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ACCELERATION OF PROTONS BY INTERPLANETARY SHOCKS

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Abstract

Observations of charged particles at the time of passage of interplanetary shocks past the satellite Explorer 34 are discussed. The short duration increases in flux seen at 1 Mev are interpreted as particle acceleration, and are found to be consistent in duration and magnitude with the idea of energy gain by successive reflection between the earth's bow shock and the incoming propagating shock. The corresponding correlation length of the interplanetary field is deduced to be $\sim 5 \times 10^{-3}$ A.U. From the small sample observed it appears that shocks occurring when the interplanetary magnetic field at the observers position does not intersect the bow shock do not show particle flux increases, and that particles from the solar wind are not accelerated to 1 Mev by any of the observed shocks.

Introduction

Observations by Asbridge (1968), and by Frank (1967) have demonstrated the existence of particles streaming from the earth's bow shock in the general direction of the sun. These particles have energies greater by a factor of three or four than those characteristic of the solar wind protons. This might be interpreted as acceleration of particles of energy of order 1 KeV at the standing bow shock, and suggests the possibility of particle acceleration by interaction with propagating interplanetary shocks.

Van Allen and Ness (1967) showed simultaneous observations of the magnetic field and of approx. 0.5 Mev protons on Explorer 33. At the time of passage of an interplanetary shock past the satellite, which was situated about 4×10^5 Km from the earth, a discontinuous drop in particle intensity was observed. As the particles originated at the sun simultaneously with the shock, the average particle on the outward side of the shock before it passed the spacecraft would be expected to have higher energy than the average particle on the sunward side, as a result of collisions with the shock. Such acceleration has been suggested by Vernov et al. (1969), in connection with so-called "Storm Particle Events". The increases discussed here, of duration about 1000 seconds, are not to be identified with such events. Axford and Reid (1963) have examined increases of low energy (~1 Mev) particle flux before the occurence of an ssc, interpreting these enhancements in terms of acceleration by successive reflections between the incoming shock and the earth's bow shock.

An orbit-theoretical treatment of the process of reflection of solar wind particles at the earth's bow shock has been published by Sonnerup (1969). Subject to the assumption that the particle energy is conserved in the coordinate frame in which the interplanetary electric field vanishes, acceleration of particles by about four times is predicted. The energising mechanism is the interplanetary electric field, doing work on the particles, supposedly trapped in the shock during the reflection process. This mechanism is discussed further below.

Events showing apparent particle acceleration have also been studied by Singer (1970), who lists most of the events studied here and a number of others. He favors the hypothesis of the acceleration of particles in the shock front itself. A treatment of the reflection of relativistic charged particles by plasma shocks, for the case where the shock thickness is less than the gyro-radius has been given by Hudson (1965). This condition applies to the present case. The simple non-relativistic acceleration mechanism discussed below assumes a high reflection coefficient. The magnetic field is not deviated though a large angle at the passage of an interplanetary shock, Ogilvie and Burlaga (1969). Under this condition, Hudson finds the reflection coefficient to approach unity for particles with large pitch angles, $>75^{\circ}$. Unfortunately, pitch angle information was not available for the events discussed here.

In this paper we combine observations of protons in the range 1-10 Mev with plasma and magnetic field observations, and with the help of information on the solar proton spectra obtained on the same satellite and kindly supplied by Dr. Lanzerotti, we show:

1). Shocks in the interplanetary medium do not always accelerate protons with solar wind energies to energies of order 1 Mev.

2). If particles with energies of a few hundred kev exist in the interplanetary medium at the time of arrival of a shock, an increase in flux above a threshold, (say 1 Mev) is sometimes observed. Increases produced by the mechanism discussed below can only be recorded when the particle spectrum is sufficiently steep and the interplanetaty magnetic field is suitably oriented. The flux drops to the ambient value or below after the passage of the shock. A mechanism for this effect, being essentially that proposed by Axford and Reid, will be discussed below.

