitude and the relatively small change in field direction are characteristic. The event shown in Figure 1b is a tangential discontinuity. It is characterized by a large change in the field direction and thus cannot be a shock. This is event 3 in the table and occurred July 6, 1965.

In Figures 2 and 3 information from all 26 possible shock events has been superimposed for the purpose of comparison. Figure 2 shows the 26 possible shock events projected onto the ecliptic plane (by rotation about the earth-sun line). The line plotted is the projection of $\vec{\Delta B}$ on the ecliptic and represents the orientation of the event if it is assumed that the discontinuity surface is normal to the ecliptic or equivalently that the surface normal lies in the ecliptic. The error in each measurement may be obtained from the $\sigma/\Delta B$ column of Table 1. The arrow plotted for each event is the projection of the unit normal on the ecliptic. This normal is calculated assuming that the discontinuity is a shock. This figure shows that the orientation of the discontinuity surfaces is not in general perpendicular to the sun-earth line as is often assumed.

Figure 3 shows that in an average sense there is some order to the orientation of the discontinuities. By plotting the direction of the change vectors in this way it is evident that there is a preferred orientation for these vectors. There is apparently no preference in the θ direction, but in the azimuthal angle φ, the events scatter about an angle of about 115° (or 295°). It is probably significant that this direction is intermediate between the perpendicular to the sun-earth line (90° or 270°) and the magnetic field spiral angle (135° or 315°). The dashed lines are the average angles for the outward and inward directed groups of changes.

Thus statistically there is evidence for a preferred orientation of the surfaces of the discontinuities responsible for s.s.c. events on the ground. Further information can be obtained by examining the events for which parent flares could be tentatively selected.

The 26 possible shock events together with information about the identification of the probable parent flare are listed in Table 2. The first two columns are the date and time of the event on the ground as in Table 1 and the third column gives the IMP 3 orbit number. The next 5 columns give for the flare: the date, the time of onset, importance, latitude and longitude, respectively. Note that for the first event there was a type II radio burst but no flare observed. The next two columns give the delay time between the occurrance of the flare and the onset of the s.s.c. at earth and the average sun-earth transit velocity implied by this delay. The last columns gives the estimate of the near earth velocity calculated from the IMP 3 measurements for which the time delay was longer than 6 minutes. There is an estimated uncertainty of 50% associated with this last velocity.

This table shows that flares were identified for 14 of the 26 possible shock events. It is interesting that the identification of flares for only about half of the 26 possible shock events is statistically similar to the findings of Kuleshova (1961) who found geomagnetic activity associated with 50% of the class three flares which occurred over a three year period. Of the remaining 12 events for which no flare could be found 9 had no flares greater than importance 1 in the period between 10 and 120 hours before the s.s.c. while the other 3 had multiple flares of comparable importance. Examination of the IMP 3 measurements related to the 14 flare-associated discontinuities showed that for 6 of these events the RMS deviations were less than 65% of the magnitude of $\vec{\Delta B}$. Two others were included because plasma data have already been published for these events (January 20, 1966 - Gosling et al., 1968; and July 8, 1966 - Lazarus and Binsack, 1968). For the January 20 event $\sigma/\Delta B$ was 0.8 and for the July 8 event additional data from the Explorer 33 experiment (Ness and Taylor, 1968) was used to supplement the IMP 3 measurements. Thus reasonable orientation data is available for a total of 8 flare-associated events. These are plotted in Figure 4 in an ecliptic plane view of the earth-sun system. The discontinuity vector, $\vec{\Delta B}$ projected on the ecliptic is plotted at the heliocentric longitude of the earth at the time of the flare. The longitudes are specified as seen from the earth. For example the flare associated with the s.s.c. of July 15, 1966 during orbit 71 occurred at 90° W on the solar disk and thus is plotted at 90° W in the figure. This method of plotting the events strongly suggests that for the events occurring west of the central meridian on the sun the φ angle of the discontinuity surface is less than 90° while those occurring East of the central meridian have a φ angle greater than 90°. This is in agreement with the work of Hirshberg (1968) and is also predicted by the qualitative picture of the plasma outburst from a flare presented by Gold (1959).

A final observation can be made about the velocity of the shock in the vicinity of the earth relative to the average velocity of propagation between the sun and the earth. Although it was possible to determine the near earth velocity with reasonable accuracy in only 2 of the 14 flare-associated events, both cases indicate that the near earth velocity is less than the average sun to earth velocity in agreement with the findings of Gosling et al. (1968) and of Ness and Taylor (1968).

DISCUSSION

The identification of the events as to the type of discontinuity is not unambiguous from the magnetic field data alone. It is possible to rule out shocks in cases where the directional change is too large. It is also possible to rule out rotational discontinuities whenever the magnitude of the field changes. However, tangential discontinuities overlap both shocks and rotational discontinuities in their possible magnetic signatures and thus cannot be ruled out without plasma data. In the 36 events studied in the work reported here 10 were clearly not shocks. Of these 10, two might possibly have been rotational discontinuities but the rest must have been tangential discontinuities because the magnitude of the field changed by more than 20%. Among the 26 possible shocks were 2 events for which plasma data have been published (January 29, 1966 - Gosling et al., 1968 and July 8, 1966 - Lazarus and Binsack, 1968). These two events were clearly shocks and thus it does not seem unreasonable to assume that many of the remaining 24 possible shock events were indeed shocks. As a rough estimate, perhaps half of the 36 events studied were shocks and the other half tangential discontinuities.

Of the 26 events labelled as possible shocks a probable flare can be associated with only 14 of them; others were ambiguous. The events which were related to their parent flares showed orientations in good agreement with the findings of

Hirshberg (1968). A simplified picture of her resulting large scale structure for the shock is included in Figure 4 as the dashed line. This line is an arc of a circle of radius 0.75 a.u. and centered on the 0° line 0.5 a.u. from the sun. It was drawn as an aid in visualizing the large scale structure of the interplanetary shock.

