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FINAL REPORT

PRELIMINARY INVESTIGATION OF INTERPLANETARY SHOCK STRUCTURE: QUASI-PARALLEL SHOCKS

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INTRODUCTION

This is the final report on a one year "Preliminary Investigation of Interplanetary Shock Structure" in which it was proposed to review and examine Pioneer 9's magnetic field and plasma data to develop arguments for or against the observation of oblique interplanetary shocks.

In a word, the argument is <u>for</u>. Although the mere existence of such shocks could never have been doubted, there was no report of them at the time this survey was suggested, and certainly no serious consideration had been given to their structure or to the extent of the role they might play in solar wind phenomenology. This investigation provided an opportunity to contemplate the interplanetary shock from a structural viewpoint and to give some thought to, and seek some evidence for, what might be expected on the basis of experience with the earth's bow shock.

The approach to oblique interplanetary shocks has gone from naive to semi-sophisticated in the course of this small study, largely because of the results concurrently developed in related investigations by this and other researchers: A nearly parallel interplanetary shock was identified by another worker even before this study began; the "oblique" shock designation was supplanted by a more comprehensive classification scheme in which we now use the term "quasi-parallel" to denote the geometric class of interest; this class is now itself divided into subclasses based on mach number and energy ratio (β); the slow shock and the reverse shock have been found to be necessary contributors to the practical study of quasi-parallel interplanetary shocks; finally, the simple, visual search of spacecraft data for quasi-parallel shocks has been found to be useless, and computer techniques found to be essential.

The report begins by defining briefly the new structural classifications. We then review the justification for seeking some of these classifications in the solar wind and the shock profiles that might reasonably be anticipated by analogy with the bow shock. We describe the approach taken in the light of concurrent developments and the results obtained. Finally, we discuss the results and conclude with recommendations for further investigation and action.

A key role in this investigation was played by a survey of interplanetary shocks observed by HEOS 1, and made available through Vittorio Formisano. The survey was part of a thesis written by Gustavo Mastrantonio of the Laboratorio per il Plasma nello Spazio of the Consiglio Nazionale delle Ricerche, Frascati. This document, listed under Mastrantonio in the reference list, will be cited often below as "Reference 1".

DEFINITIONS

New shock-structural classification schemes derived from extensive observation of earth's bow shock have been described recently in several papers (Greenstadt et al, 1970b; Formisano and Hedgecock, 1973; Dobrowolny and Formisano, 1973; Greenstadt, 1974). The following parametric summary will suffice for this report:

Quasi-perpendicular	$\theta_{nB} > 45°$
Quasi-parallel	$\theta_{nB} < 45°$
Laminar	$M \lesssim 3$, $\beta << .1$
Turbulent	$M \gtrsim 3$, $\beta \gtrsim 1$
Quasi-laminar	$M \gtrsim 3$, $\beta << 1$
Quasi-turbulent	$M \lesssim 3$, $\beta \gtrsim 1$,

where θ_{nB} is the angle between shock normal $\underset{\sim}{n}$ and upstream $\underset{\sim}{B}$, M is the upstream (magnetosonic) mach number V_{SW}/V_{MS}, β is the field to (plasma) thermal energy ratio $B^2/8\pi NkT$, V_{SW} and V_{MS} are solar wind and magnetosonic velocities, N is the upstream density, and T is the total upstream plasma temperature.

JUSTIFICATION

Special Conditions

There are three fundamental reasons for undertaking an effort to examine interplanetary shocks and, particularly, to isolate quasi-parallel structures. These are: 1. increased opportunity to observe low mach number shocks, 2. enhanced accessibility of quasi-turbulent conditions, and 3. potential observation of shock-associated acceleration of charged particles. Each of the reasons is elaborated separately below.

1. Low mach number. The earth's bow shock is, on the average, a supercritical, high mach number shock, with magnetosonic mach number $M_{MS} \gtrsim 4$. This condition results from the essentially stationary, solar-radial velocity of the earth, which exposes the magnetosphere to the full streaming-speed of the solar wind. The speed is usually in the range 300-500 Km/sec and rarely falls as low as 250 Km/sec. Interplanetary shocks, in contrast, propagate in, generally with, the solar wind. They need only exceed the interplanetary magnetosonic velocity, typically about 80 Km/sec, to exist. Their velocity relative to the "upstream" plasma is often below 250 Km/sec, giving $M_{MS} \lesssim 3$ as a common occurrence. Thus the whole category of subcritical plasma shocks is opened up to spacecraft measurement with considerably greater opportunity then the bow shock affords. Indeed, of the twenty-four shocks identified in reference 1, fifteen had mach numbers below 2.5. Furthermore, four were classified as slow shocks, with $M_{MS} < 1$. In the case of the earth's bow shock, at most about 10 percent of the observed crossings are at low M_{MS}.

2. Quasi-turbulence. One of the identified subcategories of shock structure has been called quasi-turbulent by Formisano (1974; Formisano & Hedgecock, 1973). This subclass is defined by shocks of subcritical M_{MS} but high β. High β discourages plasma instabilities (Greenstadt & Fredricks, 1974), so this type of shock offers the chance to isolate some of the processes that heat protons highly, without the accompanying complication introduced by supercritical flow.

Quasi-turbulent bow shocks are rather rare, occurring only about 4 percent of the time (Formisano, 1974). This is expected from the definitions of M and β and the nature of the solar wind. By appropriate grouping and rearranging of n,B,T factors, it can be shown that

$$M_A \sim \frac{V_{SW}}{\sqrt{T_+}} \sqrt{\beta_+} \quad .$$

But $V_{SW} \sim \sqrt{T_+}$ (Burlaga and Ogilvie, 1973); hence, $M_A \sim \sqrt{\beta_+}$, so that M and β tend to rise and fall together, making reversed combinations unusual. In a typical solar wind, $M_A = 7$, $\beta_+ = .5$, implying $M_A \approx 10\sqrt{\beta_+}$, and requiring, for $M_A < 3$, $\beta_+ < .09$. Quasi-turbulence, in contrast, demands $\beta_+ \gtrsim .1$ when $M_A \lesssim 3$. Comparisons of M_{MS}, rather than M_A, with total β, rather than β_+, change the numbers and improve somewhat the prospects for quasi-turbulence, since $M_{MS} < M_A$ and $\beta > \beta_+$, but the general trend is the same.

The trend is no deterrent, however, in dealing with interplanetary shocks. Indeed, since high temperature (high β) implies high V_{SW} (Burlaga & Ogilvie, (1973), an interplanetary shock propagating into a high β plasma is likely to be overtaking a fast solar wind and is therefore likely to have a low mach number. Interplanetary shocks are therefore an appropriate source of quasi-turbulent structures: of the twenty-four shocks of reference 1, ten, or 42 percent, satisfied quasi-turbulent conditions, i.e., $\beta > .5$, $M < 3$.

3. Charged particle acceleration. Reverse streaming protons of energies up to 100 Kev have been detected coming from the earth's bow shock (*Asbridge et al.*, 1968; *Scarf et al.*, 1970; *Lin et al.*, 1974), and protons of 300 eV have been associated with interplanetary shocks (*Armstrong et al.*, 1970). However, the process or processes creating these backstreaming particles have not been fully determined. *Sonnerup* (1969) outlined a theory of proton reflection from the bow shock that appeared to provide ions of suitable energy. *Sarris & Van Allen* (1974) have proposed a model of multiple proton reflection from interplanetary shocks to explain the generation of relationistic particles, and it seems reasonable that multiple reflection should play a role in the bow shock as well, if 100 keV particles (*Lin et al.*, 1974) are to be explained by Sonnerup's process. The anomalous appearances of high energy solar ions from unexpected directions or at unexpected times may yet be explained in part through a better understanding of particle energization by shocks propagating outward from the sun.

