X-692-71-327
PREPRINT

NASA TM X- 65673

DISCONTINUITIES IN THE INTERPLANETARY MEDIUM AND THEIR RELATION TO THE PROPAGATION AND ACCELERATION OF COSMIC RAYS

L. F. BURLAGA

AUGUST 1971

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

DISCONTINUITIES IN THE INTERPLANETARY MEDIUM AND THEIR RELATION TO THE PROPAGATION AND ACCELERATION OF COSMIC RAYS

L. F. Burlaga

Laboratory for Extraterrestrial Physics
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Presented at the Seminar on Acceleration of Particles near the Earth, and in Interstellar Space, the Galaxy and the Metagalaxy.

Leningrad, Russia, July, 1971.

ABSTRACT

Recent measurements of the electron temperature ($T_e \approx (1.5\pm.5) \times 10^5\ {}^oK$) show that $\beta \equiv nk(Te + Tp)/(B^2/8\pi)=1$, indicating that magnetic and thermal pressures are equally important in the solar wind. Hydromagnetic theory, rather than hydrodynamics, must thus be used. MHD theory predicts several types of discontinuities. Tangential and rotational discontinuities are important in cosmic ray scattering theory. Observations show that most discontinuities in the interplanetary magnetic field are tangential. Forward and reverse fast shocks and slow shocks, predicted by hydromagnetic theory, have all been observed. Forward fast shocks can accelerate interplanetary particles, increasing their energy several fold to $\sim$ 1 MeV. Fermi acceleration of particles trapped between the shock and magnetic fluctuations can explain the observations.

I. Introduction

The aim of this paper is to discuss recent work by the author and his colleagues at Goddard Space Flight Center concerning discontinuities in the interplanetary medium and their relation to the propagation and acceleration of cosmic rays. Some related work by others will be referred to, but no attempt is made to represent all such work.

The discontinuities which are observed near 1 AU are hydromagnetic (MHD) discontinuities - hydromagnetic because the magnetic pressure is comparable to the thermal pressure near 1 AU. The thermal pressure has been uncertain until recently because of ignorance of the electron temperature T_e, but this situation has been remedied by both indirect and direct determinations of T_e, discussed in Section II. With this result, the important fact that the solar wind is a $\beta \approx 1$ plasma is now established.

Three kinds of MHD discontinuities are important to cosmic ray physics: tangential discontinuities, rotational discontinuities, and shocks. Tangential and rotational discontinuities are important in theories of cosmic ray propagation. Shocks are of special interest because they can accelerate cosmic rays.

Tangential and rotational discontinuities interact in distinctly different ways with cosmic rays. Despite their fundamental physical difference, however, it is difficult in practice to distinguish between a rotational and tangential discontinuity. This has led to a controversy concerning the basic questions of the relative abundance of these two types of discontinuity and their contribution to the power spectrum. The controversy seems to have been resolved, however. These results are presented in Section III together with the implications concerning cosmic ray propagation.

A series of interesting experimental and theoretical papers has recently appeared concerning the acceleration of particles by forward fast shocks. New kinds of shocks have also been discovered. Some of this work is discussed in Section IV.

II. β at 1 AU

One of the most important characteristics of the solar wind is the ratio of the thermal pressure to the magnetic pressure,

$$\beta = \frac{nk(T_p+T_e)}{B^2/8\pi}$$

Measurements of the density n, proton temperature T_p and magnetic field intensity B have been available for years, but the electron temperature T_e has remained obscure until recently. Now both indirect and several direct measurements of T_e have been obtained. The indirect measurements (Burlaga, 1968; Burlaga and Chao, 1971; Ogilvie and Ness, 1969) are based on the pressure balance condition at tangential discontinuities,

$$\left.\frac{B^2}{8\pi} + nk(T_p+T_e)\right|_1^2 = 0$$

The direct measurements are from electrostatic analyzers of Bame, Ogilvie, and Serbu. All of these determinations give essentially the same result,

$$T_e = (1.5 \pm .5)\times 10^5\,{}^{\circ}K$$

The electron temperature is nearly constant. It changes little with time. Unlike the proton temperature, T_e is independent of the bulk speed (Burlaga and Ogilvie, 1970a) (see Figure 1) and of gradients in the bulk speed (Burlaga et al., 1971). Burlaga et al. (1971) suggested that the near constancy of T_e is due to the high thermal conductivity of electrons near 1 AU this has been supported by more a detailed study of Hundhausen and Montgomery (1971).

Using $T_e = 1.4\times 10^5\,{}^{\circ}K$, Burlaga and Ogilvie (1970b) found that the most probable value of β was unity in the period June-November, 1967 (Figure 2). Thus, the magnetic pressure and the thermal pressure tend to be equal, and so $\beta \approx 1$. For this reason, one must use magnetohydrodynamics rather than hydrodynamics to describe the solar wind. The form of hydromagnetic theory which is applicable to the solar wind near 1 AU has been presented by Burlaga (1971a).

II. Tangential and Rotational Discontinuities

A. Scattering properties of RD's and TD's

Although several people have studied the interaction of cosmic rays with rotational and tangential discontinuities, most of these computations remain in their files; relatively little has been published. The theory is straightforward but the results are complex and the application to a realistic propagation situation is even more complicated. Here we shall simply say a few words about the important differences between scattering by RD's and TD's.

Consider the interaction of a charged particle with a tangential discontinuity. The discontinuity may be viewed as a surface in space. Generally, such surfaces are appreciably bent on a scale of .01 AU, at least near the earth, (Burlaga and Ness, 1969), but let us consider a plane surface. The magnetic field is parallel to the surface, but otherwise arbitrary. Consider the simplest case of oppositely directed fields on the two sides of the surface (Figure 3a). If the field is uniform, a particle will move along the surface, perpendicular to $\underset{\sim}{B}$. A tangential discontinuity can thus act as a highway in space, transporting particles perpendicular to $\underset{\sim}{B}$ at a rapid rate nearly equal to the particle speed. In the absence of such a discontinuity, the particles would be constrained to move parallel to $\underset{\sim}{B}$. Generally the fields are not anti-parallel, but make some small angle to one another (Burlaga, 1969a). The same principle applies however; the result is that the drift rate is lower in this case and the trajectory is more complicated.

In practice fluctuations, gradients, and the curvature of the surfaces will tend to remove particles from the surface; in addition one must consider how they arrive at a surface. This problem is full of complications. It is being studied by Fisk and Schatten who suggest that TD's near the sun may provide paths to carry particles rapidly from the east limb to the west limb.

Although TD's can transport particles, they do not act as scattering centers. A region containing only TD's and uniform fields would not act as a diffusing medium.

Now consider scattering by a rotational discontinuity. Such a discontinuity can be viewed as a kink in the magnetic field lines (Figure 3b). The problem was treated by Parker (1963). When particles move from a weak field to a strong field, some are reflected; the transmission coefficient is $\psi = \cos\theta$ where θ is the angle between B and the direction of the particle flux. When particles move from a strong field to a weak field some might be reflected, but they return and ultimately all are transmitted.

The result is that some rotational discontinuities can act as efficient scattering centers for cosmic rays. Thus, a region containing numerous rotational discontinuities could act as a diffusing medium.

Quenby (1971) has suggested that rotational discontinuities may have been the dominant scattering centers in a diffusive cosmic ray event that he analyzed. He also suggested, based on indirect evidence, that TD's and RD's occur equally frequently, but the results in the next section do not support this.

B. Relative number of TD's and RD's

As discussed above, TD's and RD's interact very differently with cosmic rays, so it is essential to determine the relative number of tangential and rotational discontinuities. This has been a controversial subject. Smith et al. (1970) stated that most interplanetary discontinuities are rotational, Davis (1970) and Quenby (1971) suggested that tangential and rotational discontinuities occur with nearly equal frequency, and Ness et al. (1966) held the view that most discontinuities are tangential. A meaningful discussion of this subject requires an operational definition of a discontinuity. We shall use the definition given by Burlaga (1969a) for a "directional discontinuity", which, with some simplification, is a change $>30^{\circ}$ in the magnetic field direction which occurs in <30 sec as a result of the motion of the discontinuity past the spacecraft. (Some directional discontinuities are shown in Figure 4). This definition includes the discontinuities discussed by Ness, it is nearly equivalent to that for the discontinuities analyzed by Siscoe et al. (1968), and it specifies the kinds of discontinuities referred to by Smith et. al. (1970).

Recent results of Burlaga (1971) indicate that most directional discontinuities are tangential. The argument is as follows: If directional discontinuities are rotational, then the charge in the velocity across a discontinuity would be related to the change in the magnetic field. Specifically, Hudson (1970) showed that

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

where

$$A \equiv \left(1 - \frac{P_{11} - P_{11}}{B^2 / 4\pi} \right)^{1/2} \tag{2}$$

This can be written

$$\frac{V_{1i} - V_{2i}}{Q_i} = \pm A \tag{3}$$

where

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

A depends on the thermal anisotropy of the plasma and is .9 ± .1 for typical solar wind conditions near 1 AU.