It seems clear that the measurements imply that the typical shock front has a radius of curvature less than, but of the order of, 1 a.u. Such a picture seems to be intermediate between Parker's (1963) spherical blast wave model and Gold's (1959) magnetic tongue model. It is not really inconsistent with either.

A close look at figure 4 reveals two events which are not consistent with the shock surface drawn. These two events can be understood if one is viewed as an example of Gold's model while the other is an example of Parker's. Orbit 101a shows a discontinuity vector with a large component in the sunward direction. If this discontinuity were the result of a magnetic tongue reaching out from the central meridian, perhaps deflected slightly along the spiral angle, then the orientation measured would be expected. Orbit 101b is also at variance with the shock front drawn because it has an azimuthal angle of slightly more than 90° where it should be less. It is, however, not greatly different from 90° and thus might be interpreted as an example of a spherical blast wave. Of course for flares near the central meridian the three pictures (Gold's, Parker's and Hirshberg's) all predict the same orientation.

Because the events on the Eastern limb of the sun seem to show a slightly larger average inclination while apart from orbit 101a those on the Western limb show slightly less inclination than the shock drawn, there seem to be a suggestion that the best center of symmetry might be to the west of the central meridian. This shift would be slight ($\sim 10^\circ$) and the data cannot be said to be conclusive. Hirshberg's study seemed to show a similar skewness.

Another conclusion with marginal support in the data is related to the relative orientation of the shock and tangential discontinuity events. Specifically, the shock events might be expected to scatter about an orientation of 90° while the tangential discontinuities might be found to scatter about the spiral angle direction or about 135°. Then with roughly equal numbers of each type with similar scatter about their respective means, the resulting distribution would be very much like that shown in Figure 3. The average φ of the change vector would be between 90° and 135° (or 270° and 315°) and few or no points would lie in the ranges 0° - 45° and 180° - 225° precisely as the figure shows. Clearly this is highly speculative but it does seem to be a plausable explanation of the data.

CONCLUSIONS

In this study 36 sudden commencement events which occurred while IMP 3 was in the interplanetary medium have been examined. It has been found that there are two distinct types of magnetohydrodynamic discontinuity associated with these events. Some are tangential discontinuities while others are shock waves. It is suggested that among the s.s.c. events reported by more than 10 stations both types may be found. The events identified by a large number of stations are more likely to be shocks than those reported by relatively few stations.

The possible shock events are characterized by a discontinuous increase in the magnetic field magnitude (20% or more) accompanied by a small change in the field direction (always less than 90°). The events cannot positively be identified as shocks without information about the density and temperature of the plasma. Some events can, by elimination, be positively identified as tangential discontinuities. They are characterized by a relatively large directional change and a significant change in the field magnitude.

When all the possible shock events are taken together a preferred azimuthal orientation is found between 90° and 135° (or 270° and 315°). When the 8 reliable measurements of events for which the parent flare is identified are plotted as a function of heliocentric longitude it is apparent that a shock front with a radius of curvature of the order of, but less than

1 a.u. is suggested in agreement with the findings of Hirshberg (1968). There are indications that some events may be of Parker's blast wave type while others may be like Gold's magnetic tongue model, but apparently the bulk of the events are intermediate between these two models.

Although useful information can be obtained from the magnetic field data alone it is clear that the complete picture cannot be obtained without complete plasma data. In addition, it would be useful to have simultaneous and independent data from other spacecraft in cis-lunar space. An ideal opportunity for such a study exists during 1967 and 1968 when the three spacecraft Explorers 33, 34 and 35 are all operating and much of the time they are making simultaneous measurements of both the magnetic field and the plasma at three separate points in space. Studies of interplanetary discontinuities using simultaneous data from all three spacecraft should provide definitive information on these interesting events.

ACKNOWLEDGEMENT

I am deeply indebted to Dr. N. F. Ness for encouraging me to work with his experimental data from IMP 3. I enjoyed informative discussions with Drs. J. T. Gosling and A. J. Hundhausen at Los Alamos Scientific Laboratories and with Dr. L. F. Burlaga here at Goddard. I would also like to acknowledge the support of the National Academy of Sciences through whom my research position was arranged.

REFERENCES

Colburn, D.S. and C.P. Sonett, "Discontinuities in the Solar Wind" Space Sci. Rev., 5, 439 - 596, 1966.

Fairfield, D.H., and N.F. Ness "Magnetic Field Measurements with the IMP 2 Satellite", J. Geophys. Res., 72, 2379 - 2402, 1967.

Fredricks, R.W., E.W. Greenstadt and C.P. Sonett, "Magnetodynamically Induced Ambiguity in the Data from Tilted Spinning Fluxgate Magnetometers: Possible Application to IMP-1," J. Geophys. Res., 72, 367 - 382, 1967.

Gold, T., "Discussion of Shock Waves and Rarefired Gases" in Gas Dynamics of Cosmic Clouds, p. 193 (North Holland Publishing Co., Amsterdam, 1955.)

Gold, Thomas, "Plasma and Magnetic Fields in the Solar System" J. Geophys. Res., 64, 1665 - 1674, 1959.

Gosling, J.T., J.R. Asbridge, S. J. Bame, A.J. Hundhausen and I.B. Strong, "Measurements of the Interplanetary Solar Wind during the Large Geomagnetic Storm of April 17 - 18, 1965," J. Geophys. Res., 72, 1813 - 1821, 1967a.

Gosling, J.T., J.R. Asbridge, S.J. Bame, A.J. Hundhausen and I.B. Strong, "Discontinuities in the Solar Wind Associated with Sudden Geomagnetic Impulses and Storm Commencements," J. Geophys. Res., 72, 3357 - 3363, 1967b.

Gosling, J.T., J.R. Asbridge, S.J. Bame, A.J. Hundhausen and I.B. Strong, "Satellite Observations of Interplanetary Shock Waves," J. Geophys. Res., 73, 43 - 50, 1968.

Hirshberg, Joan "The Relationship Between Solar Wind Velocities and Surface Magnetic Disturbances During Sudden Commencement Storms," J. Geophys. Res., 70, 4159 - 4163, 1965.