Experimental

The identification of shocks and the measurement of their properties was carried out using the GSFC-University of Maryland plasma experiment and the GSFC magnetic field experiment on Explorer 34. Both of these instruments have been described before (Ogilvie and Burlaga, 1969) in a reference where the properties of most of the shocks used in this study are also described. The method of determination of the fluid quantities from the raw data is treated in Burlaga and Ogilvie (1968). The magnetic field observations were used for two purposes; to unequivocally identify the passage of an interplanetary shock past the spacecraft, and to establish the direction of the magnetic field vector at the shock front. The shock normal direction could sometimes be obtained, using the methods described in Ogilvie and Burlaga (1969).

The 1-10 Mev protons were detected by an 86μ thick surface barrier detector which looked perpendicular to the satellite spin axis, the axis being normal to the ecliptic plane. The opening aperture was round with 60° full diameter. Each data sample accumulated counts from several revolutions, so azimuthal anisotropy information was not obtained.

Results

Between May 30, 1967 and 11 Jan. 1968 fourteen interplanetary shocks were detected by Explorer 34. Some details of these events are set out in Table I. Seven of them have been used as examples of hydromagnetic shocks in the solar wind to test the applicability of the Rankine-Hugoniot relations; the remaining seven were not used, for a variety of reasons which are given in Table I. The observations made by the 1-10 Mev channel of the energetic particle apparatus were examined around the time of occurrence of all 14 events to look for evidence of particle acceleration or deceleration.

In some events an increase in particle flux was observed starting about 20 minutes before the passage of the shock, and reaching a peak at the shock time, afterwards decaying to the pre-shock value or below. An increase in particle flux (nv) can be due to an increase in density or speed or both. Thus the mechanism must be identified in order to prove the occurrence of acceleration. Five events noted in Table I show appreciable flux increases. Two of these, which occurred on 30 May and 29 November 1967 are shown in Figures 1 and 2. The inset in Figure 1 shows the event on a larger time scale, and is included to emphisize the short duration of the increase. The quantity "Ambient rate" in Table I represents the counting rate which was observed in the 1-10 Mev channel immediately before the shock. It will be seen at once that all of the events showing acceleration occurred when this rate was ≥ 10, and that none of the shocks which occurred when the ambient rate was <10 showed an increase in the number of particles greater than 1 Mev at the time of the shock. It then appears that for these events the action of interplanetary shocks will not accelerate protons from the solar wind energies, (of order 1 KeV), to energies of order 1 Mev contrary to the suggestion of Vernov (1969). In column eight of Table I we note whether the detection of the shock was immediately followed by a decrease in particle flux below the previous ambient level, of the type noted by Van Allen and Ness. A total of five such occurrences was seen.

TABLE I

Date	Time of Shock	Increase	Time of Max. Counting rate	Ambient Rate	r	Normal Direction Known?	Followed by Decrease?	
May 30	1429	17x	1429	500	33		Yes	Spacecraft in Sheath
June 5	1915	9x	1920	80	24		No	Spacecraft in Sheath
June 25	0215			2	30		No	
June 26	1455			70	32	Yes	No	
July 2[illegible]	1739			0.2	33		No	Small event
Aug 11	0554			1000	31		Yes	Plasma obs. ambiguous
Aug 29	1732			0.1	34	Yes	Yes	
Sept 13	0340			0.3	26	Yes	---	
Sept 19	1954			100	31	Yes	No	
Sept 20	1736	3.3x	1727	300	34		Yes	Complex event
Oct 28	1632			3.0	30		No	Weak shock
Nov 29	0515	4.5x	0515	10	33	Yes	Yes	
Dec 29	2227			0.5	30		---	Weak shock
Jan 11	1256	x50	1256	10	33	Yes	No	
	U.T. ± 3 min.		U.T.	Counts/sec	R_e			

The decrease referred to in column 8 is similar to that discussed by Van Allen and Ness.