Applying the above test to the 200 discontinuities which passed Pioneer 6 in the period Dec. 18-25, 1965, Burlaga (1971b) found the result in Figure 5. Clearly, (3) is not satisfied. Instead, the most probable value of ΔV, is zero. Thus, most directional discontinuities are <u>not</u> rotational discontinuities. Since they do not have signatures characteristic of shocks, we infer that most of the discontinuities are tangential.

Directional discontinuities are not isolated features like shocks. They form a complicated network of surfaces which underlie the basic structure of the solar wind, as suggested by the artist's drawing in Figure 6, from Burlaga (1971c). They occur throughout the region between 8 AU and 1 AU (Burlaga 1971b) and are separated by ~ .01 AU (Burlaga, 1969). This separation is comparable to the mean free path obtained from models of solar cosmic ray events; since directional discontinuities are mostly tangential and thus do not scatter cosmic rays appreciably, this relation is probably coincidental.

What then is the role of directional discontinuities in cosmic ray transport? Although they do not act as scattering centers, they must be considered in cosmic ray diffusion theories for the reason discussed in the next section.

C. Contribution of Discontinuities to Power Spectra

Sari and Ness (1969) showed that at certain times directional discontinuities dominate the power spectrum, i.e. The power spectrum calculated from the discontinuities alone is identical to the measured power spectrum. This presents a problem for cosmic ray propagation theories: calculating the diffusion coefficient from the power spectrum using the standard scattering theory would imply appreciable scattering and diffusion in this case, whereas in fact the particles would not diffuse appreciably since most of the power is due to tangential discontinuities.

Clearly, one must determine how much power discontinuities contribute to the spectrum before he calculates diffusion coefficients from a theory which assumes scattering by waves. It is important, therefore, to determine how frequently the spectrum is dominated by discontinuities and what fraction of the power is due to discontinuitie at other times. This problem is being studied by Sari at Goddard. His investigation is not complete, but the preliminary results indicat that discontinuities dominate the spectrum only occasionally, when the solar wind is quiet (low speed and temperature). At other times, discontinuities make a similar contribution to the power spectrum, but in addition waves, non-linear fluctuations, and various types of static structures contribute to the spectrum in still greater amounts. An example of the type of static structures that are present is shown in Figure 7 from Burlaga and Ogilvie (1970b). Any analysis of cosmic ray propogation which uses power spectra should consider the kinds of features that are contributing to the spectrum during the interval of interest. This changes appreciably from day to day.

IV. Shocks

A. Existence of various types of shocks. Shocks can be classifie in several ways (e.g.; see Burlaga, 1971a). Here we shall consider 2 types of shocks - fast shocks and slow shocks. Relative to the solar wind, each of these types can propagate either away from the sun (forward shocks) or toward the sun (reverse shocks). One can thus speak of four kinds of shocks:

forward fast shock

reverse fast shock

forward slow shock

reverse slow shock

The reverse shocks move away from the sun even though they move toward the sun relative to the plasma, because they are convected outward by the solar wind. An important difference between a fast shock and a slow shock is that the magnetic field intensity increases across a fast shock but decreases across a slow shock.

The existence or fast forward shocks is well known. Currently, interest is centered on the shape of the shock surfaces, the interaction of shocks with other discontinuities, and the effects of the thermal anisotropy on the jump conditions. Lepping and Argentiero (1971) have developed a technique for accurately calculating shock normals which will be of use in studying the first two problems above. Lepping is currently studying the interaction of a shock with the bow shock. He has also shown that the anisotropy does not significantly change the jump conditions, i.e. the use of the Rankine Hugoniot conditions for an isotropic medium is a good approximation for fast shocks.

The existence of a reverse fast shock in the solar wind was demonstrated by Burlaga (1970) using Explorer 34 plasma and magnetic field data obtained by Ogilvie and Ness, respectively. The basic observations are shown in Figure 8 together with a plot of the pressure $P = B^2/(8\pi) + nk(T + T_e)$. n, T, and B decrease with time because one sees the back side of the shock first. This was, in fact, a perpendicular shock, i.e. $\underset{\sim}{B}_1$ and $\underset{\sim}{B}_2$ were perpendicular to the shock normal and parallel to one another. As required for a perpendicular shock, $B_1/B_2 = \frac{n_1}{n_2}$. The shock speed and direction were determined using simultaneous observations from Ness' magnetometers on Explorers 33, 34, and 35. The shock normal was found to be in the ecliptic plane and perpendicular to the spiral direction ($\sim 45^{\circ}$ from the earth-sun line). It moved toward the sun, relative to the solar wind, at a speed V = 141 km/sec. It was verified that the Rankine-Hugoniot conditions were satisfied for this shock. The origin of this shock is a mystery. The shock appears ahead of a high speed stream, suggesting it might be due to a stream-stream interaction. This should produce both a forward and a reverse shock. However a forward shock was not seen.

Evidence for forward slow shocks in the solar wind was first published by Chao and Olbert (1970). Additional evidence for such a shock was presented by Burlaga and Chao (1971) (see Figure 9). The latter shock occurred at ~1423 UT on Jan. 20, 1966. Note that the shock does not appear as a sharp discontinuity in the magnetic field data, and that there are large fluctuations in $\underset{\sim}{B}$ near the shock. These characteristics, common to all the slow shocks that have been observed, make the identification of slow shocks rather difficult. The procedure used by Burlaga and Chao (1970) was to find a solution to the Rankine-Hugoniot equations which was consistent with the observations within the uncertainties due to the measurements and fluctuations, and which satisfied other necessary conditions for a slow shock. The solutions to the R-H equations are shown by the horizontal lines in Figure 9. Clearly they are consistent with the observations, but one would have hoped for smaller fluctuations in the data. Additional evidence supporting the identification of the discontinuity in Figure 9 as a slow shock is the following: (a) predicted values of $\underset{\sim}{V}_2$ are in good agreement with the observed values, (b) the flow speed normal to the shock did decrease across the shock (from 37 km/sec to 27 km/sec), (c) the Alfven Mach number was less than 1 on both sides of the shock (.9 ahead and .8 behind), and (d) the slow mode Mach number was greater than 1 ahead of the shock (1.3) and less than 1 behind it (.8), as required by the theory of slow shocks.

A reverse slow shock was also found in the Pioneer 6 data by Burlaga and Chao (1971). The observations and a solution to the Rankine-Hugoniot equations are shown in Figure 10. Here too it was found that (a) predicted values of $\underset{\sim}{V}_2$ are in agreement with observed values, (b) the flow speed decreased across the shock (from 29 km/sec to 23 km/sec), (c) the Alfven number was <1 on both sides of the shock (.9 ahead, .8 behind), and (d) the slow mode Mach number was >1 ahead of the shock (1.2) and <1 behind it (.8).

Thus, there is evidence for all 4 of the types of shocks listed at the beginning of this section. Ivanov (1970) predicted still another kind of shock, which he called a "rotational discontinuity" because it should propagate at nearly the Alfven speed. The coplanarity theorem applies for such a shock, but unlike most shocks, $n_1=n_2$. The magnitude of $\underset{\sim}{B}$ does change, and the change in entropy is due to a change in the anisotropy. Ivanov suggested that most of the discontinuities in Burlaga (1969b) were such shocks, but a more detailed study by Burlaga (1971c) shows that this is not the case. Burlaga and Chao (1971) show that discontinuities with $B_1 \neq B_2$ and $n_1=n_2$ seldom if ever occur.

Given the existence of fast and slow shocks, one may now ask how they relate to cosmic rays. In the case of fast forward shocks there is a very fundamental relation which is discussed in the next section - shocks can accelerate cosmic rays. Whether or not reverse fast shocks and slow shocks can accelerate particles remains to be determined. This problem has not yet been investigated, but it promises some interesting results.

B. Proton acceleration by forward fast shocks.

Ogilvie and Arens (1971) showed that increases in the flux of 1-10 Mev protons are sometimes associated with forward fast shocks (Figure 11). Similar increases were observed by Armstrong et al., (1970) who found that heavy particles ($Z>2$) are accelerated as well as protons but electrons are not accelerated. Such increases occur only when there is an appreciable flux of 1-10 Mev particles present before the arrival of the shock. The peak flux is ≈ 10 times this ambient flux. The spectra of the ambient flux tends to be rather steep. These increases are brief (≈ 10 min), and are thus distinct from the kind of shock-associated events discussed by Vernov et al. (1970).

It is generally agreed that such increases are due to the acceleration of ambient energetic particles. Acceleration lifts the more abundant low energy particles above the detector threshhold and thus gives an apparent increase in the flux of particles at energies near the threshhold. The flux increase should be greater for steeper spectra, for a given acceleration mechanism; the observations of Ogilvie and Arens show this effect.

The nature of the accelerating mechanism is controversial. Axford and Reid (1963) had suggested that particles would be accelerated if they were trapped between the earth's bow shock and an interplanetary shock moving toward the earth. This mechanism requires only that there is a certain probablility for reflection of particles by the shock and that the magnetic field lines which guide the particles should intersect both shocks. The latter condition was met for all except perhaps one of the five shock associated increases observed by Ogilvie and Arens, so their results were interpreted as support for the Axford-Reid model. They did not exclude other accèlerating mechanisms,however.