Hirshberg, Joan "The Transport of Solar Flare Plasma From the Sun to the Earth," Planet. Space Sci., 16, 309 - 319, 1968.

Kuleshova, V.P. "The Connection Between Class 3 and 3 Chromospheric Flares and Geomagnetic Disturbances," Geomagnetism & Aeronomy, 1, 806 - 808, 1961.

Lazarus, A. J. and J. H. Binsack, "Observations of the Interplanetary Plasma" (Associated with the July 7, 1966 Flare) Annals of the IQSY

Ness, N.F., C.S. Searce, and J.B. Seek, "Initial Results of the IMP 1 Magnetic Field Experiment," J. Geophys. Res., 69, 3531 - 3570, 1964.

Ness, N.F., and H.E. Taylor, "Observations of the Interplanetary Magnetic Field July 4 - 12, 1966," Annals of the IQSY

Ogilvie, K.W., L.F. Burlaga and T.D. Wilkerson, "Plasma Observations with Explorer 34," Submitted to J. Geophys. Res., June, 1968.

Parker, E. N., Interplanetary Dynamical Processes, Interscience Publishers, New York, 1963.

Sonett, C.P., D.S. Colburn, L. Davis, Jr., E.J. Smith and P.J. Coleman, Jr., "Evidence for a Collision-Free Magnetohydrodynamic Shock in Interplanetary Space," Phys. Rev. Letters, 13, 153 - 156, 1964.

Sugiura, Masahisa, "Propagation of Hydromagnetic Waves in the Magnetosphere," Radio Sci. J. Res. NBS Part D, 69D, 1133 - 1147, 1965.

Van Allen, J.A. and N.F. Ness, "Observed Particle Effects of an Interplanetary Shock Wave On July 8, 1966," J. Geophys. Res., 72, 935 - 942, 1967.

FIGURE CAPTIONS

Figure 1. The magnetometer measurements from IMP-3 while in the interplanetary medium along with ground magnetograms. The field magnitude scale is in gammas. Δ is a measure of the short period ($\lesssim$ 5 sec.) fluctuations in the field. θ is the latitude angle of the field (90° is toward the north ecliptic pole, 0° is in the ecliptic plane) and φ is the azimuth angle. (0° is toward the sun, 90° toward dusk etc.) The coordinates are geocentric solar ecliptic.

Figure 2. A plot of the orientation of the observed discontinuity surfaces relative to the earth and its magnetosphere. Each surface is labelled with the IMP-3 orbit number for identification purposes. All events actually occurred in the interplanetary medium although some are inside the average position of the bow shock.

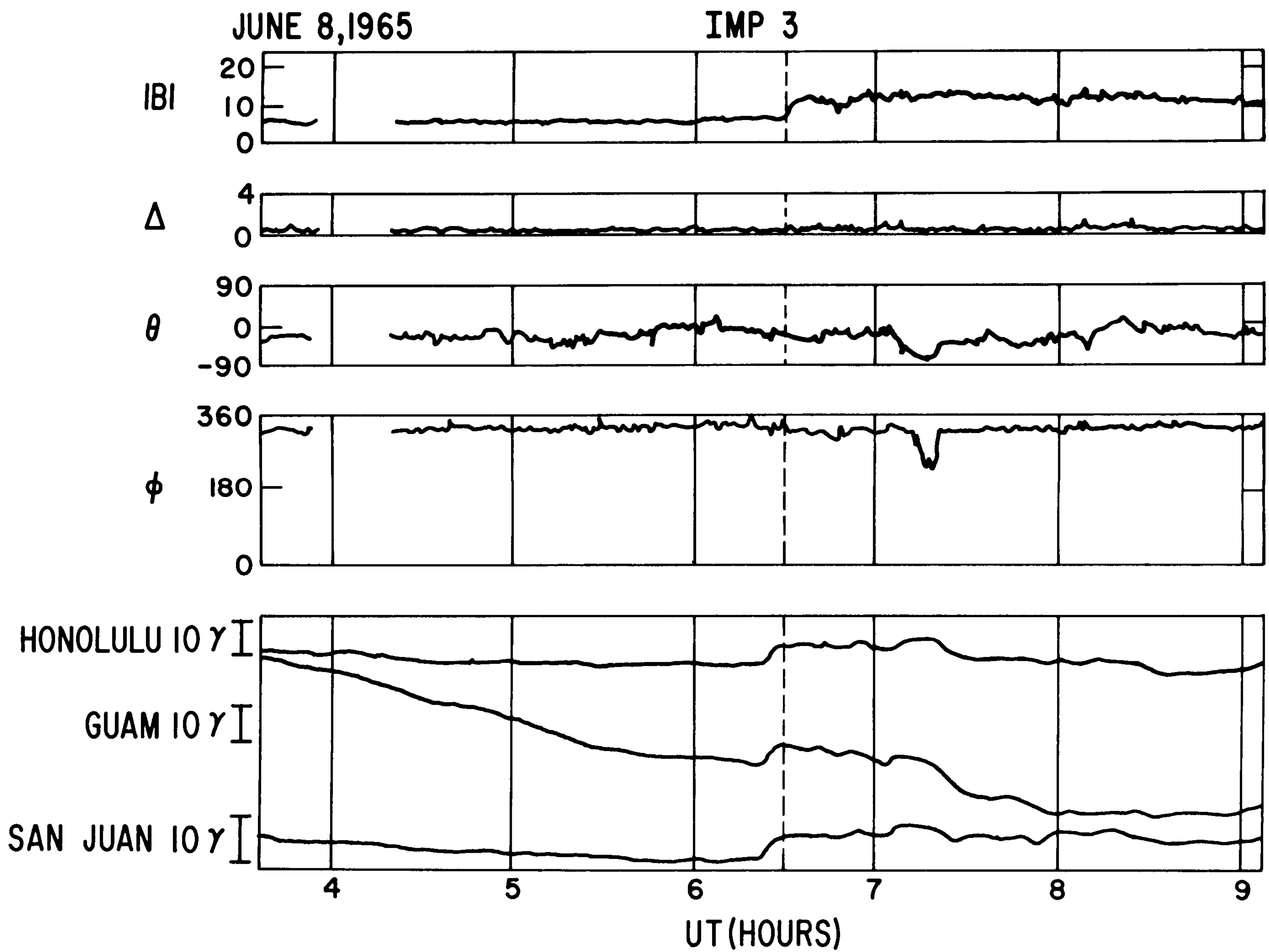
Figure 3. A scatter plot of the direction of $\vec{AB}$. As in Figure 1 θ is the latitude angle of the field and φ is the azimuth angle.