The events on June 26, Aug. 11 and Sept 19 took place at times when the ambient flux was ≥10, and yet no appreciable flux increase at energies >1 Mev was observed. Events for which an increase was observed in the presence of an ambient solar proton flux are compared with these three in Table II. It will be seen that the only striking difference between the two classes of events in this small sample are the values of the ratio R. This quantity, the ratio of the fluxes in 2 channels of the Bell Telephone Laboratory energetic particle experiment, is a measure of the steepness of the ambient solar proton spectrum. Its average value for the five events showing increases is 34.8, while that for the three events not showing increases is 9.6.

Thus a steep spectrum is required for a large increase to be seen. This conclusion is exhibited quantitatively in Fig. 3, where we see a plot of the expected increase in particle flux in a differential energy window against the differential spectrum exponent γ. The corresponding values of the ratio R are also shown, and points for the eight events in Table II are plotted. The diagonal lines represent the increase which would be observed as a function of γ, if the particles in this region of the spectrum had their energies increased by α=1, 2, 3, etc. times.

The events showing increases require, on this acceleration hypothesis, values of α of three or four. The three anomalous events, 26 June, 11 August, and 19 Sept., are characterised by relatively flat spectra. Nevertheless, if the value of α had been 3 or 4 for these events, increases of about a factor of two would have been seen, so an explanation for this effect must be sought .

Table II

	I_{max}/I_{before}	R	β	θ_B	ϕ_B
May 30	20	16			
June 5	10	41	10^o	-60^o	316^o
Sept 20	4	10	57^o	12^o	264^o
Nov 29	5	31	47^o	10^o	151^o
Jan 11	20	76	75^o	0.5^o	258^o
Events with ambient solar protons not showing acceleration.					
June 26	1	9	30^o	-27^o	27^o
Aug 11	1	10	31^o	21^o	300^o
Sept 19	1	10	58^o	-24^o	272^o

Note:- $R = \frac{\text{Flux (0.56 - 0.60 Mev)}}{\text{Flux (1.2 - 2.4 Mev)}}$

θ_B, ϕ_B hourly average values.

III. Acceleration of particles by reflection between a moving shock and the bow shock.

We assume the guiding centers of the particles (protons) to be constrained to move with speed $V_{\parallel}$ along the interplanetary field lines. If the magnetic field line through the point of observation does not intersect both the bow shock and the moving shock we assume that there will be no acceleration. The flux ratio is also a function of γ, the exponent of the differential energy spectrum of the particles, in agreement with the experimental results discussed above.

We now estimate the increase in flux which would be seen by a detector situated at the point A in Figure 4, as the incoming shock moves with speed U along its normal direction. We assume that the particles pick up energy ΔE upon reflection at the moving shock and are merely turned around at the bow shock. Thus the interval of time during which acceleration takes place is the time required for the point of intersection of the field line through the observers position with the shock to move from a point distant L_1 from the intersection with the bow shock to A, distant L_2 from the bow shock. The length L_1 is to be identified with the correlation length characteristic of the motion of protons of this energy in the medium. A test of the hypothesis will be to determine that the necessary flux increase can be obtained with a reasonable value of L_1.

Let $\hat{n}$ be the normal to the moving shock and the angle between this vector and $\overline{B}$ be β. The assumption that $\overline{B}$ intersects the bow shock is implicit. We assume that $V_{\perp}$, the velocity of the particle perpendicular to the field line, is unchanged by the collision, but $V_{\parallel}$ is increased by 2U Sec β by interaction with the shock.

Thus, E^1, the energy after reflection, $=\frac{1}{2}m(V_\perp^2+V_\parallel^2+4UV_\parallel \mathrm{Sec}\beta+4U^2\mathrm{Sec}^2\beta)$

and this result does not hold for large values of β,

$$\frac{E^1-E_1}{E_1} = \frac{4UV_\parallel \mathrm{Sec}\beta + 4U^2\mathrm{Sec}^2\beta}{V^2}$$

$$\simeq 4\frac{U}{V}\mathrm{Sec}\beta\cdot\frac{V_\parallel}{V} \quad \text{(since } V \gg U\text{)}$$

$$= f.4\frac{U}{V}\mathrm{Sec}\beta$$

where f is the cosine of the pitch angle. The sense of the field is unimportant

Since the number of collisions per second with either shock is $V/_{2L}$, where L is the distance between the 2 shocks along the extended magnetic field line,