An alternative accelerating mechanism was proposed by Fisk (1971). His idea is that particles are retained near the shock by diffusing in the magnetic field fluctuations which are ahead of the shock. In this model, the fluctuations play the role of the bow shock in the Axford-Reid model.

The flux of reflecting low energy particles at the shock is

$$S_n = V_s U_r - \frac{2}{3} V_s \frac{\partial}{\partial T} (TU_r) \qquad (5)$$

where V_s is the shock speed, T the particle kinetic energy and U_r is the differential number density of reflecting particles which is proportional to the upstream density of particles, U. The density of particles U is determined by solving the convection diffusion equation

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial r} (V'U') = \frac{\partial}{\partial r} \left(K' \frac{\partial U'}{\partial r}\right), \qquad (6)$$

where V' and K' are the wind speed and diffusion coefficient ahead of the shock. A similar equation describes particles behind the shock, U''. The solution for large times is

$$U' \sim A\left(\frac{T}{T_1}\right)^{-\mu} \left[\frac{C}{1-C} + \frac{(T/T_1)^{\mu-1}(3C-1)}{2(C-1)} e^{\frac{V_2 \eta}{K'}} + 1\right], \qquad (7)$$

where $\eta \equiv r - V_s t$ (V_s being the shock speed), $V_2 = V_s - V'$, and $C = (1+2\mu)/3$ (μ being the spectral index, $U_a = A(T/T_1)^{-\mu}$). It is assumed that the shock is nearly a perfect reflector for low energy particles. Equation (7) has several free parameters: K', T_1, μ, V_s and V'. Only 2 of these parameters can be determined by fitting the data. Fisk uses typically measured values for V_s and V', and he then finds pairs of value of μ and T_1 which give the measured peak intensity at the shock. K' is determined uniquely. An example of such a fit for the Nov. 29, 1967 event is shown in Figure 12. It gives $K' \approx 10^{18} cm^2/sec$, or $K_{\parallel}$ (parallel to $\underset{\sim}{B}$) $\sim 10^{19} cm^2/sec$. Clearly, Fisk's model can fit the observations and gives reasonable values of K', but the fit is not unique.

If Fisk's model is correct, one expects to find shock-associated increases far from the earth. On the other hand, if the Axford-Reid mechanism is the only one that operates, one should not find shock-associated increases far from the earth. Well, such an increase has been observed by a deep space probe, Pioneer 8, 1.5×10^8 km (~1 AU) from the earth by Palmeira et al. (1971). Strong support for Fisk's mechanism!

But further complications were revealed in a paper by Singer (1970). For example, he observed strong anisotropies in the energetic particles near the shock, which seems inconsistent with Fisk's idea of diffusion. He also found that the intensity maximum can occur 5-10 min after the shock. Singer believes that the gain of a factor of ~5 occurs in a single encounter rather than by multiple encounters as in the Fisk and Axford-Reid models.

Clearly, much remains to be learned about acceleration by shocks.

V. Summary

This brief review has considered several distinct, but closely related topics: the electron temperature and value of β in the solar wind, the relative number of tangential and rotational discontinuities and their relation to the theory of cosmic ray propagation, the existence of various types of shocks, and the acceleration of particles by fast forward shocks. Rapid progress in these areas has been made in recent years due to the availability of good data and to the development and application of relevant theories. Several new problems have also come into focus: What is the thermal conductivity of electrons? What are the origins of the various discontinuities? How does one describe cosmic ray propagation in a medium where the power is due to structures other than linear waves? How are particles reflected by a shock? Which of the several accelerating mechanisms is dominant in various circumstances? Hopefully, the answers to these questions will appear within the next several years.

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Figure Captions

Fig. 1 Temperature speed relation. Explorer 34 observations show a linear relation between $\sqrt{T_p}$ and U, where T_p is the proton temperature and U is the bulk speed. Observations from other experiments fall on the same line. The electron temperature observations, although still sketchy, suggest that T_e is independent of U; this is indicated by the horizontal line. Some theoretical models are also shown. See Burlaga et al (1970) for the details.

Fig. 2 Distribution of β based on Explorer 34 data. The most probable value is 1.0 ± 1.

Fig. 3 Tangential and rotational discontinuities. The top illustration shows how a tangential discontinuity (viewed edge on) transports a cosmic ray along it surface when $\underset{\sim}{B}_1$ and $\underset{\sim}{B}_2$ are antiparallel. The lower illustration shows a special kind of rotational discontinuity.

Fig. 4 Some directional discontinuities.

Fig. 5 Distribution of $\Delta V/Q$ for $\approx$ 200 directional discontinuities. Since the peak does not occur near .9, most of these discontinuities are not rotational.

Fig. 6 Simplified view of 3 discontinuity surfaces and magnetic fields between them, illustrating how a .05 AU segment of the solar wind might look.

Fig. 7 The magnetic pressure P_B and thermal pressure P_k tend to be anticorrelated on a scale of .01 AU tending to keep the total pressure P_T constant on that scale, even though P_T changes on a larger scale. The anticorrelation suggests static features. These will contribute to the power spectrum of B.

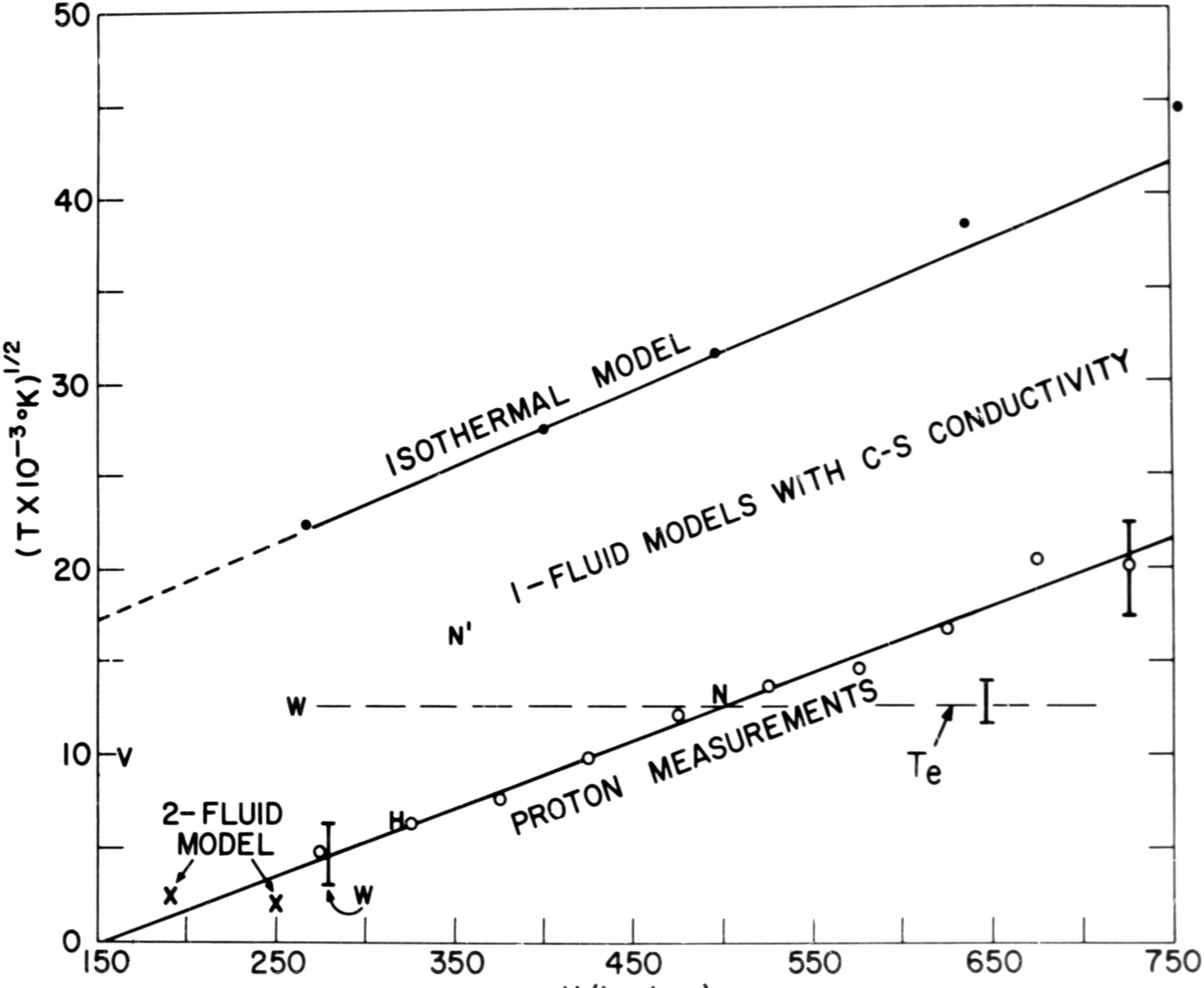
Fig. 8 A reverse fast shock.