Figure 4. A plot of the orientation of 8 probable shock surfaces at the appropriate heliocentric longitude relative to the flare. The dashed line is an arc of a circle of radius 0.75 a.u. centered on the 0° line 0.5 a.u. from the sun.

	GROUND					IMP 3				$\vec{B}^1$			$\vec{B}^2$			$\vec{B}^1 - \vec{B}^2$				
	DATE	UT	# STN	ORB	DAY	UT ± Δt	X_{SE}	Y_{SE}	Z_{SE}	B_x	B_y	B_z	B_x	B_y	B_z	ΔB_x	ΔB_y	ΔB_z	σ/ΔB	S #
1	6/8/65	0623	19	2	159	0632.5±1.0	-17.5	32.9	-10.1	5.4±0.6	-3.5±1.1	-1.8±1.2	6.1±1.3	-7.9±0.8	-4.2±1.8	-0.7	4.4	2.4	0.6	1
2	6/17	2144	31	4	168	2150.4±0.4	- 7.0	34.4	-15.8	-0.5±0.6	-4.8±1.2	-5.4±1.2	-2.8±0.4	-4.9±0.4	-1.3±0.8	2.2	0.1	-4.1	0.4	
3	7/6	0451	42	7a	187	0447.7±1.0	1.8	39.1	-14.1	4.3±0.7	-5.7±3.1	-7.8±2.3	-3.3±0.6	5.2±0.6	-4.8±0.6	7.6	-10.9	-3.0	0.3	
4	7/7	2139	11	7b	188	2141.7±0.4	- 1.5	32.6	- 5.9	-0.1±0.7	3.4±1.4	-4.5±0.6	-1.0±0.8	-0.4±1.0	2.3±1.7	0.9	3.8	-6.7	0.4	
5	7/12	1602	41	8	193	1558.8±1.0	4.6	38.6	-11.8	-1.5±0.3	0.3±0.5	0.6±0.4	-1.7±0.4	0.1±0.6	1.6±0.6	0.2	0.2	-1.0	1.1	2
6	7/18	1553	52	9	199	1528.8±0.4	8.1	37.7	-11.1	1.0±0.6	-0.1±0.5	-0.5±0.5	1.0±0.9	-0.3±2.0	-2.6±1.1	0.0	0.2	2.1	1.2	3
7	7/27	0619	11	11	208	0623.9±1.0	9.8	11.7	-12.1	-3.4±0.4	-2.0±0.7	7.1±1.7	-6.0±0.4	3.5±1.5	4.5±0.6	2.7	-5.5	2.6	0.4	
8	8/18	1339	18	14	230	1348.6±0.4	10.6	16.8	0.8	-2.1±1.4	-1.6±1.8	-2.0±1.9	1.1±0.7	-7.0±0.7	4.5±2.7	-3.2	5.4	-6.4	0.5	
9	8/23	1519	33	15	235	1517.0±3.0	21.9	23.7	- 4.8	-2.5±0.6	0.2±0.7	8.8±0.2	0.3±0.7	-0.5±0.6	7.8±0.2	-2.8	0.7	1.0	0.2	
10	9/15	1452	35	19	258	1445.0±1.0	32.2	13.6	- 5.9	5.2±2.7	-2.5±0.8	-3.4±1.9	6.2±0.6	-2.1±1.8	-7.4±1.6	-1.0	-0.4	3.9	1.0	4
11	9/26	2110	26	21	269	2104.3±1.0	36.8	7.0	- 7.5	2.1±0.7	-1.8±1.0	-1.6±2.0	1.9±1.5	-2.5±2.6	-4.3±1.6	0.3	0.7	2.7	2.0	5
12	10/7	0900	52	23	280	0855.1±1.0	38.0	-2.2	13.6	5.6±0.5	-3.8±0.5	0.8±0.6	9.1±0.4	-7.7±1.8	-2.9±1.5	-4.0	3.9	3.8	0.4	6
13	11/4	0059	52	28	308	0056.6±0.4	18.8	-14.8	16.4	0.7±0.5	-2.3±0.4	1.2±0.6	0.0±1.2	-4.3±1.8	-0.4±4.0	0.7	2.0	1.6	1.8	7
14	11/12	1430	22	29	316	1421.0±0.4	30.6	-21.6	- 6.2	-1.7±0.5	0.4±1.5	5.8±0.7	-1.1±0.2	-1.4±1.8	9.5±0.6	-0.6	1.8	-3.7	0.6	8
15	12/4	0946	14	33	338	0952.0±1.0	16.4	-31.7	-14.2	-3.2±0.3	1.0±0.3	0.4±0.4	-3.2±0.4	2.4±1.1	1.2±0.6	0.0	-1.4	-0.7	0.9	9
16	12/18	0620	32	35	352	0621.6±1.0	12.0	-29.3	0.5	-0.6±0.5	1.7±0.6	-1.9±0.6	-1.4±0.5	4.1±1.0	-2.6±0.7	0.8	-2.4	0.8	0.6	10