Details of shock-particle interaction have not been reported, however. In principal, interplanetary shocks offer an advantage over the bow shock: whereas ions reflected from the bow shock must be detected in directions opposite, or at large angle, to the solar wind flow, ions reflected from an interplanetary shock may appear from the same general direction as the solar wind and could be detected, at the lower energies, by a solar wind plasma probe.

Quasi-Parallel Structure

In all the above reasons for examining interplanetary shocks, quasi-parallel geometry is of special interest. At this time, only *one* case of laminar (low M, β), quasi-parallel structure has been detected in the bow shock, and *no* quasi-turbulent, quasi-parallel bow shock crossing has been found. Moreover, the laminar case was contaminated by a change in field direction during the crossing (Greenstadt, 1974) and is not a good example.

In dealing with particle energization, the orientation of the magnetic field with respect to the shock in the upwind plasma is of critical importance, for the field direction determines which reflected particles will be trapped at the shock and which will escape (Greenstadt, 1974). A first-order, qualitative picture of interplanetary shock-particle association suggests that quasi-perpendicular geometry should tend to keep ions from escaping, allowing them to accelerate to appreciable energy by repeated reflection (this is the model of Sarris and Van Allen), while quasi-parallel geometry should permit them to escape ahead of the shock, even dissociating themselves from it in the record of an interplanetary monitor. Also, a considerable increase in scale (radius of curvature) in going from the bow shock to interplanetary shocks may have a bearing on the opportunity for high energization by multiple reflection. A propagating interplanetary shock may encounter numerous ambient, local, upwind fields as it progresses away from the sun, and may alternately accelerate and emit ions, creating a pattern for particle detectors that might be more comprehensible if shock structure were taken into account.

Since particle energization is likely to increase with mach number, quasi-parallel structure is of interest for all shocks, not just for those in the laminar and quasi-turbulent classes. Of the twenty-four shocks in reference 1, seven were quasi-parallel, i.e., had $\theta_{nB} < 40°$. Thus quasi-parallel geometry is not unusual at 1 AU and, since the stream angle of the field becomes more radial toward the sun, there should be an increase in incidence of Q-parallel shocks among events observed by inward-bound spacecraft.

INTERPLANETARY SHOCK PROFILES

While certain types of structure should, in principle, be more accessible in interplanetary shocks than in the bow shock, the practical observation of these structures is more difficult in interplanetary cases because of the higher relative speeds of shock and spacecraft. There are, excluding the perpendicular shock, two basic structures whose (magnetic) thicknesses are known from observation. The first is the quasi-perpendicular, laminar structure, which consists of a clear ramp of thickness on the order of 4 c/ω_{pi} (Greenstadt et al., 1974); the second is the turbulent, quasi-parallel structure, which consists of a region of large-amplitude, mixed oscillations of thickness on the order of at least 1 R_e (Greenstadt et al., 1970a).

The observational requirements associated with these thicknesses can be easily estimated. In a spacecraft's frame of measurement, the observed shock duration Δt_S would depend on the shock's thickness, its speed V_{SH}, and its direction of propagation in the solar wind frame. If we place ourselves in the plane of the solar wind and the shock normal and take X positive outward from the sun, then the shock normal is given by components $\underset{\sim}{n} = (\cos\theta_{nx}, \sin\theta_{nx})$, where θ_{nx} is the angle between $\underset{\sim}{n}$ and $\underset{\sim}{X}$ (i.e., $\underset{\sim}{n}$ and $\underset{\sim}{V}_{SW}$). We have $\Delta\underset{\sim}{S}_S = \underset{\sim}{V}_{SS}\Delta t_S$ and $\Delta\underset{\sim}{S}_S \cdot \underset{\sim}{n} = \Delta S$, where $\Delta\underset{\sim}{S}_S$ is the satellite path through the shock structure, $\underset{\sim}{V}_{SS} = \underset{\sim}{V}_{SW} + \underset{\sim}{V}_{SH}$ is the shock velocity in the spacecraft frame, and $\underset{\sim}{V}_{SH} = (V_{SH}\cos\theta_{nx}, V_{SH}\sin\theta_{nx}$. The resulting expression for the observed shock thickness duration is

$$\Delta t_S = \Delta S/(V_{SW}\cos\theta_{nX} + V_{SH}) .$$

We consider, for numerical illustration, the laminar, quasi-perpendicular and turbulent, quasi-parallel cases. If we postulate a typical solar wind speed of $V_{SW} = 400$ Km/sec and if, to make β low for a laminar condition, we take density $N_{SW} = 1\ cm^{-3}$, $B = 10\gamma$, $T_p = 10^4$°K, $T_e = 15 \times 10^4$°K ($\beta = .08$), a laminar interplanetary shock ramp would have thickness $\Delta S \approx 900$ Km. Now the limiting, minimal speed of a fast shock in the solar wind is the magnetosonic speed in the plasma, of which our laminar parameters give a value 220 Km/sec (for $M_{MS} = 1$). Then $\Delta t_S \leq 900/(400 \cos \theta_{nx} + 220)$.

For a turbulent, quasi-parallel, interplanetary shock, we must interpret ΔS and Δt_S in terms of a "pulsation region" thickness rather than a "ramp." We *may, in this case, take more typical plasma parameters, say,* $N = 7\ cm^{-3}$, $B = 5\gamma$, $T_p = 7 \times 10^4$°K, and, with $\Delta S = 1\ R_e = 6380$ Km, the minimal magnetosonic shock velocity is 84 Km/sec. Then $\Delta t_S \leq 6380/(400 \cos \theta_{nx} - 84)$.

The two expressions found for Δt_S are plotted in Figure 1. The vertical lines represent the angles at which the spacecraft path is parallel to the shock itself, so Δt_S becomes indeterminate; negative Δt_S signifies that the spacecraft crosses the shock "backwards" from downstream to upstream. We see that, except within 13° of the angle of the vertical asymptote, the thin, laminar shock crosses the observation point in 10 seconds or less. For most angles, the crossing time should be 2 to 5 sec, requiring in consequence a high sampling rate for any detailed measurement. Long crossing times occur only for reverse shocks with normals in a narrow range around 120° to the outward solar radial. The nominal quasi-parallel shock, being much thicker than any quasi-perpendicular one, takes 13 seconds or more to cross a spacecraft, but the really long transits occur only for reverse shocks travelling almost directly across the solar wind flow at 100° to the outward solar radial.

We may recall that in addition to its pulsation region, the quasi-parallel structure has a "foreshock" of smaller amplitude oscillations which precedes it upstream and which, in the case of the earth's bow shock, may often be tens of earth radii thick. Thus, the total quasi-parallel structure could be observable up to an order of magnitude longer than the quasi-perpendicular structure, even at relatively unfavorable propagation angles, but the foreshock could probably be interpreted with confidence only if the shock itself were also observed in detail.

The nominal crossing times plotted in Figure 1 illustrate the practical difficulty inherent in seeking structural data on interplanetary shocks. The 10-25-second Δt_S's expected for most quasi-parallel shocks must be contrasted with the hour-long crossings of such structures sometimes occurring in the bow shock. An interval of 20 seconds or so is only a little longer than that usually afforded by the much thinner laminar structure in the bow shock, even when the latter is almost stationary. Thus, any truly meaningful study of IP shock structures should be undertaken principally with high resolution instruments obtaining (magnetic) samples once per second or faster. We say principally because there is the very considerable possibility of observing IP shocks at large angles of propagation giving quite long crossing paths. Of the 24 shocks in Reference 1, 15 were propagating at angles greater than 45° from the solar radial, and, of these, five were at angles between 90° and 135°, where relatively large Δt_S could be expected.