Fig. 9 A forward slow shock.

Fig. 10 A reverse slow shock

Fig. 11 This shows an increase in the intensity of ~ 1 MeV cosmic rays ahead of a shock.

Fig. 12 This shows Fisk's theoretical fit to the observations shown in Figure 11.



ISOTHERMAL MODEL
1-FLUID MODELS WITH C-S CONDUCTIVITY
PROTON MEASUREMENTS
2-FLUID MODEL
N'
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W
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Te
(T X 10⁻³ °K)^1/2
0
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30
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250
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450
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650
750
U (km/sec)

Figure 1

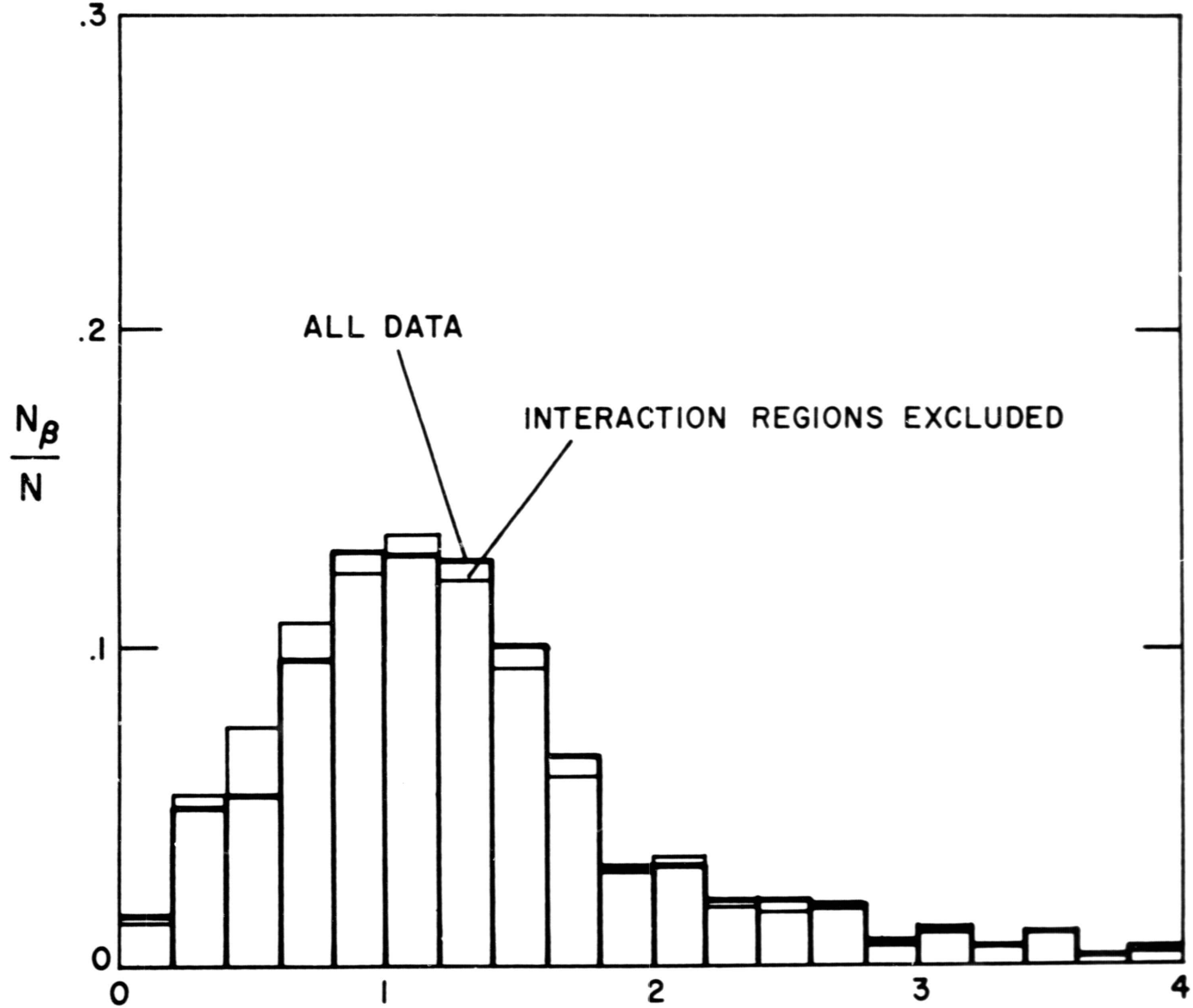
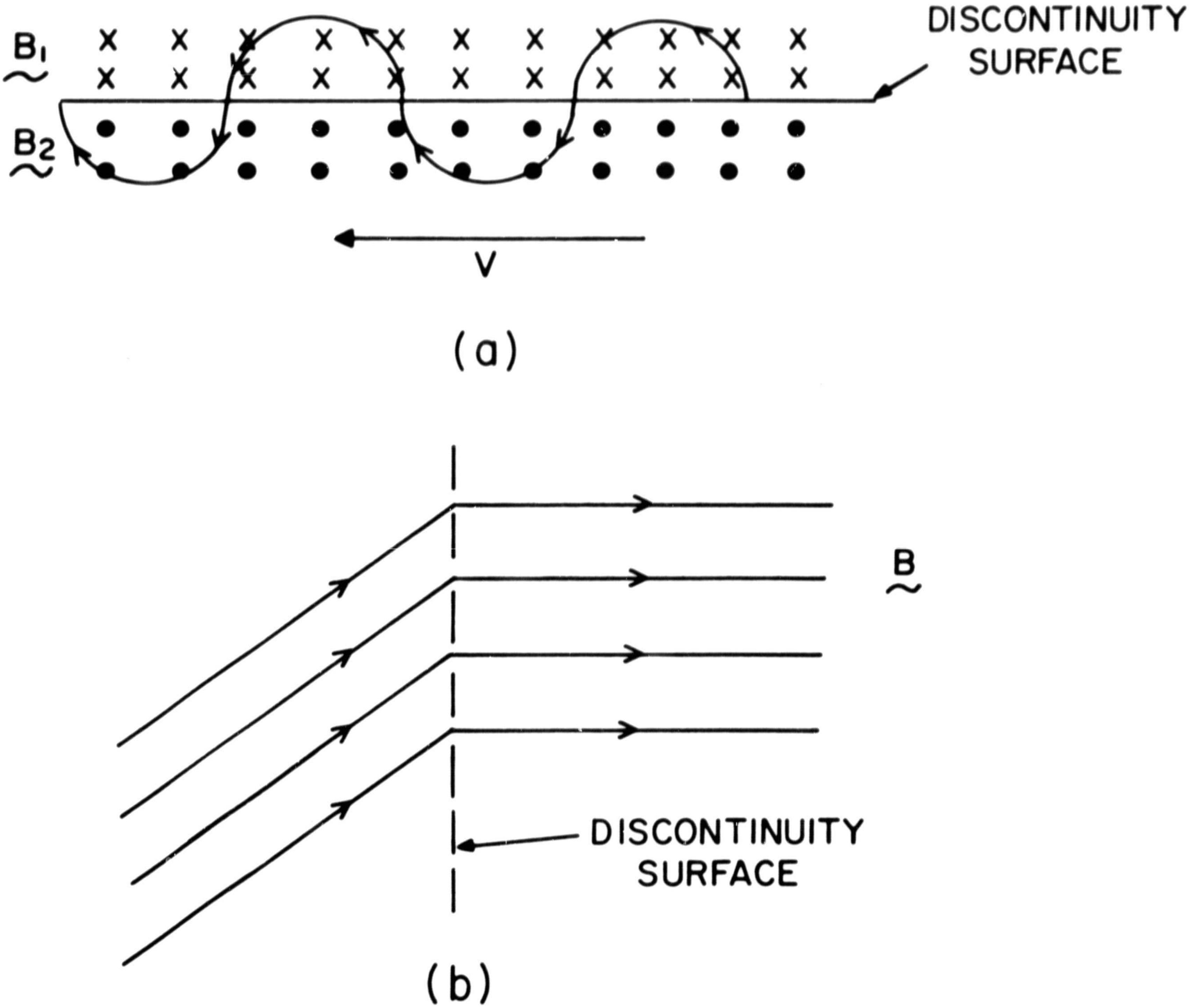
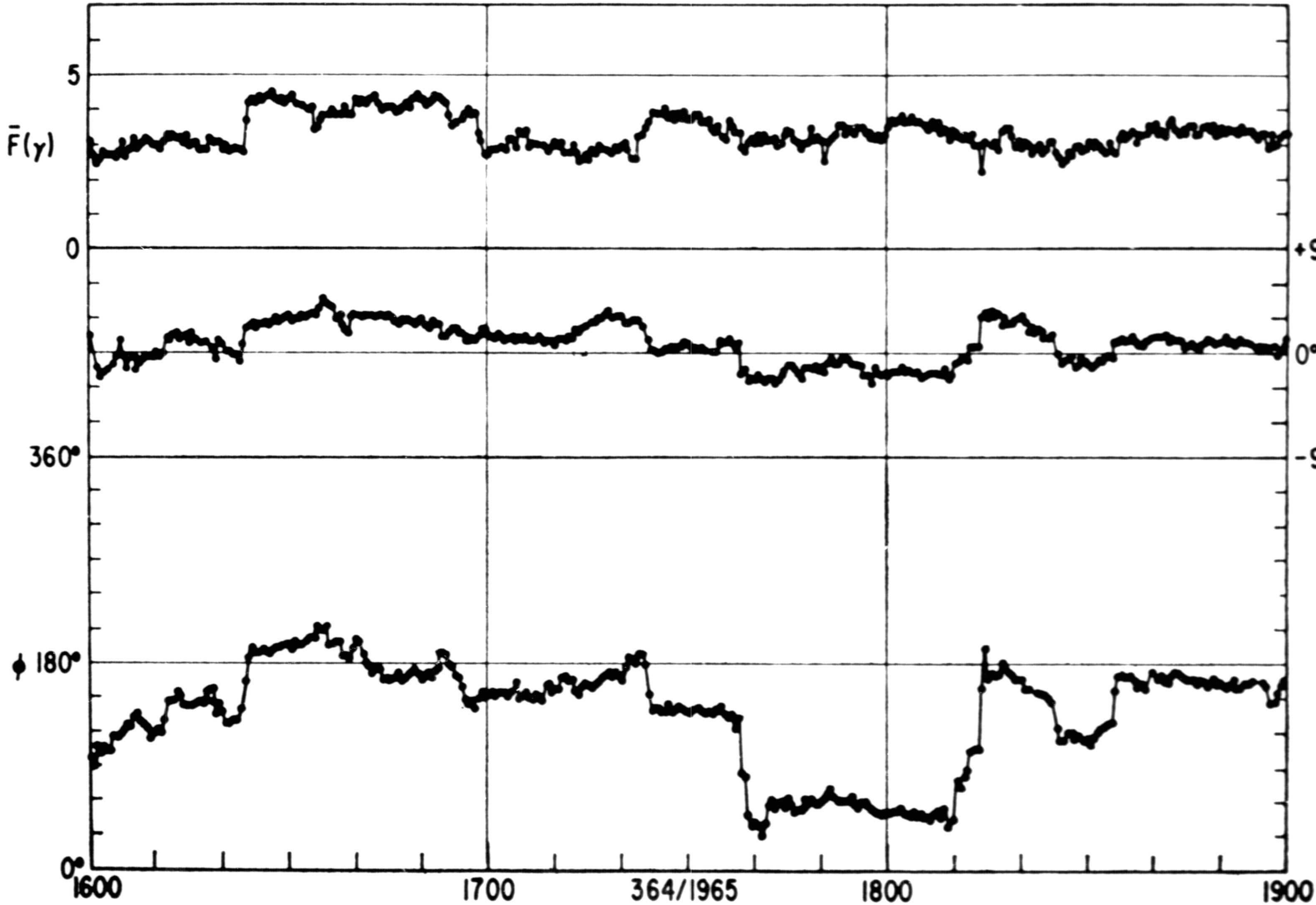