17	1/7/66	1501	51	39	7	1507.9±1.0	- 6.1	-27.9	-16.6	0.5±0.6	-1.5±3.0	2.3±0.9	0.0±1.1	1.2±2.5	6.2±0.6	0.5	-2.7	-3.9	0.9	11
18	1/20	0204	57	41a	20	0205.7±0.4	-12.6	-33.2	-13.9	0.6±1.5	5.9±1.2	0.1±1.1	-0.9±2.4	11.7±3.1	-3.7±2.9	1.5	-5.8	3.8	0.8	12
19	1/21	0759	16	41b	21	0809.9±1.0	-10.8	-35.8	- 6.0	4.6±1.7	-3.9±1.8	2.6±3.1	6.5±3.7	-5.9±3.4	5.9±2.0	-1.8	2.0	-3.3	1.6	13
20	7/8	2102	40	70	189	2105.9±0.4	2.6	36.7	- 5.7	7.3±1.0	-10.0±0.8	-1.5±1.3	7.1±3.3	16.9±4.0	-1.0±6.9	0.2	6.9	-0.5	1.3	14
21	7/15	1500	43	71	196	1457.1±0.4	3.8	34.7	2.3	-0.7±0.3	-4.6±0.2	-2.2±0.2	-1.0±0.4	-4.9±0.7	-4.0±0.6	0.4	0.3	1.8	0.6	15
22	7/27	0603	46	73	208	0604.3±0.4	10.5	33.3	2.3	4.7±1.1	-3.9±1.2	-2.4±0.5	4.2±0.8	-5.7±3.7	-6.3±3.1	0.5	1.8	3.9	1.2	16
23	8/3	0951	20	74	215	0947.3±1.0	4.2	17.1	11.8	1.6±0.6	-2.4±1.0	-5.5±0.6	4.4±1.8	-5.3±1.3	6.9±1.4	-2.8	2.9	-12.4	0.2	
24	8/29	1315	54	79a	241	1309.3±0.4	27.2	18.0	-11.1	2.6±0.7	-1.1±1.0	1.7±0.7	2.7±1.2	-7.9±1.8	3.6±3.7	0.0	6.9	- 1.8	0.6	17
25	8/30	1112	53	79b	242	1057.2±0.4	29.6	21.6	- 3.6	3.5±1.4	0.6±1.5	-5.5±1.1	4.5±2.5	-1.0±2.8	-5.5±1.4	-1.0	1.6	0.0	2.5	18
26	9/3	2114	10	80	246	2116.5±0.4	25.1	12.3	-13.9	5.7±0.8	4.6±0.9	-12.0±0.6	9.1±1.5	12.7±1.1	-27.7±1.1	-3.4	-8.1	+15.7	0.2	19
27	9/14	1511	43	82a	257	1511.2±1.0	13.5	1.5	-15.6	-4.6±0.8	-1.2±0.8	- 0.2±1.3	7.3±1.1	-1.1±0.6	2.8±1.8	2.7	-0.1	- 3.0	0.7	20
28	9/19	0251	43	82b	262	0248.9±0.4	11.7	7.7	13.6	-0.2±2.1	2.2±3.0	- 4.5±1.6	3.2±6.2	-4.6±8.6	-2.0±4.2	-3.4	6.9	- 2.5	1.5	
29	9/23	0856	48	83	266	0853.5±1.0	34.0	9.5	3.5	0.0±1.1	-6.1±1.8	- 3.0±1.0	-0.5±6.6	-1.5±8.2	-1.0±7.0	0.5	-4.6	- 2.0	2.5	21
30	10/4	1324	12	85	277	1317.2±0.4	36.7	1.8	- 0.9	-2.1±1.0	-2.3±0.8	1.7±2.8	-5.0±0.9	-0.3±2.1	-6.2±0.8	2.9	-2.6	7.9	0.5	
31	10/15	0954	45	87	288	0947.9±0.4	33.6	- 6.4	- 7.9	-0.4±0.6	-3.9±0.8	-3.1±0.9	-1.6±2.2	-8.6±1.2	-4.5±2.3	1.3	4.7	1.4	0.7	22
32	11/25	1339	32	94	329	1334.4±1.0	22.2	-27.3	- 4.7	1.9±2.3	-4.6±1.4	-1.3±3.0	3.2±3.4	-6.5±5.2	1.2±4.6	-1.3	1.9	-2.5	2.6	23
33	12/13	0109	19	97	347	0111.8±0.4	12.6	-32.7	- 4.0	6.0±0.7	-1.9±1.0	5.1±1.3	2.3±5.3	-1.1±4.1	-2.7±7.0	3.6	-0.8	7.8	1.1	
34	1/6/67	0714	41	101a	6	0716.0±0.4	0.5	-35.6	5.3	2.1±0.7	-4.6±0.9	-3.2±0.8	4.3±0.6	-4.4±1.7	-7.4±0.6	-2.2	-0.2	4.2	0.5	24
35	1/7	0800	51	101b	7	0802.1±0.4	2.8	-27.1	13.4	-3.6±1.3	11.4±0.8	1.3±1.3	6.2±1.7	16.5±0.7	0.0±1.3	2.7	-5.1	1.3	0.5	25
36	1/13	1203	54	102	13	1205.4±1.0	1.0	-22.4	14.9	5.5±1.1	-6.9±1.2	-2.4±2.9	9.0±9.5	-15.1±5.1	-2.0±14.	-3.5	8.2	-0.3	2.0	26