To complete the above treatment, we examine briefly the more realistic conditions when the limiting restriction $M_{MS} = 1$ is removed. The crossing times for both laminar and quasi-parallel cases are plotted in Figure 2 at several selected mach numbers. As might be expected, the longer Δt_S's move, with their associated asymptotes, toward $\theta_{nx} = 180°$ as M_{MS} increases, and the negative values of Δt_S at 180° increase with M_{MS} (at fixed V_{SW}), since the reverse shocks at that angle behave more and more like the stationary bow shock. The net result of increasing mach number is therefore to increase the observability of reverse shocks, and this effect is quite dramatic in the quasi-parallel case. Unfortunately, the prospect of finding numerous reverse shocks at elevated mach number is not very good.

It may be concluded from the foregoing that the interplanetary shock as it is usually envisioned, i.e., as a fast forward shock propagating approximately in the antisolar direction, is likely to appear as a fairly abrupt profile regardless of its internal structure to any but the highest resolution instruments. There are, however, many more shocks of low mach number and nonradial direction than might be anticipated. These ought to be suitable for study when observations are available, but they cannot be identified readily from visual records and require sophisticated computing procedure early in the search phase of investigation.

APPROACH

Redirection

It was inevitable, with the increasing resolution of satellite telemetry and the continuing attention of researchers to interplanetary shocks, that varying profiles would be observed and Q-parallel structures identified, if they were accessible at all. It was the intention of this investigator to consider the problem of accessibility and search the Pioneer 9 data to find cases of probable Q-parallel structure. After the proposal for this study was written, however, such a search became unnecessary, for one case was already exhibited by Chao at an AGU meeting (in December 72, to the best recollection of this investigator). For this reason and for a second, about to be explained, the approach and objectives of the study were altered to what it was hoped would be a more productive program of physical analysis of Q-parallel interplanetary shocks if any could be found that were observed by suitable spacecraft systems, particularly that of OGO 5 in the 8-kilobit mode.

The second reason for abandoning the initial approach was its unreliability: the idea had been that, by seeking discontinuities, i.e., sudden changes, in Pioneer 9's plasma parameters and then examining the corresponding magnetometer data, shocks would be found which, by virtue of their propagation locally along $\underset{\sim}{B}$, would have been overlooked in the magnetometer record. Alternatively, it was thought that a list of sudden commencements, coupled with a list of intervals during which $\underset{\sim}{B}$ lay close to the sun-earth line, would lead to an example, or examples, of a Q-parallel shock. In September 73, however, Chao (1973) published an experimental paper on the steepening of waves to form interplanetary shocks. Examples were shown of gradual field ramps which were not shocks at all. More directly, a new opportunity arose for this investigator to examine a preliminary list of shocks selected by computer, using Chao's program, through the courtesy of V. Formisano. Of 24 events identified as shocks and characterized parametrically through the Rankine-Hugoniot relations, seven were Q-parallel, according to computer-estimates of shock normal orientation. But of these seven, six had normals and preshocked $\underset{\sim}{B}$'s sufficiently nonradial that they would not have been selected as events likely to be Q-parallel by the simple approach originally proposed. It didn't seem advisable therefore to seek cases which, even if they fit the description of what was being looked for, would have had a significant probability either of not being shocks anyway, or of having been erroneously discarded on the basis of an inapplicable geometric assumption.

It was decided instead to take advantage of the prepared shock list and the prior existence demonstration of Chao to attempt to develop details of shock structure and behavior, using multisatellite observations, hopefully with Pioneer 9 as a useful member of any selected ensemble of spacecraft.

Sources and Methods

The pivotal source of relevant events was a list of shocks prepared by Gustavo Mastrantonio at the University of Rome as part of his laureate thesis. The list, which covers the intervals during which HEOS 1 was in the solar wind between 11 December 68 and the end of 1969, was prepared by computer search of tapes of merged field and plasma data to identify, separately, all discontinuities above selected thresholds in either field magnitude, density, or velocity. The shock analysis program of Chao (Chao and Goldstein, 1972) was applied to all such identified discontinuities to test for conformity with the Rankine-Hugoniot shock conditions, and those discontinuities that survived formed the list of 24 shocks referred to here. The computation process automatically produced such key parameters as shock velocity, mach number, shock-normal direction $\underset{\sim}{n}$, and field-normal angle θ_{Bn}, so that the classification of each event could be easily determined. The source list included shocks that were fast and slow, forward and reverse, quasi-perpendicular and quasi-parallel, and laminar and turbulent in various combinations.

Of the 24 designated shocks, 16 occurred before April 1969, at which time the HEOS trajectory entered the magnetosheath and the spacecraft stopped sampling the solar wind until October 1969, when it emerged again on the dusk side. Attention was confined in this study to these first 16 events because it was during the December 68-March 69 interval that Pioneer 9 was in its post-launch trajectory, near enough both to the earth and to the earth-sun line, to make plausible identifications of events passing the two spacecraft at different times. Figure 3 shows the trajectory of Pioneer 9 relative to a stationary earth in sun-centered polar coordinates, through 1 April 1969. A reverse shock propagating 100 Km/sec in a 300 Km/sec solar wind could have taken as long as 50 hours to travel from Pioneer to earth on April 1st. Such an event would be difficult to identify unambiguously in most instances. Fortunately, the only cases of interest here involved much shorter delays.

In addition to the shock list, magnetic field and plasma parameter data from Pioneer 9 and magnetic field data from OGO 5, Explorer 33, and Explorer 35 were consulted, these in the form of microfilms obtained from NASA/NSSDC. These data were inspected visually around the expected times of events.

RESULTS

Case Selection

Four of the sixteen shocks recorded by HEOS 1 up to the 1st of April 1969 were quasi-parallel. For purposes of this study, "quasi-parallel" was defined by the condition $\theta_{Bn} \leq 40°$. These four were examined as candidates for detailed study.

Some characteristics of the four selected events (at HEOS 1) are presented in Table 1. We see that two were fast-forward and two were slow-reverse shocks. The two fast-forward shocks were fast indeed and offered little promise of revealing their structure to any of the available instruments, their estimated crossing times having been 16 seconds or less (Figure 2). Inspection of the records from the other spacecraft showed a clear event for case 1, at all vehicles: Pioneer 9, OGO 5, Explorers 33, and 35. Every field observation exhibited a sharp jump in field strength similar to that recorded by HEOS. The 1-kilobit data from OGO (1 field sample per second) verified that the shock's crossing time was less than 3.3 seconds. Case 4 was less instructive. At the appropriate times of the shock crossings, OGO 5 and Explorer 35 suffered data gaps, while Explorer 33's magnetometer underwent one of its periodic sensor flips. The data gaps were short, but included the shock crossings, as evidenced by differences in field before and after the respective gaps. The corresponding event at Pioneer 9 could not be identified unambiguously, there having been several steps in $\underset{\sim}{B}$ around the estimated shock crossing time. Examination of the fast shocks was not pursued further.

The second of the two slow-reverse shock cases occurred on 2 February 69. The event was one part of a complex series of discontinuities which has been studied by several groups of investigators (Scarf et al., 1972; Greenstadt et al., 1974; Dryer et al., 1974). It did not seem worthwhile to attempt in this preliminary investigation to disentangle the effects sought here from the many others observed that day, especially since the event was not an obvious one in the records of field-averages from OGO and the two Explorers, and was only ambiguously identified at Pioneer 9. The remaining slow-reverse shock, that of 14 January 1969, was also effectively indistinguishable at OGO and the two Explorers except by analogous configuration of the field patterns to that at HEOS. This subtlety of shock identification by reference to magnetic records is hardly surprising for a shock with $\theta_{Bn} = 7°$. The event was an isolated one, however, and a corresponding complex of events at Pioneer 9 seemed to be definable. The circumstances surrounding this case were therefore developed in greater detail.