.3
.2
.1
0
$\frac{N_\beta}{N}$
ALL DATA
INTERACTION REGIONS EXCLUDED
0
1
2
3
4

Figure 2



DISCONTINUITY SURFACE
$\underset{\sim}{B}_1$
$\underset{\sim}{B}_2$
V
(a)
$\underset{\sim}{B}$
DISCONTINUITY SURFACE
(b)

Figure 3



INTERPLANETARY MAGNETIC FIELD PIONEER VI

Figure 4

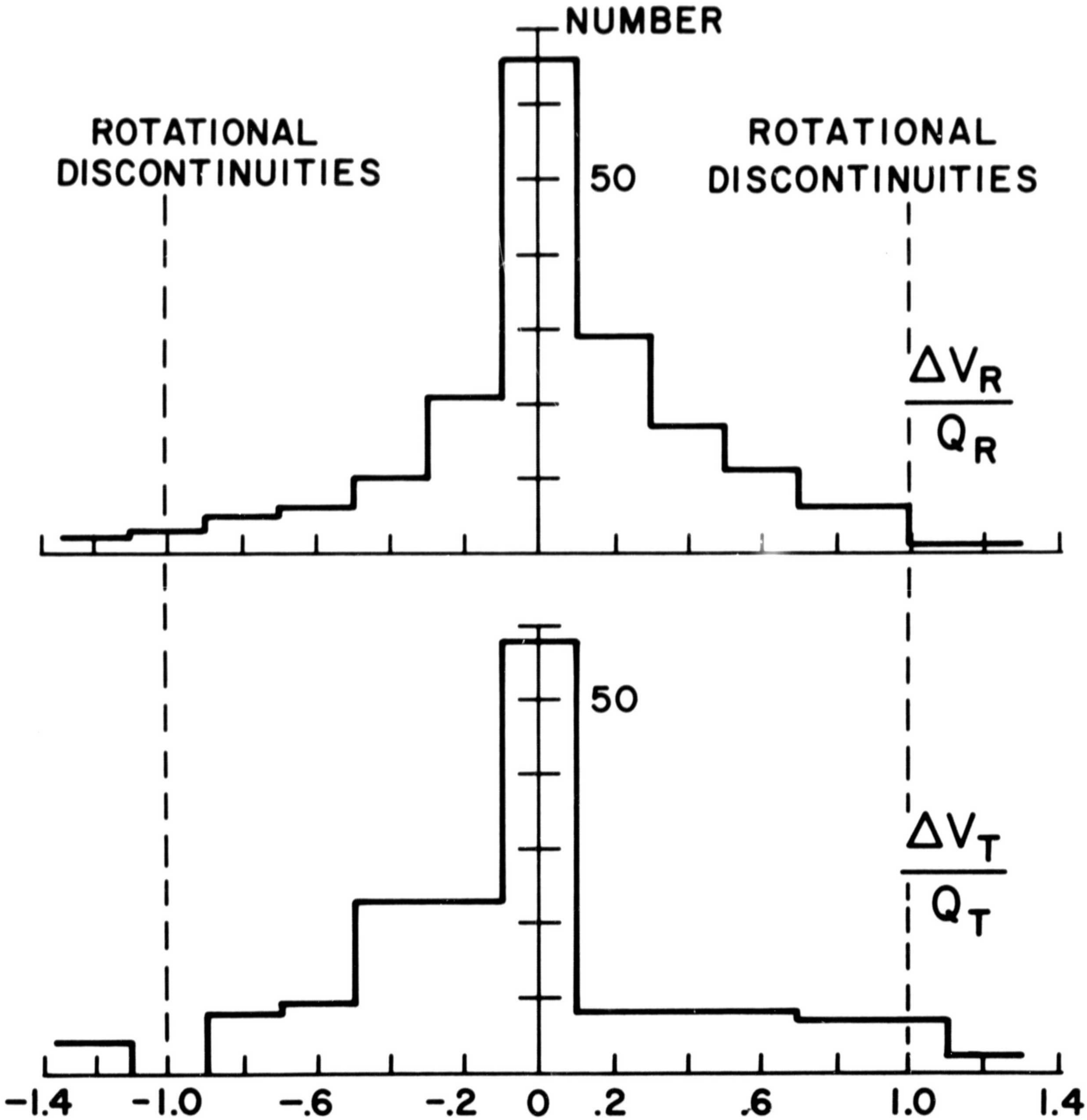
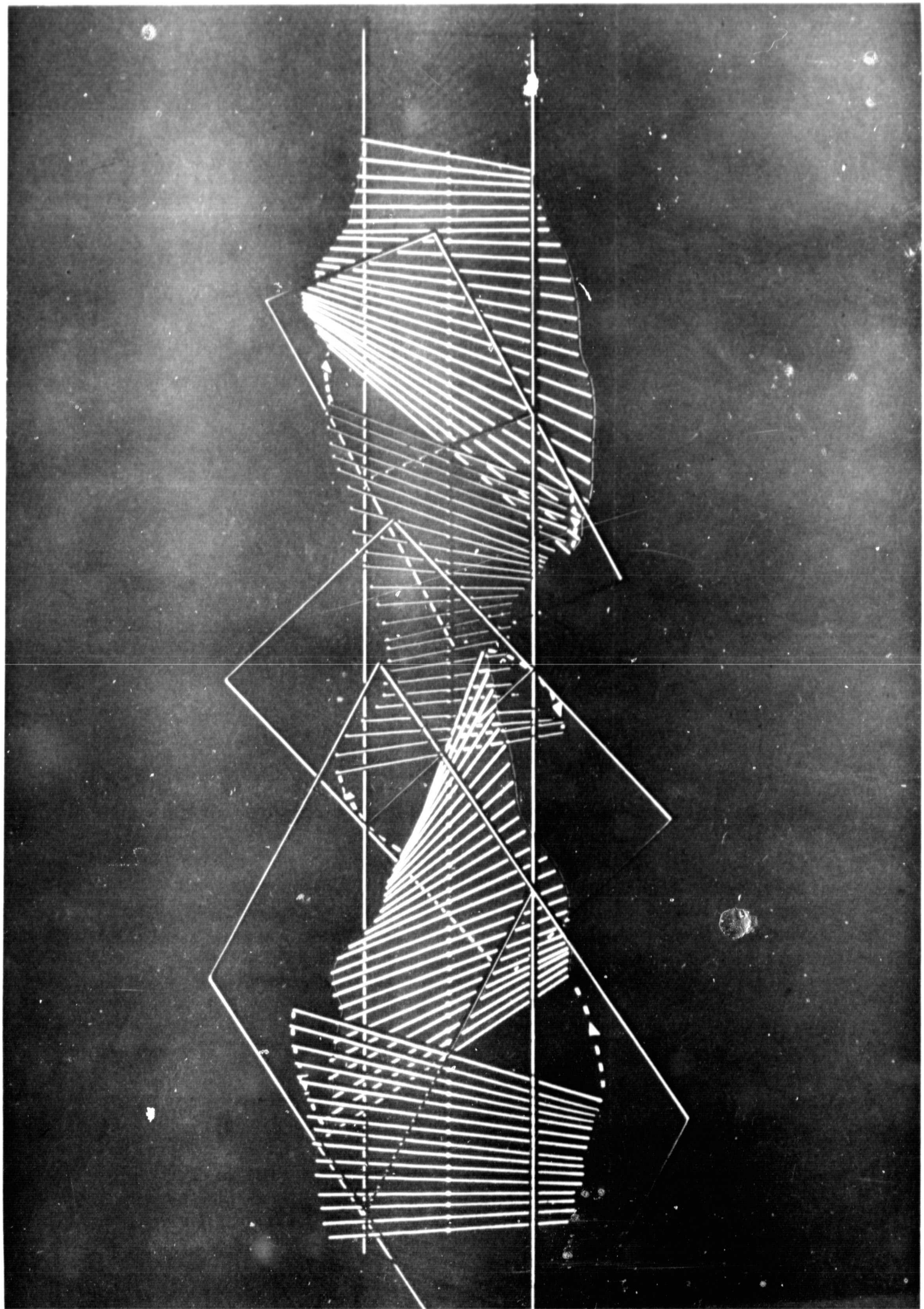
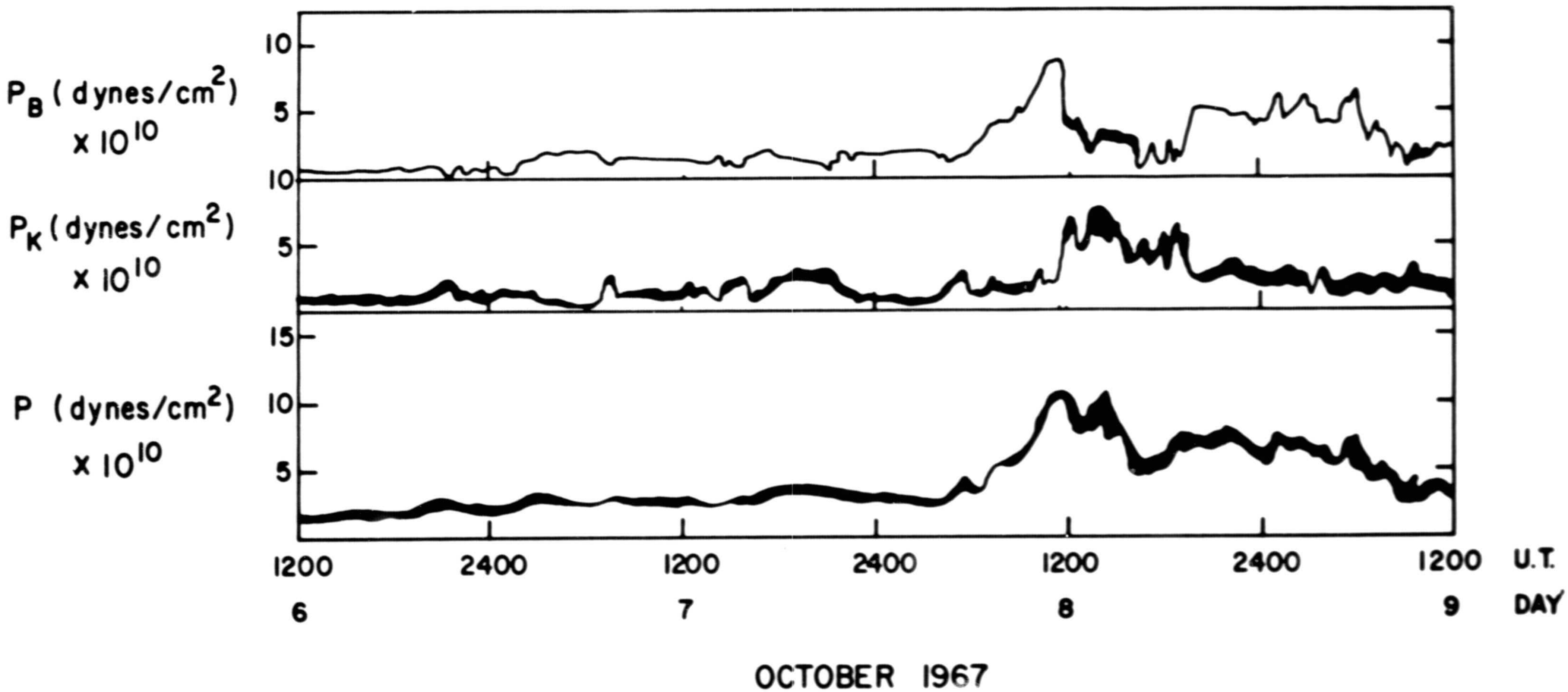