$$\frac{\Delta E}{E} = \frac{2U}{L}\cdot f\cdot \mathrm{Sec}\,\beta\cdot\Delta t$$

while the shock moves a distance $U\Delta t$ along its normal, its intersection with B moves a distance ΔL, so that $U\Delta t = -\Delta L\ \mathrm{Cos}\ \beta$, and

$$\frac{\Delta E}{E} = -2\cdot f\,\frac{\Delta L}{L}$$

or $$\frac{E_2}{E_1} = \left(\frac{L_1}{L_2}\right)^{2f}$$

Thus the effect of the motion of the shock from a remote point to the observers position is to increase the energy of each particle by a factor $k = (L_1/_{L_2})^{2f}$, which does not depend upon E_1.

Suppose the particle spectrum has the form $\frac{dN}{dE} = \underline{AE}^{-\gamma}$, so that the number of particles in a differential energy interval ΔE is $\frac{dN}{dE}\Delta E$, and N is the total number of particles. If all the particles have their energy multiplied by a constant factor k, then those which occupy ΔE at E after the acceleration are those which occupied $\Delta E/_k$ at $E/_k$ before. Thus the ratio of the fluxes observed is

$$F_2^1/F_1^1 = \frac{V(E)\ A\ k^{\gamma-1}E^{-\gamma}\Delta E}{V(E)\ A\ E^{-\gamma}\Delta E} = k^{\gamma-1}, \text{ where } A=(\gamma-1)N.$$

This is the increase in flux due to acceleration; in addition there is an increase in differential density due to the compression alone, so that finally

$$F_2/F_1 = k^{\gamma-1} \cdot \frac{L_1}{L_2}$$

$$= \left(\frac{L_1}{L_2}\right)^{2\ f(\gamma-1)+1} \qquad (2)$$

Note that the increase according to this model would be the same at any point along L. As L decreases, however, the observed flux increases and should be a maximum at the time of shock passage, in agreement with observation.

In Figure 5 we see a plot of the ecliptic plane with the average positions of the earth's bow shock and magnetopause superimposed. The position of the spacecraft and the directions of the magnetic field and shock normal on the ecliptic plane are shown for eight events. These are ones for which increases were seen (5) and also events for which an increase was not seen (3) despite the presence of an appreciable flux of solar protons before the event, Table II. The magnetic field vectors plotted are averages for the hour preceding the event, and the normals are those determined by the methods discussed in Ogilvie and Burlaga, 1969. For the events showing increases the magnetic field vector through the point of observation intersects the bow shock in each case for which we have data. For the 'anomalous' cases, Sept. 19 and Aug. 11 are clearly ones where $\overline{B}$ did not intersect the bow shock. Note that the value of the angle θ_B does not affect this result. For June 26, the magnetic field was so disturbed that particles may not have been trapped on it. Thus we see that geometrically the idea of reflection between the two shocks is possible.

We now determine whether the energy gains required are compatible with reasonable values of f and L_1. For this purpose we can use the

September 20 and November 29 events, for which we know all the relevant quantities, except f. If Hudson's treatment is correct f is of order 0.1.

TABLE III

Event	F_2/F_1	γ	L_2	$L_1(f=1)$	$L_1(f=0.1)$
Sept 20	3.3	2.03	3.8×10^{10} cm	$\sim4\times10^{-3}$ A.U.	$\sim11\times10^{-3}$ A.U.
Nov 29	4.5	3.1	1.3×10^{10} cm	$\sim2\times10^{-3}$ A.U.	$\sim4\times10^{-3}$ A.U.

We identify this length with the correlation length of the interplanetary field. Thus when the moving shock is too far away from the bow shock, the particles are lost from the region before they make enough collisions to be accelerated. Since the values obtained are entirely reasonable it appears that all the features of this set of observations may be explained by multiple reflections between the bow shock and the advancing shock.