The Case 2 Example

Table 2 displays some characteristics of the shock of 14 January 69. Subscripts 1,2 refer to the order of observation with respect to the shock in the measurement time frame, so that subscript 2 denotes upstream conditions in the plasma frame for this reverse shock. The shock normal, given in δE coordinates, was near the ecliptic and close to the average stream angle of the interplanetary magnetic field, so the normal to the shock was essentially parallel to the most common $\underset{\sim}{B}_{SW}$.

Figure 4 shows the behavior of $\underset{\sim}{B}_{SW}$ between 1800 and 2100 at both HEOS 1 (48-sec samples) and Explorer 35 (82-second averages). We note two important items: first, there was virtually no distinguishable magnetic field jump at 1940 at either satellite; second, upstream interplanetary field, which in this case appeared after 1940 was, despite moderate variability in direction, consistently within 45° of the ecliptic and 15° of the usual stream angle (∿ 315°) for at least an hour.

Figure 5 exhibits the geometry of the earth-shock-Pioneer 9 system projected on the ecliptic. The Pioneer trajectory is shown as the dashed curve with the position of the probe on 14 January indicated by the small circle at .9 AU, about 2° east of the sun-earth line. The intersection of the shock with the ecliptic is approximated by straight lines perpendicular to the projected shock normal $\underset{\sim}{n}$, and the shock is shown at three positions as if it progressed uniformly along constant $\underset{\sim}{n}$ from Pioneer 9 to earth. The average spiral $\underset{\sim}{B}_{SW}$ is drawn in the sense observed (prosolar), with the required negative step at the slow shock. As already shown in Figure 4, no pronounced step appeared near the earth, and for nearly parallel $\underset{\sim}{n}$ and $\underset{\sim}{B}_{SW}$, none should have been expected.

If the geometry of Figure 5 is accepted at face value, the approximate time of the shock's passage by Pioneer 9 can easily be computed: the delay, in hours, would have been .06(AU) × 1.5 × 10^8(Km/AU)/3600(sec/hr) × 90(Km/sec)/cos 54° = 16.3(hrs), so the time at Pioneer would have been about 0324. This is the time indicated in Figure 5.

The Pioneer 9 record indicates extremely steady conditions throughout 13-14 January, except for the interval 0520-0630 during which there was a series of plasma and field events. We identify the series as the phenomena associated with the 1940 shock at earth. The Pioneer 9 interval 0400-0800 is depicted in Figure 6. The fluctuations in field at Pioneer between 0510 and 0615 were reasonably similar to those at Explorer and HEOS between 1830 and 1940, and we adopt that tentative correspondence, noting especially the 17-minute segment of almost constant field, just under 10γ, between 0553 and 0610 at Pioneer and the similar 20-minute segment between 1905 and 1925 at Explorer 35. Exact patterns were clearly not preserved and perfect correspondence was hardly to be expected.

It seems likely, from the velocity drop at about 0545, that a rarefaction at the trailing edge of a stream-stream interaction might have contributed to formation of a reverse shock eventually seen by HEOS 1. Densities (not shown) were very low at Pioneer ($\lesssim$ 1 cm^{-3}) and not accurately described in this version of the data (from NSSDC films), but a relative average decline was evident after 0600. Any of several steps in V or B after 0600 might have developed into the event recorded as a slow shock by HEOS 1, with a time delay within 18 percent of the geometric delay estimated in the above zero-order approximation.

Whatever the event that propagated backward in the plasma between 0600 and 1940, the field which it encountered "upstream" would have been that seen by

Pioneer 9 after 0600. This field was not necessarily uniform over the two degrees and .2 AU separating Pioneer from earth, but the similarity of stream angle and field magnitudes at all spacecraft makes such uniformity a probably valid assumption. Moreover, the field remained close to the stream angle at Pioneer for the entire interval 0600-1940. It may be concluded that the upstream field geometry was essentially quasi-parallel throughout the 13-14 hours preceding the shock observation by HEOS 1.

The OGO-5 spacecraft was in its 1 kilobit mode when the event of 14 Jan. occurred. Figure 7 shows the field magnitude measured by the UCLA fluxgate between 1930 and 1950. Clearly, no outstanding event occurred and certainly no single step normally associated with an interplanetary shock was recorded. Such an indistinct magnetic outline is what should be expected for an established, steady state, nearly parallel shock. Unfortunately, the data from OGO-5's JPL Plasma Analyzer (not shown) do not confirm the plasma changes listed by HEOS 1. There were some changes in flux at 1935, 1938, and 1944 UT, but none large enough to be consistent with the one determined by the HEOS 1 valued at 1940. The OGO data, however, indicated some unusual deviations in plasma flow direction which might have affected the accuracy of the plasma parameters.

DISCUSSION

It was the good fortune of this study, by virtue of Chao's early work and the table prepared by the HEOS group, to have been able to begin at a more advanced stage than had originally been comtemplated. The investigation has therefore, in a sense, been successful: The existence of quasi-parallel interplanetary shocks is established and some elementary characteristics of them verified. Indeed, a substantial number of identified shocks have turned out to be quasi-parallel.

The accelerated stage of investigation has its drawbacks, however. With existence established, the study is propelled immediately into the more difficult process of display and analysis of shock structures, with events that don't easily lend themselves to high resolution observation, as outlined in the earlier PROFILE section. Here again, good luck prevailed: The PROFILE analysis indicated an advantage to be expected in examining reverse shocks and shocks propagating at large angle to the solar radial, and the HEOS listing obliged by providing examples of both. As usual, a number of cases satisfying all requirements, e.g., multisatellite observations, was quickly reduced to a statistically negligible set, on this occasion, a single case.

The one case selected as an example exhibited most of the superficial properties that ought to be associated with quasi-parallel geometry. Moreover, it was an event observable at four spacecraft, including Pioneer 9. Nevertheless, the event is unsuitable for really thorough analysis, because OGO-5 chanced not to have been operating at 8 kilobits at the time. Also, the shock was relatively low mach number, slow shock, so that quasi-parallel geometry was not the only factor that might have contributed to the comparatively featureless character of the event.

In sum, discontinuities in the interplanetary medium that have the average MHD signatures of parallel, or quasi-parallel, shocks are not unusual. They occurred in 29% of 24 cases selected by automatic computer fit of the Rankine-Hugoniot relations, using data from a single satellite. Several of the Q-parallel examples were found to be propagating in directions that would facilitate detailed observation, but high resolution recording (1 sec/sample or better) would be required to obtain useful new scientific results. Four cases were identified which could have passed Pioneer 9 during the early part of its flight and, in general, potential multiple satellite observations of such events would seem to have been the rule rather than the exception, despite discontinuous telemetry cycles. One particular event appeared to illustrate well the behavior sought for quasi-parallel interplanetary shocks; the discontinuity was observed by plasma, rather than field, measuring instruments on HEOS 1. It was accessible to four spacecraft, but its field signature was undistinguishable at HEOS 1, Explorer 35, and OGO-5, and was at most a very small step at Pioneer 9. The event appeared to have propagated in a solar wind environment conducive to establishment of stationary quasi-parallel geometry over an interval of many hours and a distance of at least 0.1 AU. A disparity of plasma signatures of the shock between two earth-orbiting satellites could have been caused either by local nonuniformity of the Q-parallel shock or by differing measurement sensitivities. Analysis of the event was complicated by its classification as a slow, as well as a parallel, shock.

It may be of value to restate the above in terms of answers to the five questions posed in the "objectives" section of the original proposal:

1. Can a set of promising oblique interplanetary shocks be identified by their plasma and magnetic signatures alone?

   Yes, but a visual search would identify many events that would not not be verified as quasi-parallel shocks, and most quasi-parallel shocks would probably ve overlooked.

2. If so, can a condition separating oblique from perpendicular structures be established?

   Not by inspection alone.

3. Can data be assembled in sufficient detail for at least one, but perhaps for several, cases which will serve to verify the nature of the events?

   Yes, as described in the report.