NUMBER
ROTATIONAL DISCONTINUITIES
ROTATIONAL DISCONTINUITIES
50
$\frac{\Delta V_R}{Q_R}$
50
$\frac{\Delta V_T}{Q_T}$
-1.4
-1.0
-.6
-.2
0
.2
.6
1.0
1.4

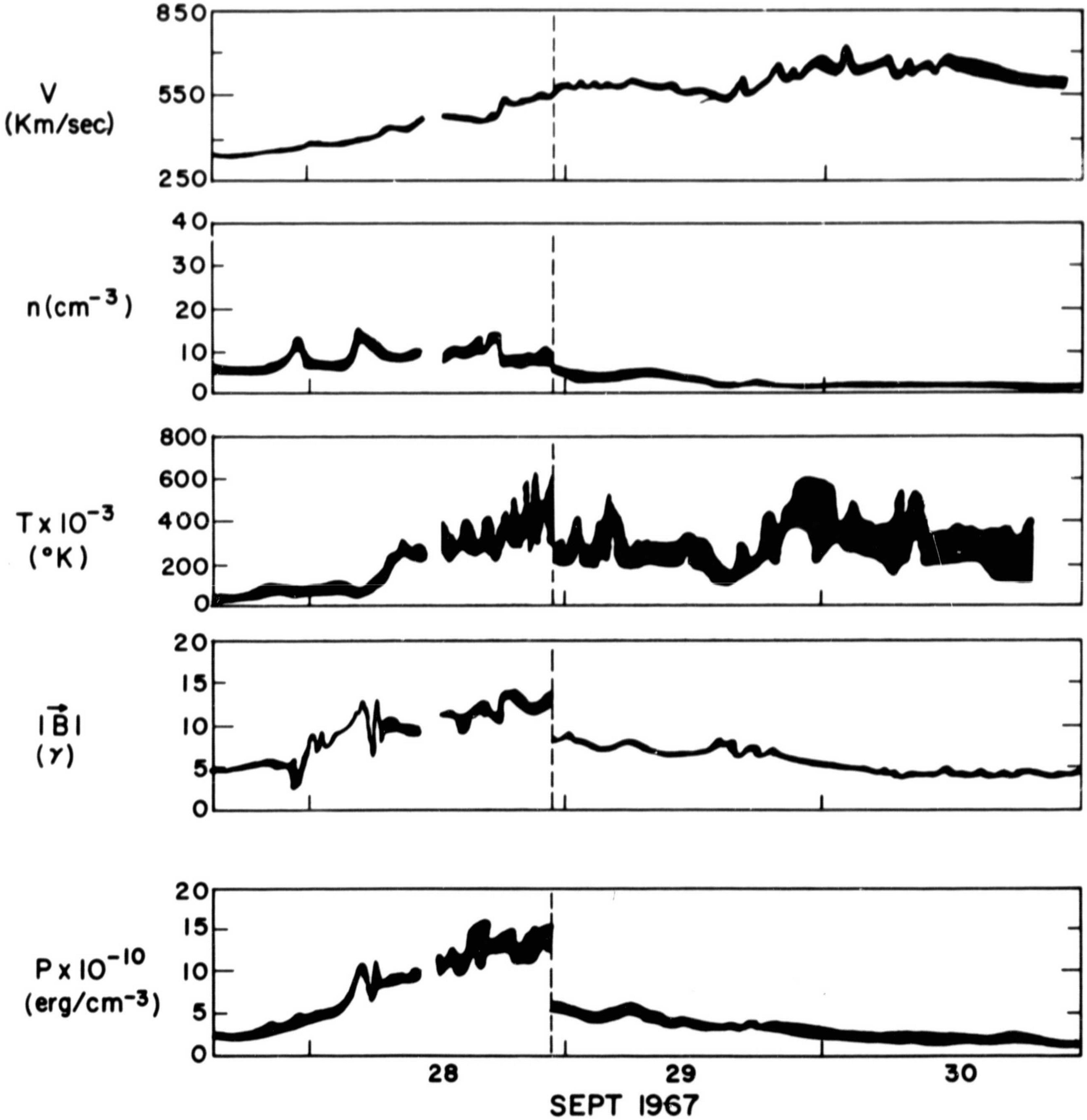
Figure 5





P_B (dynes/cm^2) x 10^{10}
P_K (dynes/cm^2) x 10^{10}
P (dynes/cm^2) x 10^{10}
10
5
10
5
15
10
5
1200
2400
1200
2400
1200
2400
1200
U.T.
6
7
8
9
DAY
OCTOBER 1967