We must now discuss the relationship of the mechanism proposed by Sonnerup, in which the energy of a solar wind particle is increased by four to six times at a single reflection at the bow shock, to the mechanism discussed here, where the energy gain per reflection is of order 10%. In the Sonnerup mechanism, a particle is quasi-trapped in the bow shock, where it can be accelerated by the action of the interplanetary electric field, which acts in a direction perpendicular to that of the shock motion. The order of magnitude of this effect for a particle of velocity V can be estimated by calculating the energy change due to accelerating a particle for a distance of one gyrodiameter in the interplanetary electric field.

$$E_2/E_1 = 1 + \frac{2eV_{sw}B \sin\psi\,(2mv/eB)}{mv^2}, \text{ Eq 11 in Sonnerup (1969)}$$

$$\simeq 1 + 4\,\frac{(V_{sw})}{V} \sin\psi,$$ ψ is the angle between the magnetic field and the radial direction.

For a 1 MeV particle $V = 1.4 \times 10^9$ cm sec^{-1}, and $V_{sw} = 4 \times 10^7$ cm sec^{-1}, $Er/E_i \sim 1.1$, but for a particle trapped in the shock so that $V \simeq V_{sw}$ the energy gain is a constant. If the particle does not become trapped in the bow shock it will gain no energy from the electric field, and merely be turned around by interacting with the material behind the shock. It will then gain energy during reflection by conservation of momentum, as assumed above.

Duration of the increased particle flux.

By measuring the duration of the particle increases we can estimate the shock speeds by using the relation.

$$\Delta t = \frac{(L_1 - L_2) \cos\beta}{U}$$

$$\simeq \frac{L_1 \cos\beta}{U} \qquad (3)$$

Both the Sept. 20 and Nov. 29 increases lasted 20 minutes ± 2 minutes. The corresponding values of U from equation 3 are 455 Km sec^{-1} for Sept. 20 and 170 Km sec^{-1} for Nov. 29. A direct determination of U for Sept. 20 is not available, due to the uncertainty in post-shock plasma density. The directly determined value of Nov. 29 is 295 km sec^{-1}. (Ogilvie and Burlaga, 1969, also see Erratum, ibid, 1970).

These shock speeds are of the correct magnitude, and the disagreement on Nov. 29 is within the rather large probable errors.

We have shown that particles of solar wind energies are not normally accelerated by the action of interplanetary shocks to energies of order 1 Mev. Flux increases with durations of about 20 minutes are, however, observed, and their characteristics are consistent with acceleration by reflection between the travelling shock and the earth's bow shock, as suggested by Axford and Reid. This hypothesis gives reasonable values for the correlation length characterising the interplanetary magnetic field, and is consistent with the measured shock speeds. It implies that acceleration will not be observed at the passage of shocks past a spacecraft far from the earth. A second mechanism might also operate to produce acceleration, but in that case one would expect to have observed an increase at the time of at least one of the three 'anomalous' cases referred to above. However a more extensive study over a wide energy range would be required to rule out such a possibility.

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FIGURE CAPTIONS

Fig. 1 The increase observed at Explorer 34 in the flux of 1-10 Mev protons on 30 May 1967.

Fig. 2 The increase observed at Explorer 34 in the flux of 1-10 Mev protons on 29 Nov. 1967.

Fig. 3 The expected flux increase in a differential energy interval plotted against the spectral exponent γ. The values of the Ratio R, and points corresponding to eight events are plotted. The diagonal lines represent the increases which would be observed if the particles had their energies increased α=2, 3 etc. times.

Fig. 4 The geometry, not necessarily in the ecliptic plane, of the reflection of particles between the shocks.

Fig. 5 A plot of the ecliptic plane, showing the position of Explorer 34 at each of the events discussed. Boxes are drawn about the three anomalous events. The average positions of magnetopause and bow shock are also shown.