4. If so, what is the result of applying the R-H MHD relations to these events?

   The events actually had to be identified by use of the MHD relations. The results were that the event's normals are usually far from the outward solar radial direction, and they were not always fast shocks.

5. If positive identifications are made, can an estimate be made of the occurrence and importance of oblique shocks among solar wind phenomena?

   An estimate of occurrence based on one set appears in this report. An estimate of importance will require further analysis.

It is concluded that quasi-parallel shocks, i.e., shocks at least temporarily subject to quasi-parallel structure, constitute a significant fraction of discontinuities propagating in the solar wind, and may make a significant contribution to the dynamics of the interplanetary medium. Such shocks are not ordinarily identified by standard surveys of solar wind discontinuities.

RECOMMENDATION

The largely qualitative results of this study will have to be extended to a more quantitative investigation before an assessment can be made of the overall impact of quasi-parallel events on solar wind dynamics or of the physics of specialized shock types. An intensive investigation of quasi-parallel interplanetary shock physics does not seem justified at this time, principally because of the inherent difficulty of obtaining high resolution examples with existing data. It would be worthwhile to extend the survey of shock classifications to an enlarged data set, using the same approach applied to the HEOS 1 data by the Frascati group. It would be of particular interest to examine some shocks in relation to what should, in general, be the nonsteady, interplanetary field geometry through which they propagate and it would be valuable to trace a possible transience of shock signature that might appear in passage from one spacecraft to another.

It is recommended that this initial attempt to generalize the study of interplanetary discontinuities to include explicitly quasi-parallel shock structures be continued at a low level with the objectives of 1) enlarging the set of examples, 2) developing a more generalizable statistic of interplanetary shock types, 3) assessing the transient variation of shock structures, and 4) analyzing one or more selected examples in sufficient detail to obtain reliable physical results in quasi-turbulent and slow-shock cases, if such cases can be discovered.

It is further recommended, with emphasis, that wherever feasible, reduced data from magnetometer and plasma probes on the same spacecraft be merged on single tapes to facilitate automatic search for shocks or any other phenomena of general interest. Such tapes ought to be made available through NSSDC.

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Table 1

Quasi-Parallel Shocks Between 11 Dec. 68 and 1 Apr. 69

Case No.	Day No.	Date	Time(UT)	β_i	M_A	θ_{Bn}	θ_{nx}	Type
1	46/1968	11 Dec.	1506	.19	2.08	2.9°	42°	Fast Forward
2	14/1969	14 Jan.	1940	.18	1.56	6.9°	123°	Slow Reverse
3	33/1969	2 Feb.	1322	.19	1.21	4.8°	131°	Slow Reverse
4	57/1969	26 Feb.	0151	.04	3.17	35.0°	39°	Fast Forward

Table 2

The Shock of 1940, 14 Jan. 69

Time	B_1 (γ)	B_2 (γ)	V_1 (km/sec)	V_2 (km/sec)	N_1 (cm^{-3})	N_2 (cm^{-3})	T_1 (10^4 °K)	T_2 (10^4 °K)	λ_n°	ϕ_n°	V_{SS} (km/sec)
1940	8	9	295	355	9.9	3.4	28	2.7	-21	306	90

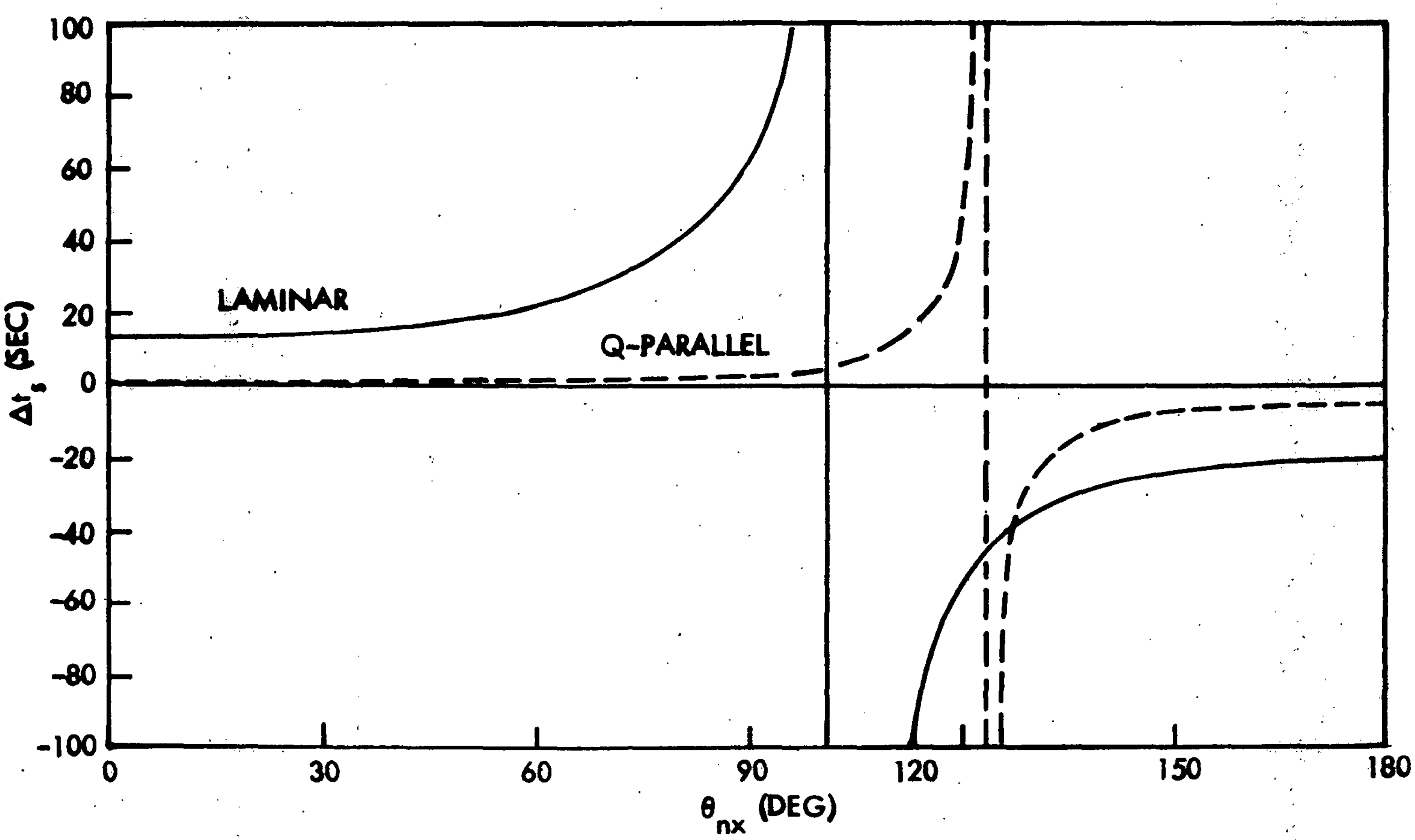

Figure 1. Estimated Limiting (M=1) Observable Crossing Times of Laminar (solid curve and asymptote) and Quasi-Parallel (dashed curve and asymptote) Interplanetary Shocks Vs. Angle θ_{nx} between Shock Normal and Solar Ecliptic X-Axis