Figure 7



V
(Km/sec)
850
550
250
n(cm^{-3})
40
30
20
10
0
T x 10^{-3}
(°K)
800
600
400
200
0
|$\vec{B}$|
(γ)
20
15
10
5
0
P x 10^{-10}
(erg/cm^{-3})
20
15
10
5
0
28
29
30
SEPT 1967

Figure 8

FORWARD SLOW SHOCK
JANUARY 20, 1966

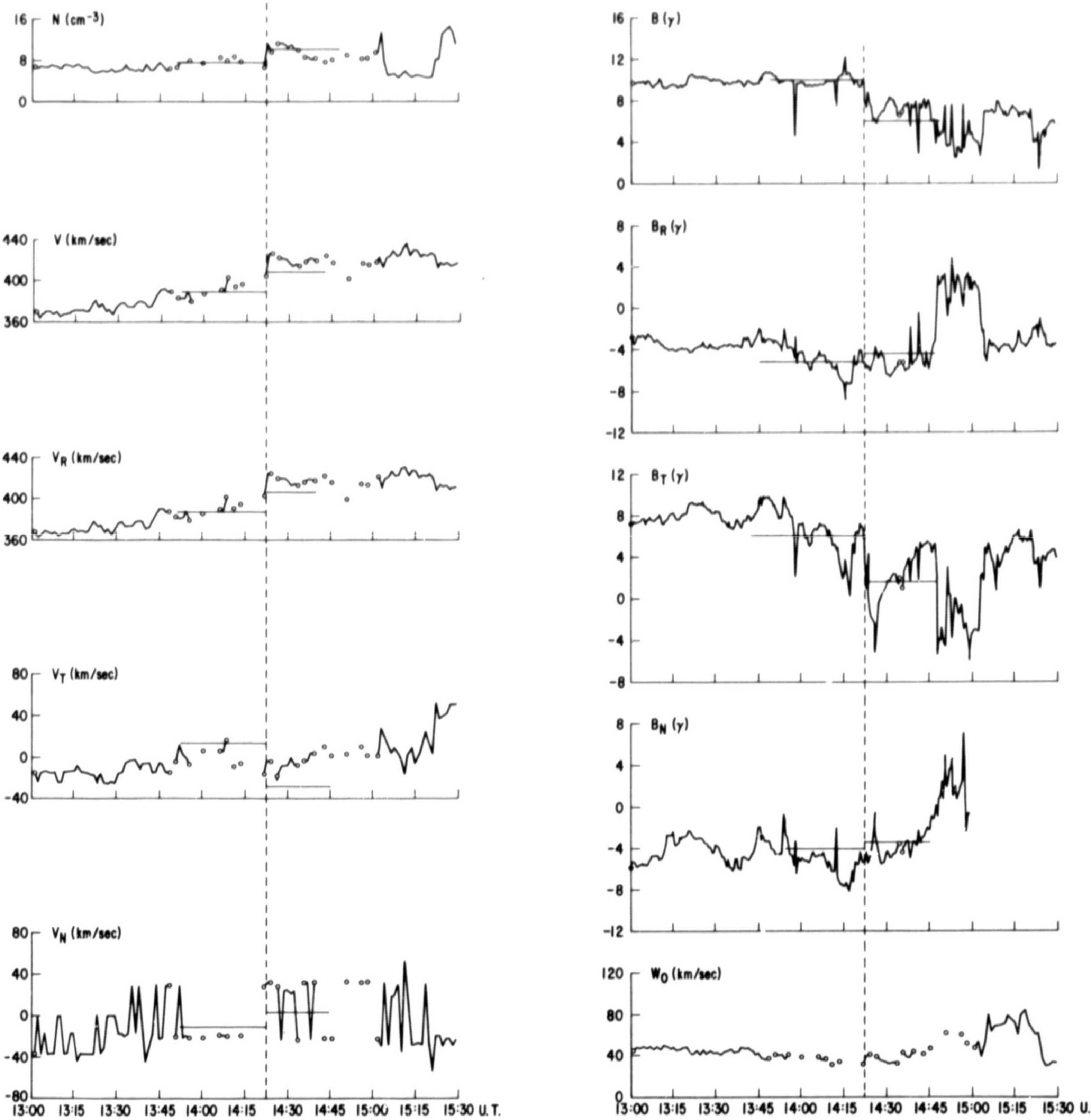
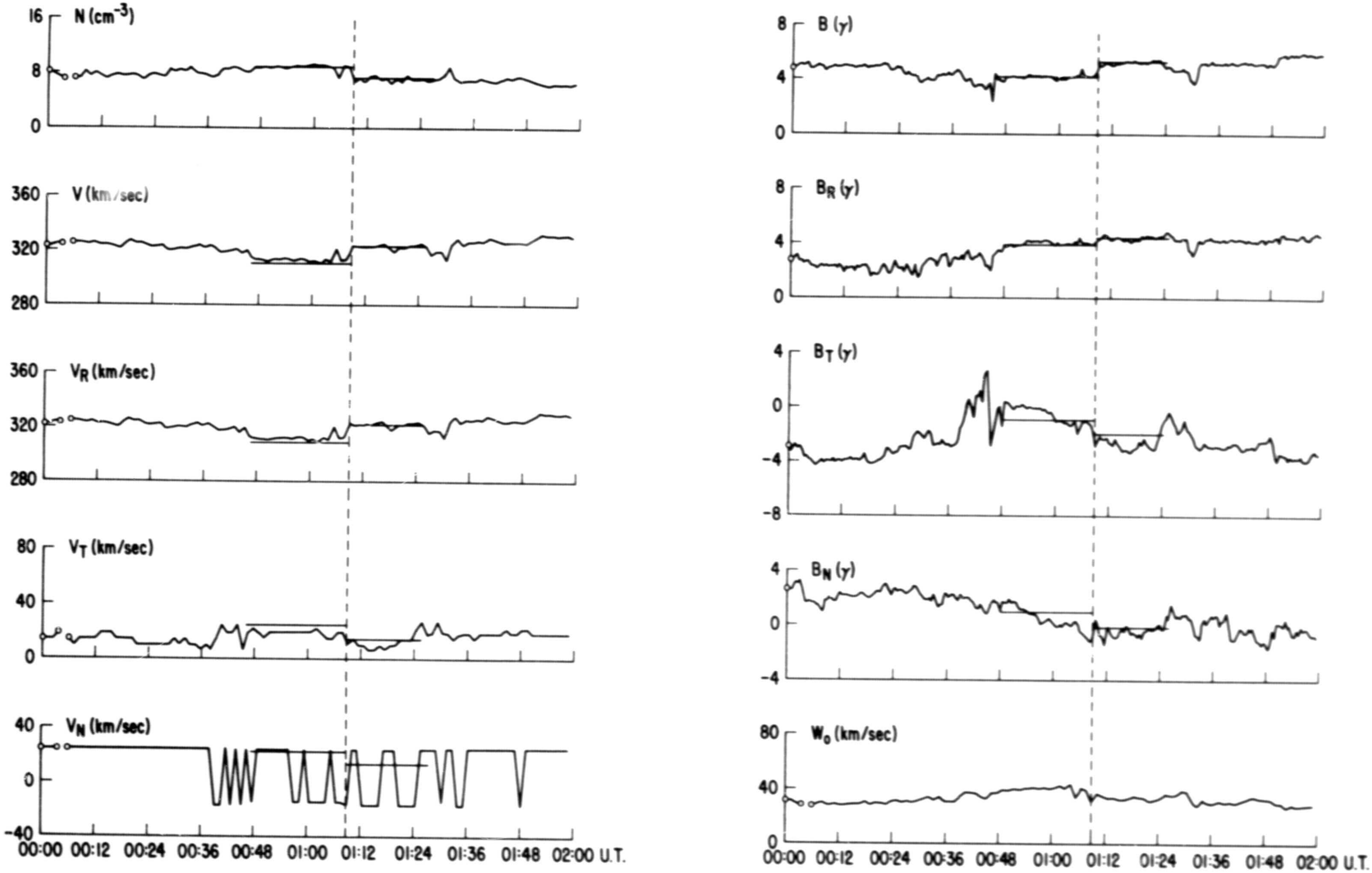


Figure 9



N (cm^{-3})
V (km/sec)
V_R (km/sec)
V_T (km/sec)
V_N (km/sec)
B (γ)
B_R (γ)
B_T (γ)
B_N (γ)
W_0 (km/sec)
00:00 00:12 00:24 00:36 00:48 01:00 01:12 01:24 01:36 01:48 02:00 U.T.