TABLE 2

GROUND		ORB	PROBABLE FLARE							
DATE	UT		DATE	UT	IMP	LAT.	LONG.	DELAY	V	Vearth
6-8-65	0623	2	6-5	1818	Type II RADIO ONLY			60.1	689	182
7-12-65	1602	8	2 POSSIBLE FLARES							
7-18-65	1553	9	NONE > IMP 1							
9-15-65	1452	19	NONE > IMP 1							383
9-26-65	2110	21	NONE > IMP 1							
10-7-65	0900	23	10-5	0729	2	23N	45E	49.5	836	
11-4-65	0059	28	NONE > IMP 1							
11-12-65	1430	29	NONE > IMP 1							422
12-4-65	0946	33	NONE > IMP 1							
12-18-65	0620	35	NONE > IMP 1							
1-7-66	1501	39	NONE > IMP 1							
1-20-66	0204	41a	1-17	1031	2+	19N	27W	63.5	652	
1-21-66	0759	41b	1-18	2253	2+	20N	07E	57.1	725	
7-8-66	2102	70	7-7	0025	2B	35N	48W	44.6	928	
7-15-66	1500	71	7-11	0900	3	35N	90W	102.0	406	
7-27-66	0603	73	7-25	0457	1B	38N	15E	49.1	843	
8-29-66	1315	79a	8-26	1805	2N	23N	22E	67.2	616	
8-30-66	1112	79b	8-28	1523	2B	22N	05E	43.8	945	157
9-3-66	2114	80	9-2	0542	3B	24N	56W	39.5	1048	
9-14-66	1511	82	3 POSSIBLE FLARES							
9-23-66	0856	83	9-20	1738	2B	06N	14W	63.3	654	
10-15-66	0954	87	3 POSSIBLE FLARES							319
11-25-66	1339	94	11-22	1835	1B	30N	18E	67.0	618	
1-6-67	0714	101a	1-3	2330	2N	21S	32W	55.7	743	
1-7-67	0800	101b	1-5	1027	1B	20N	55W	45.6	908	
1-13-67	1203	102	1-11	0131	3N	26S	47W	58.5	708	



JUNE 8,1965
IMP 3
|B|
20
10
0
Δ
4
0
θ
90
0
-90
φ
360
180
0
HONOLULU 10 γ
GUAM 10 γ
SAN JUAN 10 γ
4
5
6
7
8
9
UT (HOURS)

FIGURE 1a

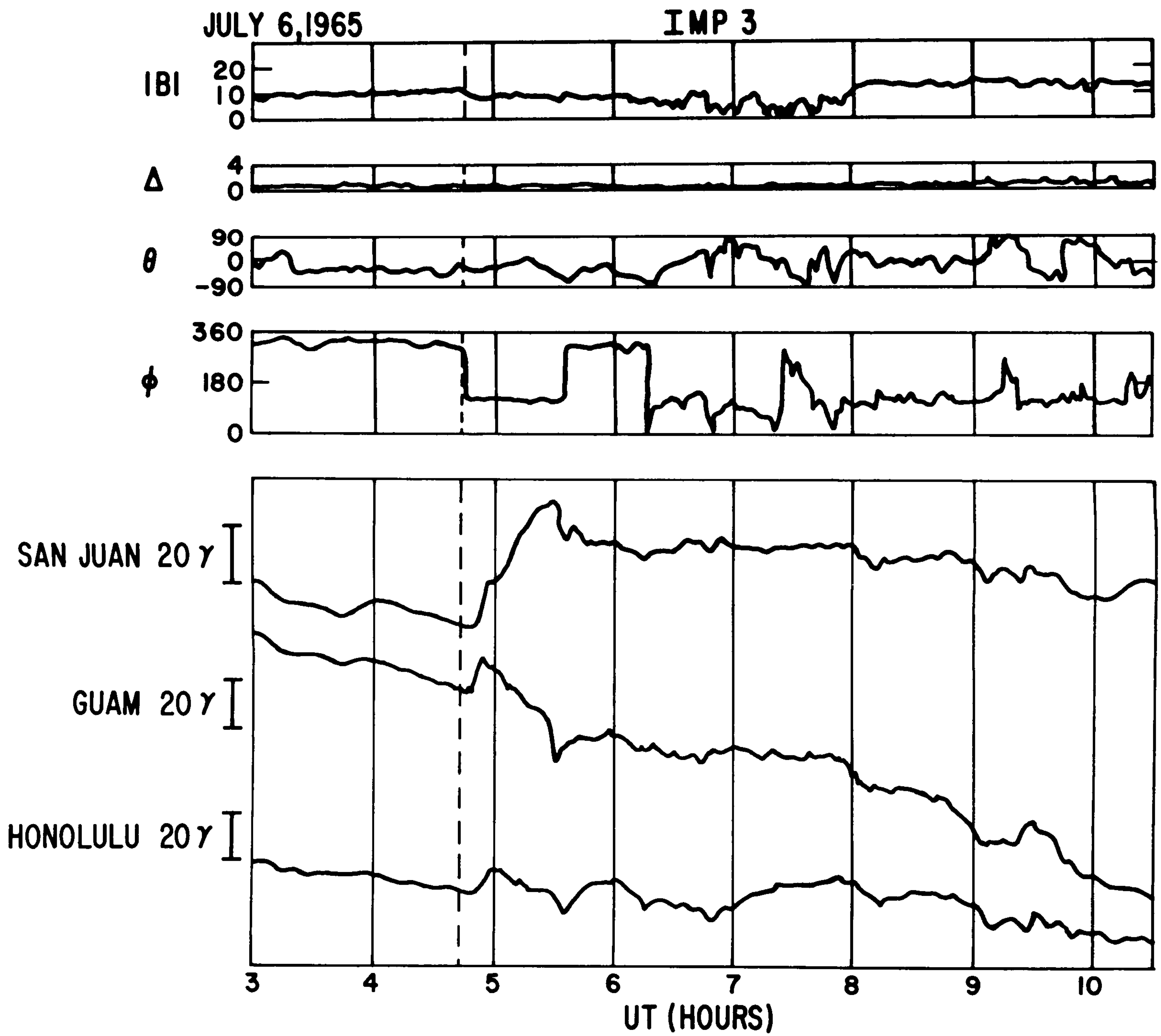

JULY 6,1965
IMP 3
|B|
20
10
0
Δ
4
0
θ
90
0
-90
φ
360
180
0
SAN JUAN 20γ
GUAM 20γ
HONOLULU 20γ
3
4
5
6
7
8
9
10
UT (HOURS)