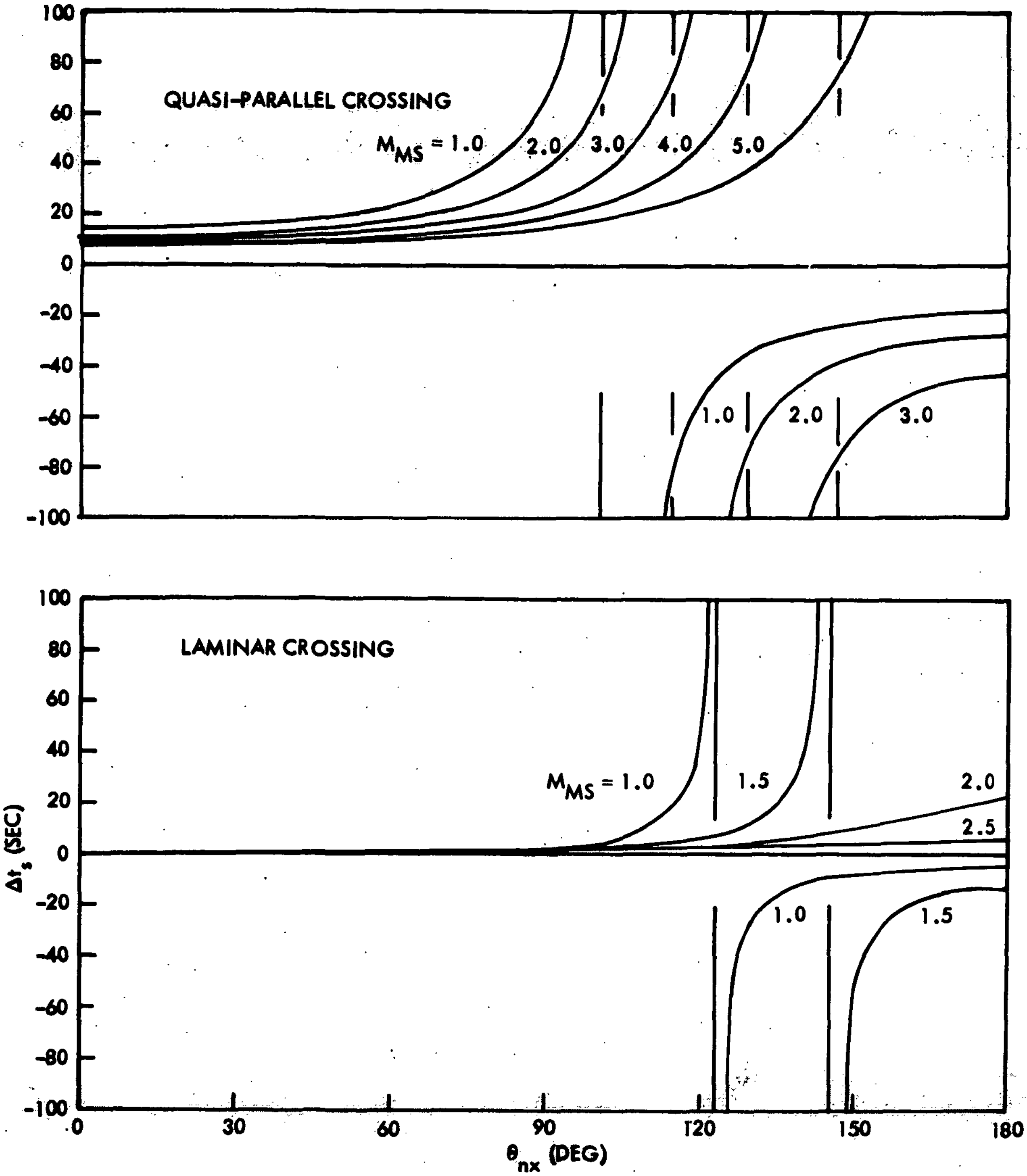

Figure 2. Estimated Observable Crossing Times Vs. θ_{nx} of Laminar (lower panel) and Quasi-Parallel (upper panel) Interplanetary Shocks for Representative Mach Numbers

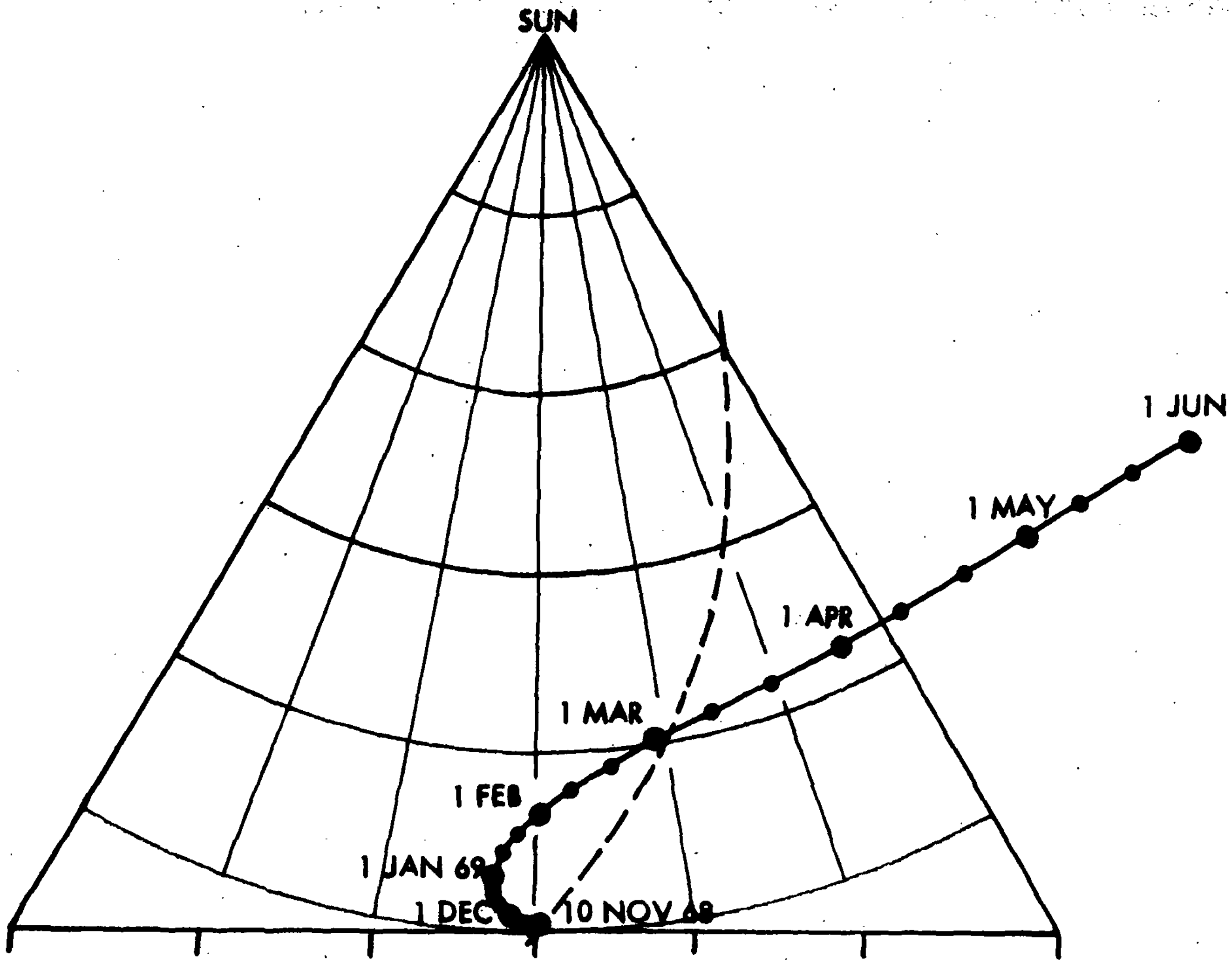

Figure 3. Pioneer 9 Trajectory on Ecliptic Plane, with respect to Fixed Sun-Earth Line. Small circles are ten-day markers.