Figure 10

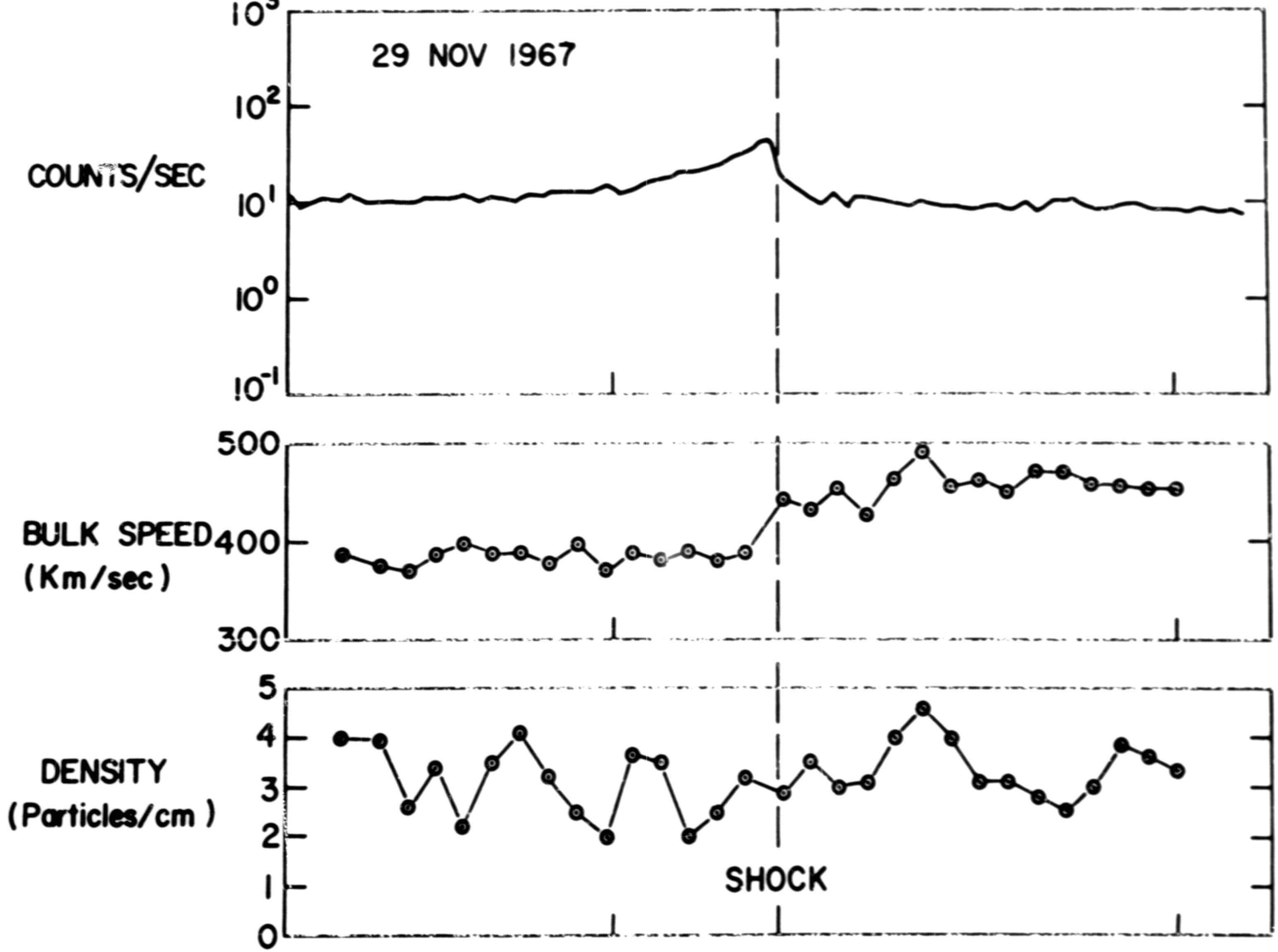

29 NOV 1967
COUNTS/SEC
10^3
10^2
10^1
10^0
10^{-1}
BULK SPEED
(Km/sec)
500
400
300
DENSITY
(Particles/cm)
5
4
3
2
1
0
SHOCK

Figure 11

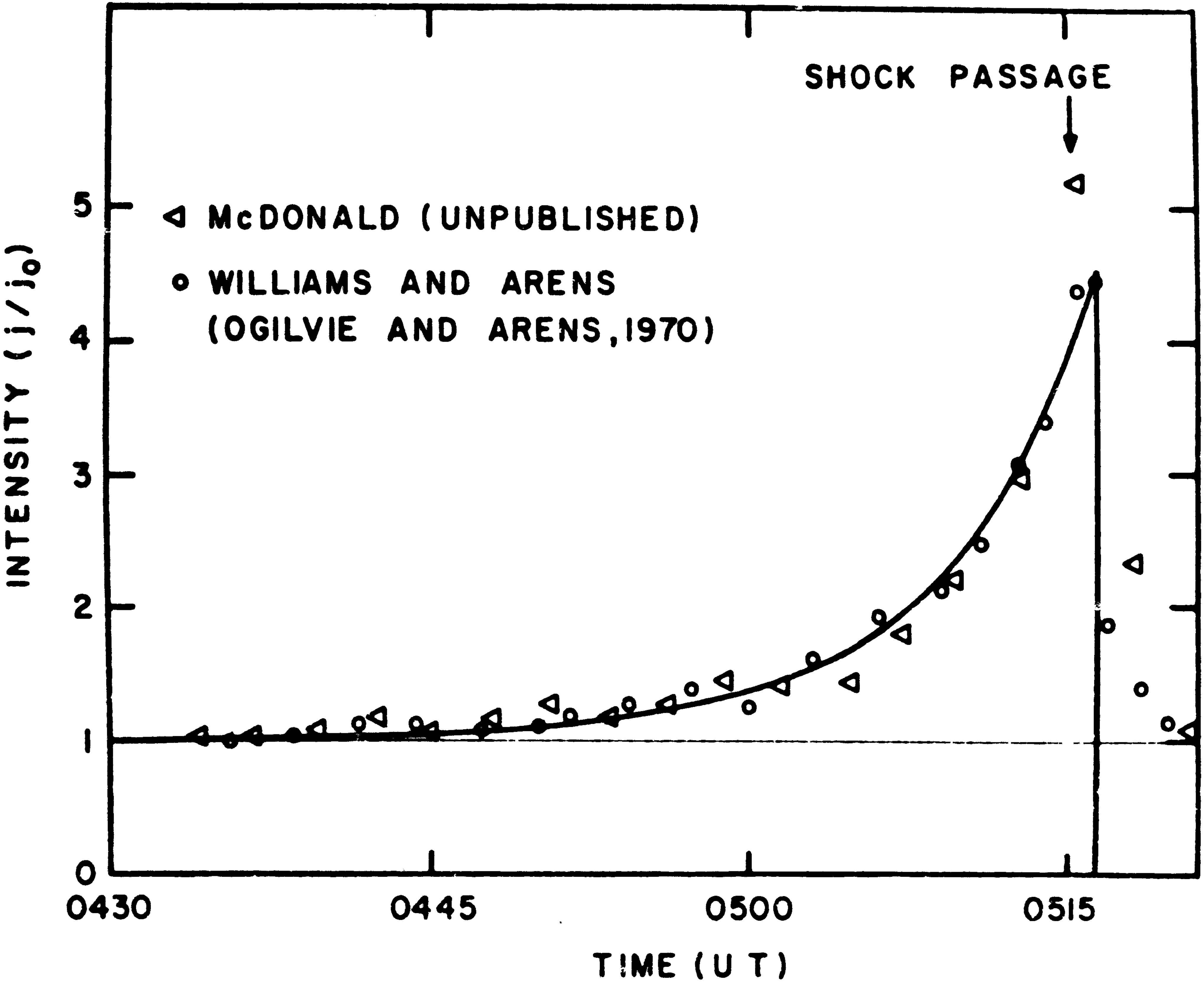

SHOCK PASSAGE
McDONALD (UNPUBLISHED)
WILLIAMS AND ARENS
(OGILVIE AND ARENS, 1970)
INTENSITY (j/j_o)
0
1
2
3
4
5
0430
0445
0500
0515
TIME (U T)

Figure 12