FIGURE 1b

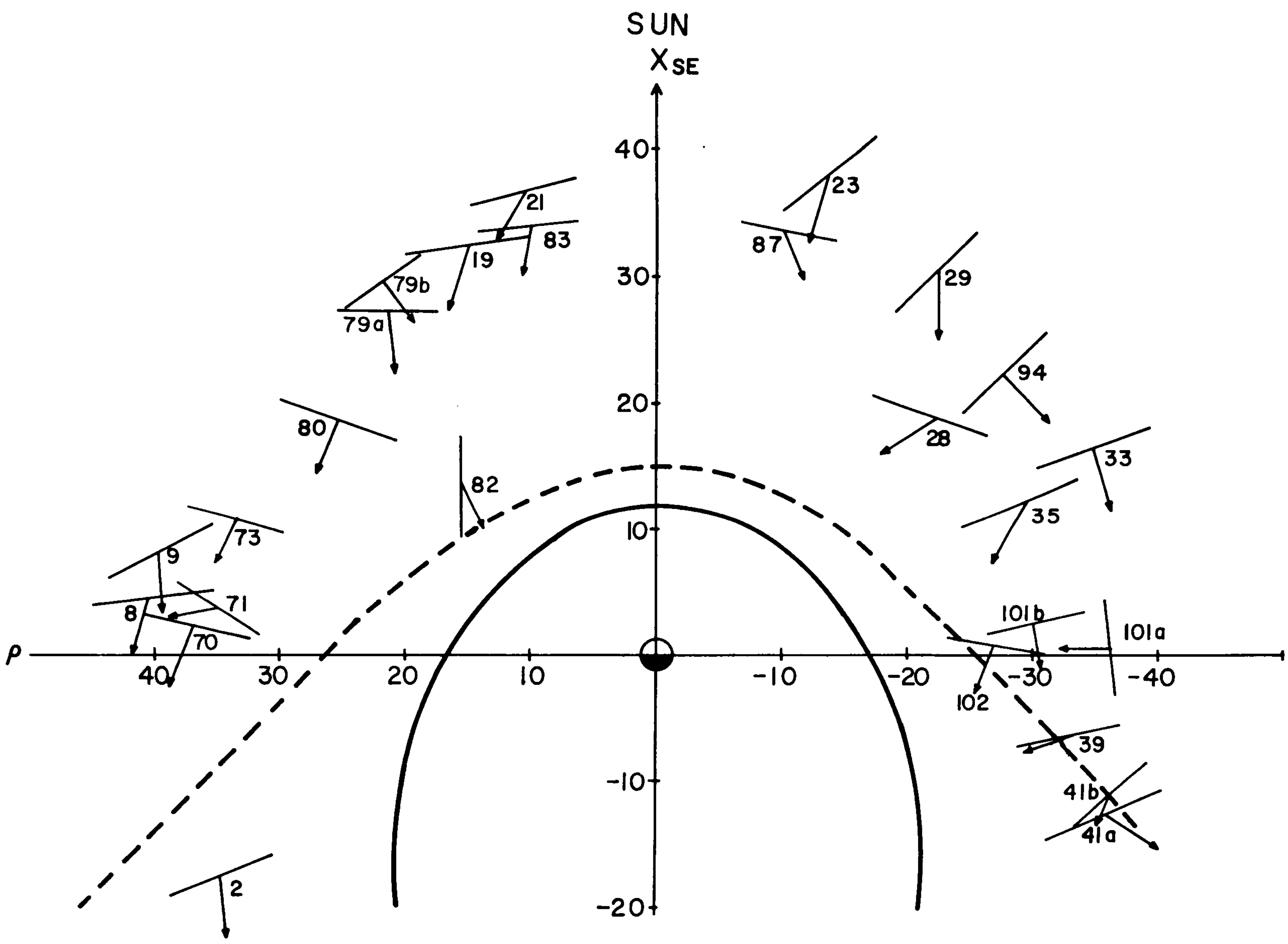
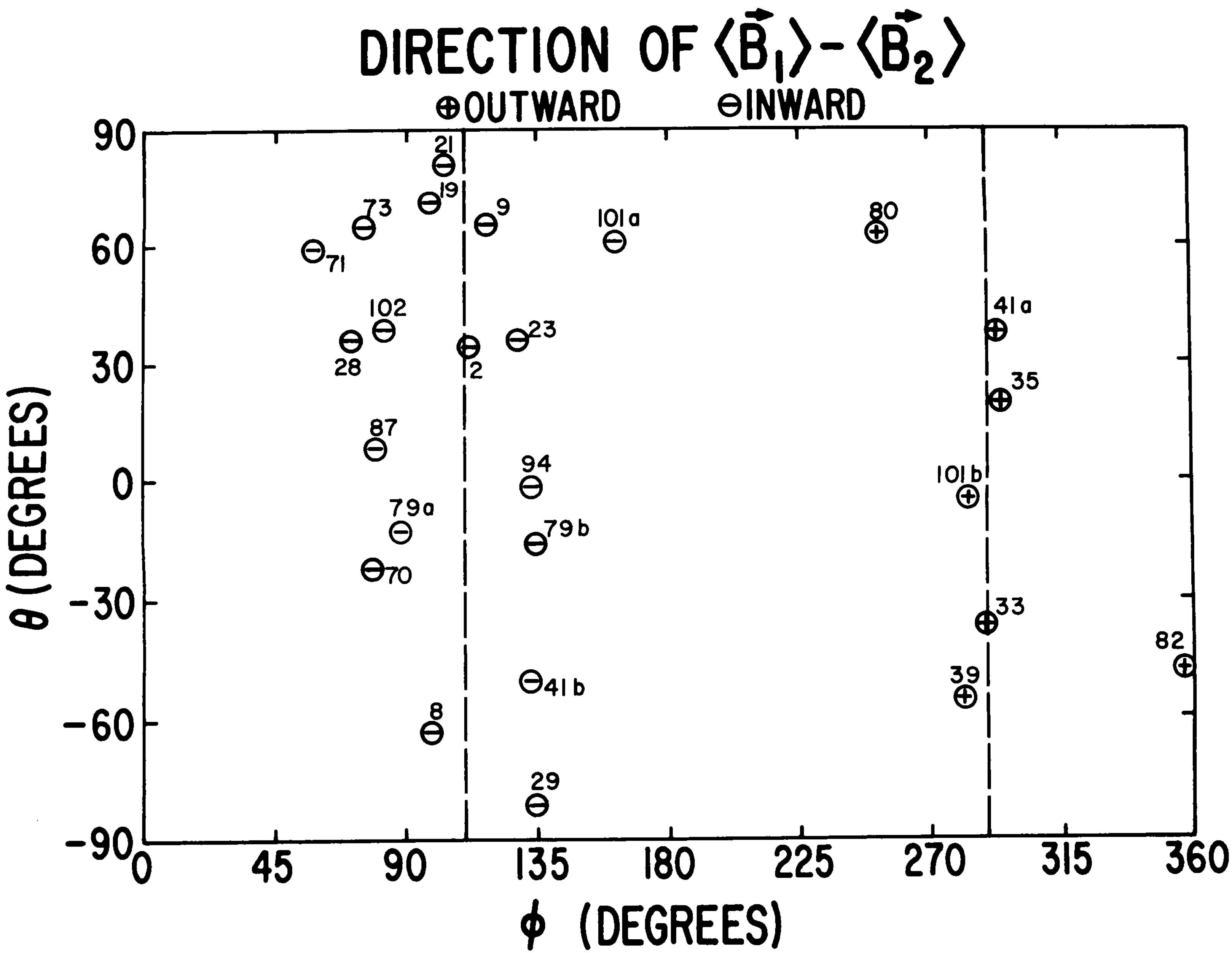