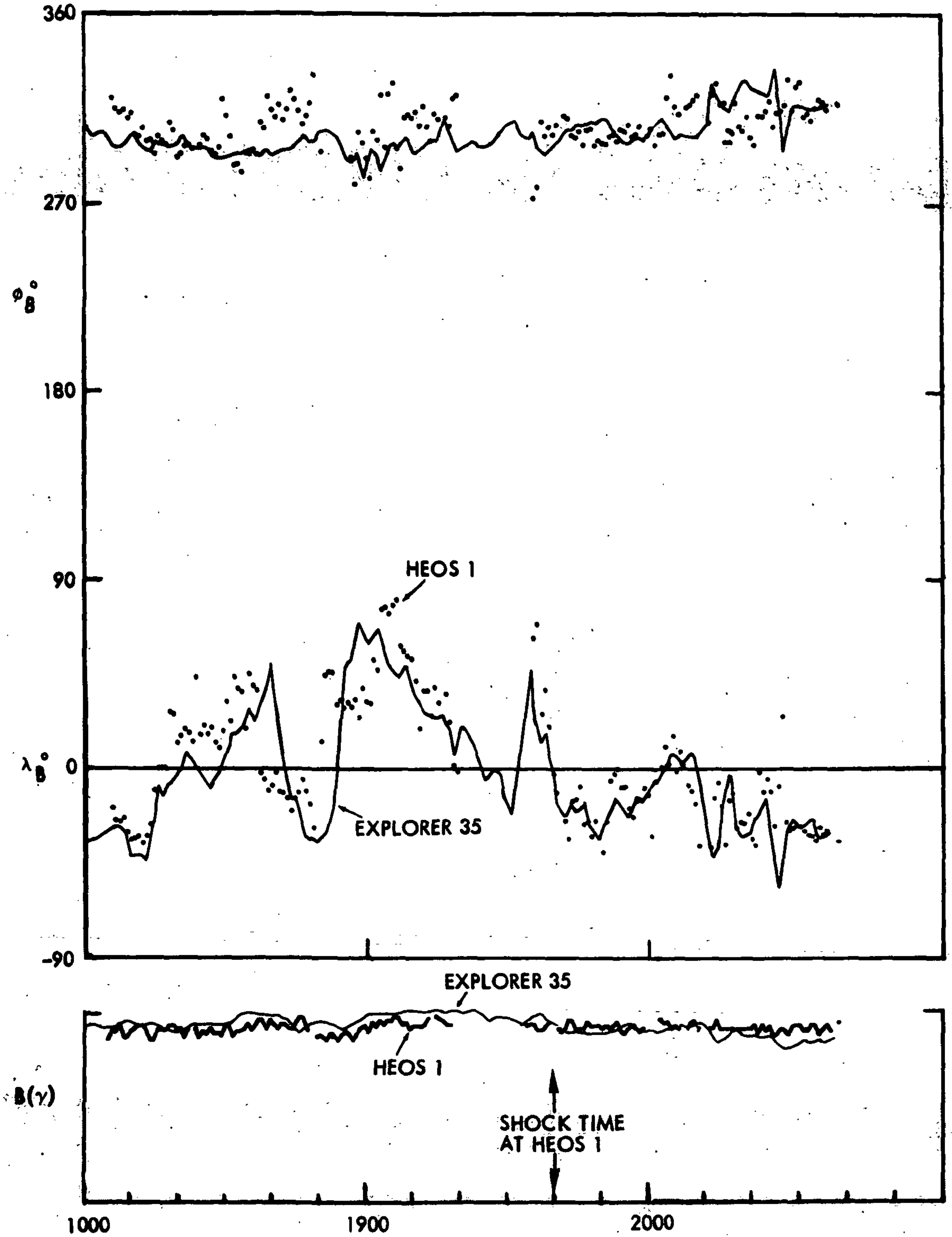

Figure 4. Interplanetary Field Behavior Recorded by Explorer 35 and HEOS 1 Around Time of 14 January Event

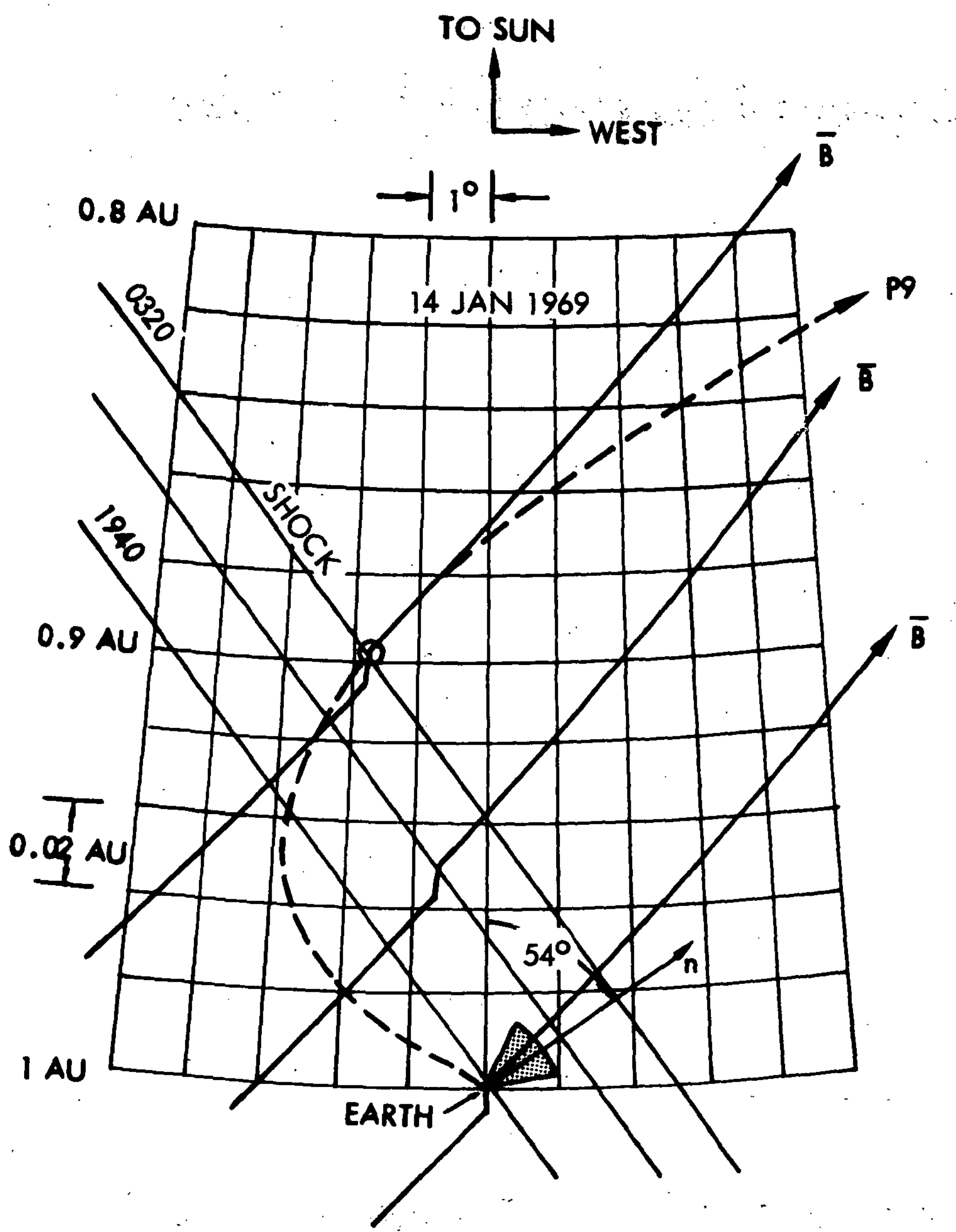

Figure 5. Approximate Geometry of Ecliptic Intersection of Hypothetical Planar Shock of 14 January, Travelling from Pioneer 9 to Earth. Shaded Sector Represents Range of Upstream (with respect to shock propagation) Magnetic Field Longitudes Observed During Travel Interval.