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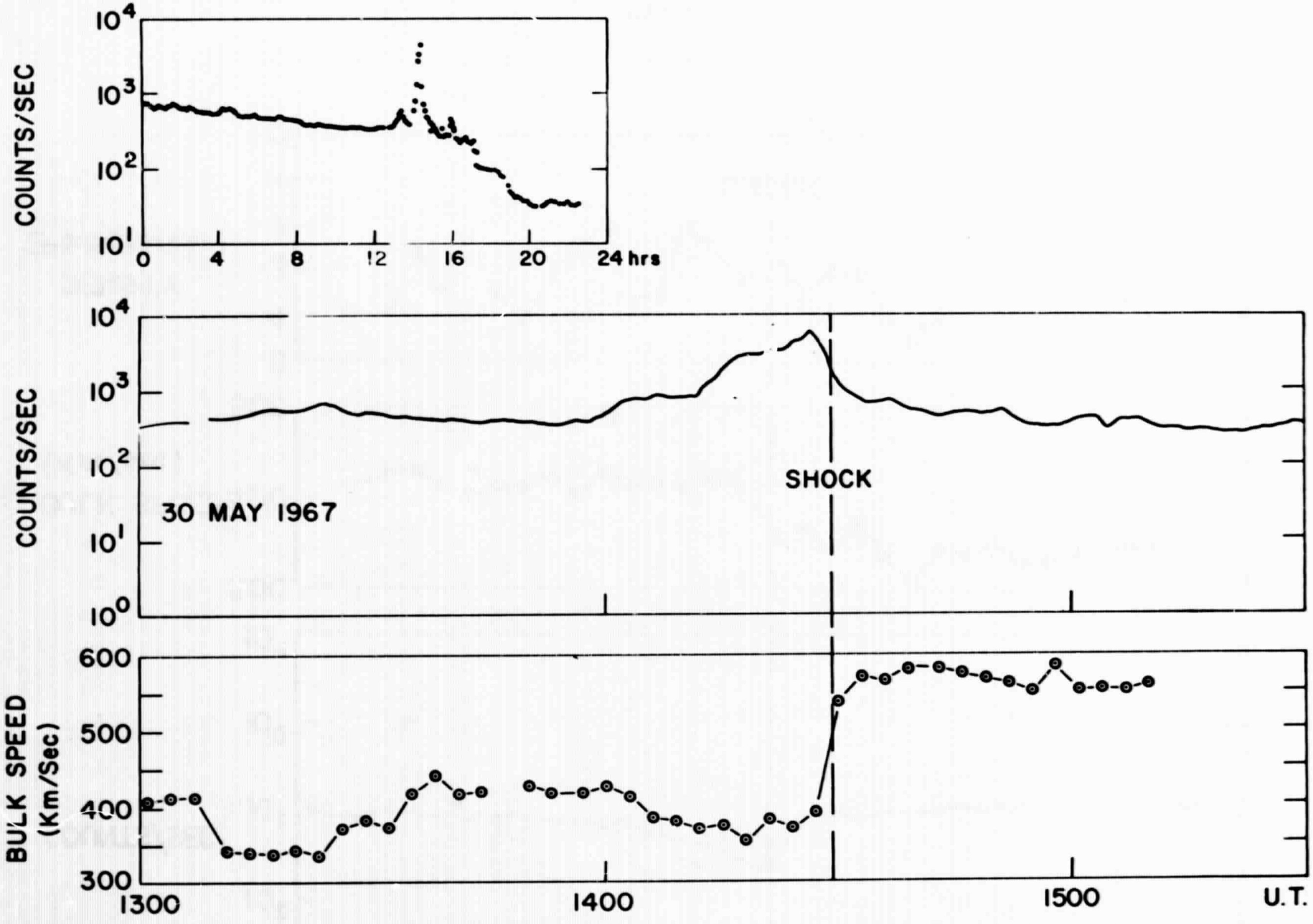


COUNTS/SEC
10^4
10^3
10^2
10^1
0
4
8
12
16
20
24 hrs
COUNTS/SEC
10^4
10^3
10^2
10^1
10^0
30 MAY 1967
SHOCK
BULK SPEED
(Km/Sec)
600
500
400
300
1300
1400
1500
U.T.