SUN
X_{SE}
ρ
40
30
20
10
-10
-20
-30
-40
21
83
19
79b
79a
80
82
73
9
71
8
70
2
23
87
29
94
28
33
35
101b
101a
102
39
41b
41a

FIGURE 2



DIRECTION OF ⟨B1⟩ - ⟨B2⟩
⊕OUTWARD
⊖INWARD
90
60
30
0
-30
-60
-90
0
45
90
135
180
225
270
315
360
θ (DEGREES)
φ (DEGREES)
21
19
73
9
101a
80
71
102
41a
23
28
2
35
87
94
101b
79a
79b
70
33
82
41b
39
8
29

FIGURE 3

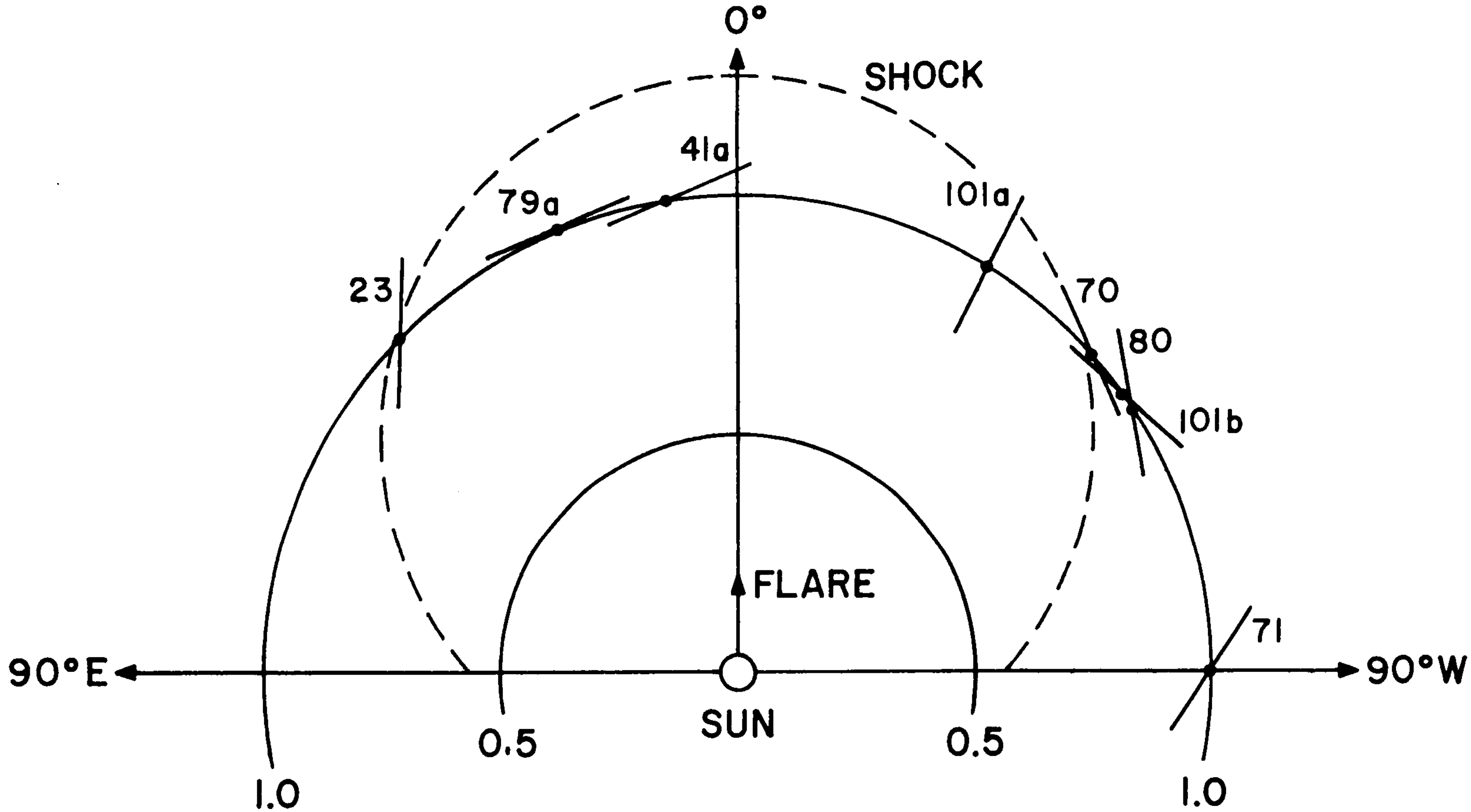

0°
SHOCK
41a
79a
101a
23
70
80
101b
FLARE
71
90°E
90°W
SUN
0.5
0.5
1.0
1.0

FIGURE 4