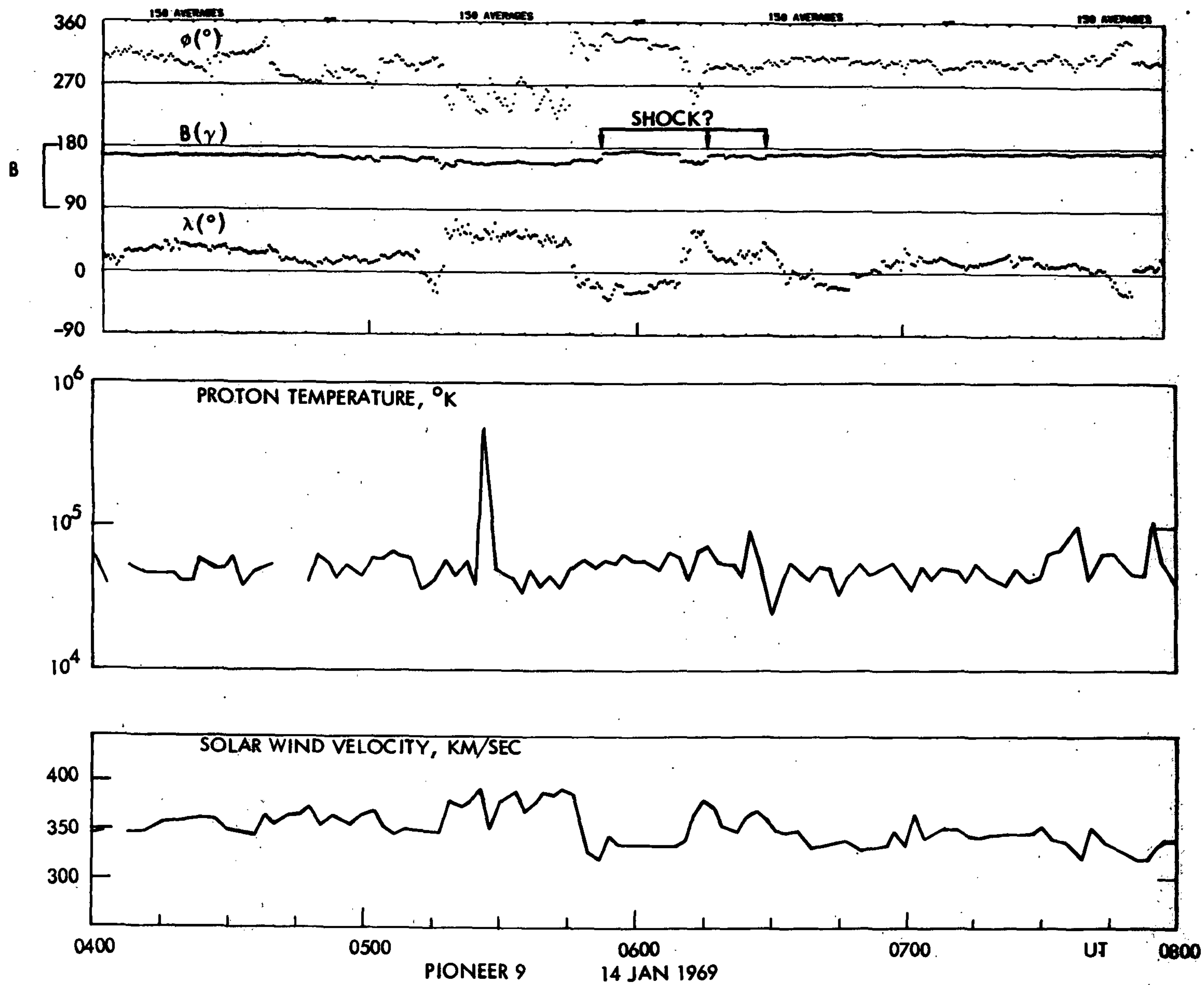

Figure 6. Interval Surrounding Probable Shock Passage at Pioneer 9 on 14 January 1969

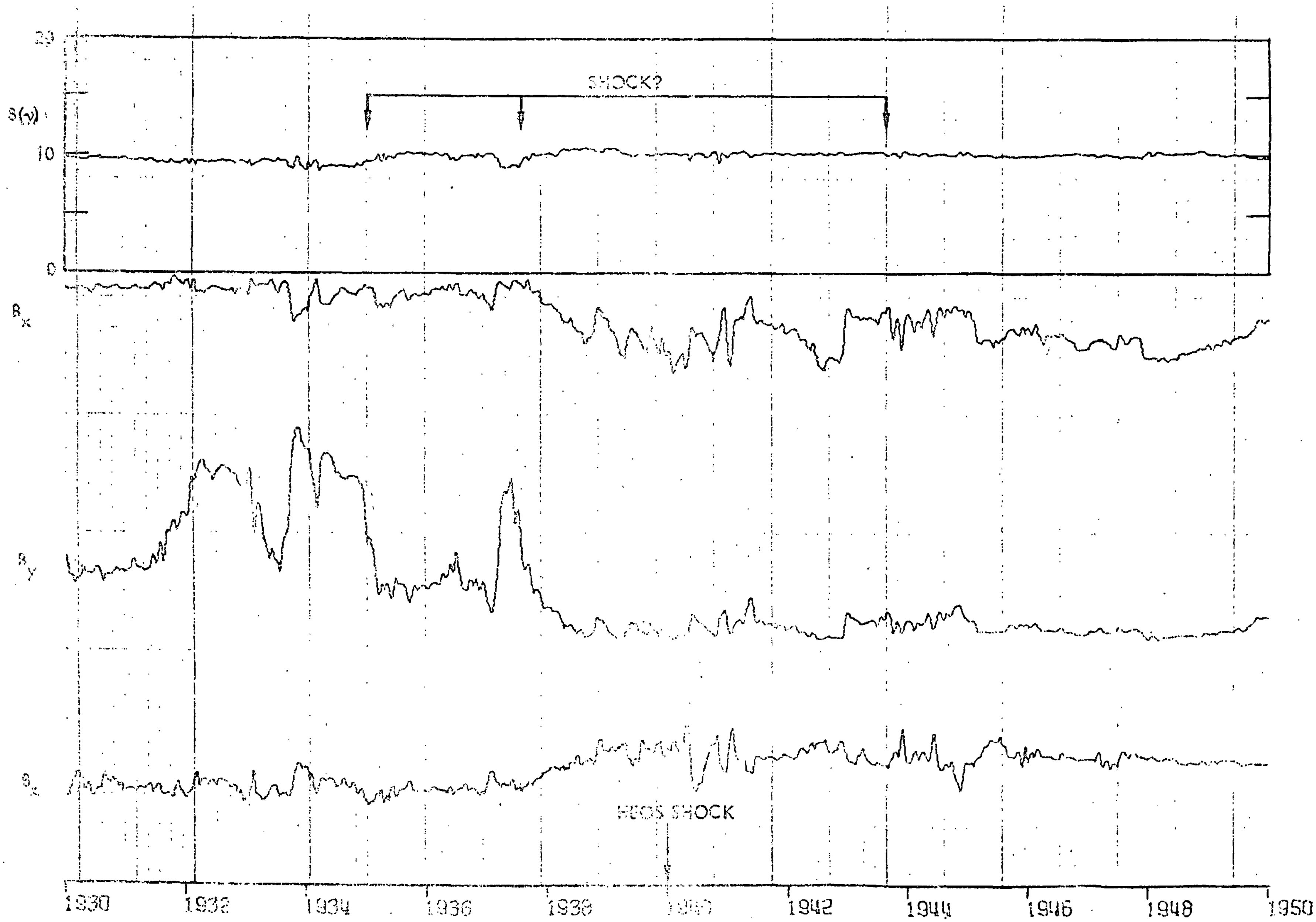

Figure 7. High Resolution Record of Shock Interval as Seen by OGO-5 Fluxgate Magnetometer (UCLA)