Figure 1

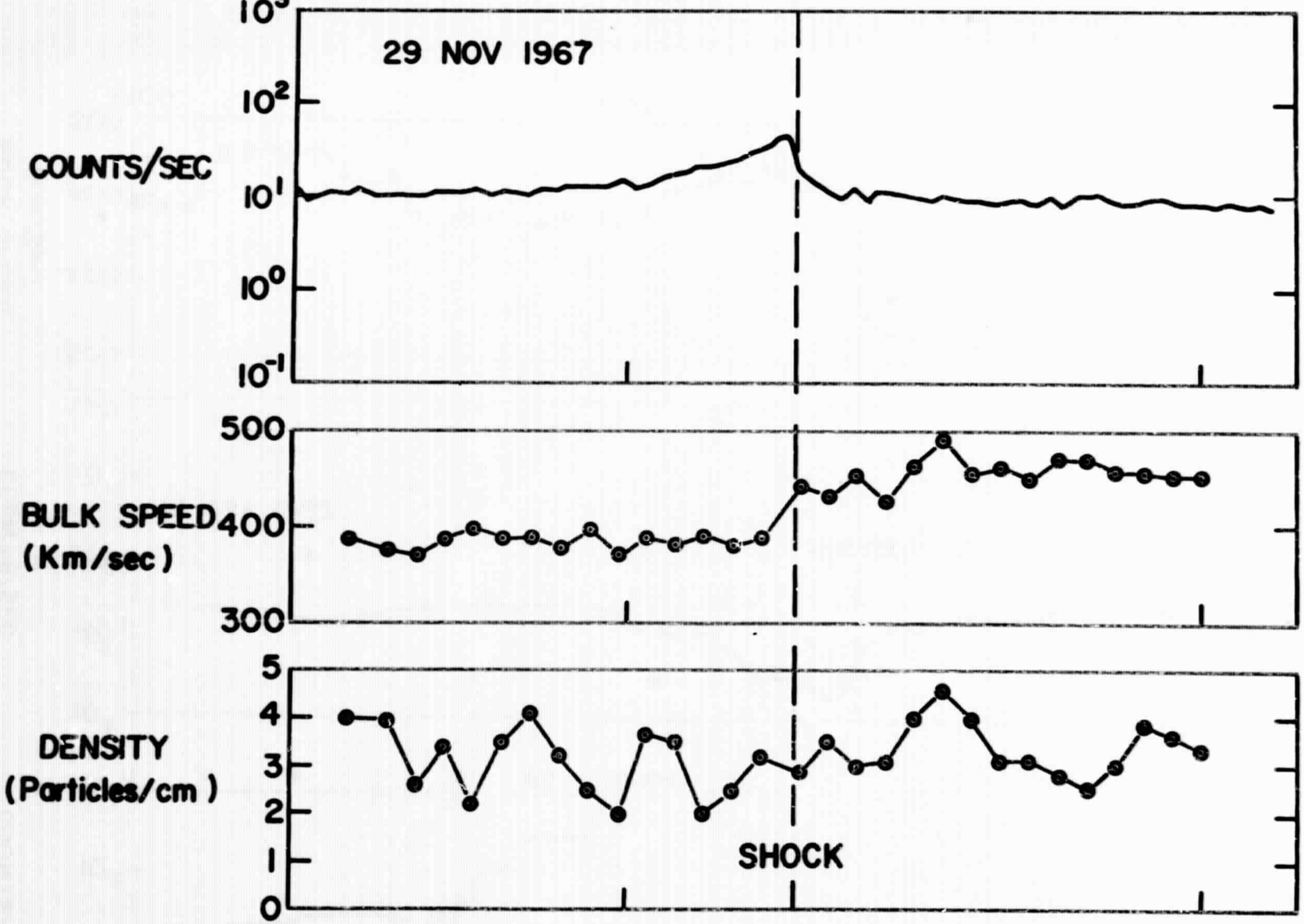

29 NOV 1967
COUNTS/SEC
10^3
10^2
10^1
10^0
10^{-1}
BULK SPEED
(Km/sec)
500
400
300
DENSITY
(Particles/cm)
5
4
3
2
1
0
SHOCK

Figure 2

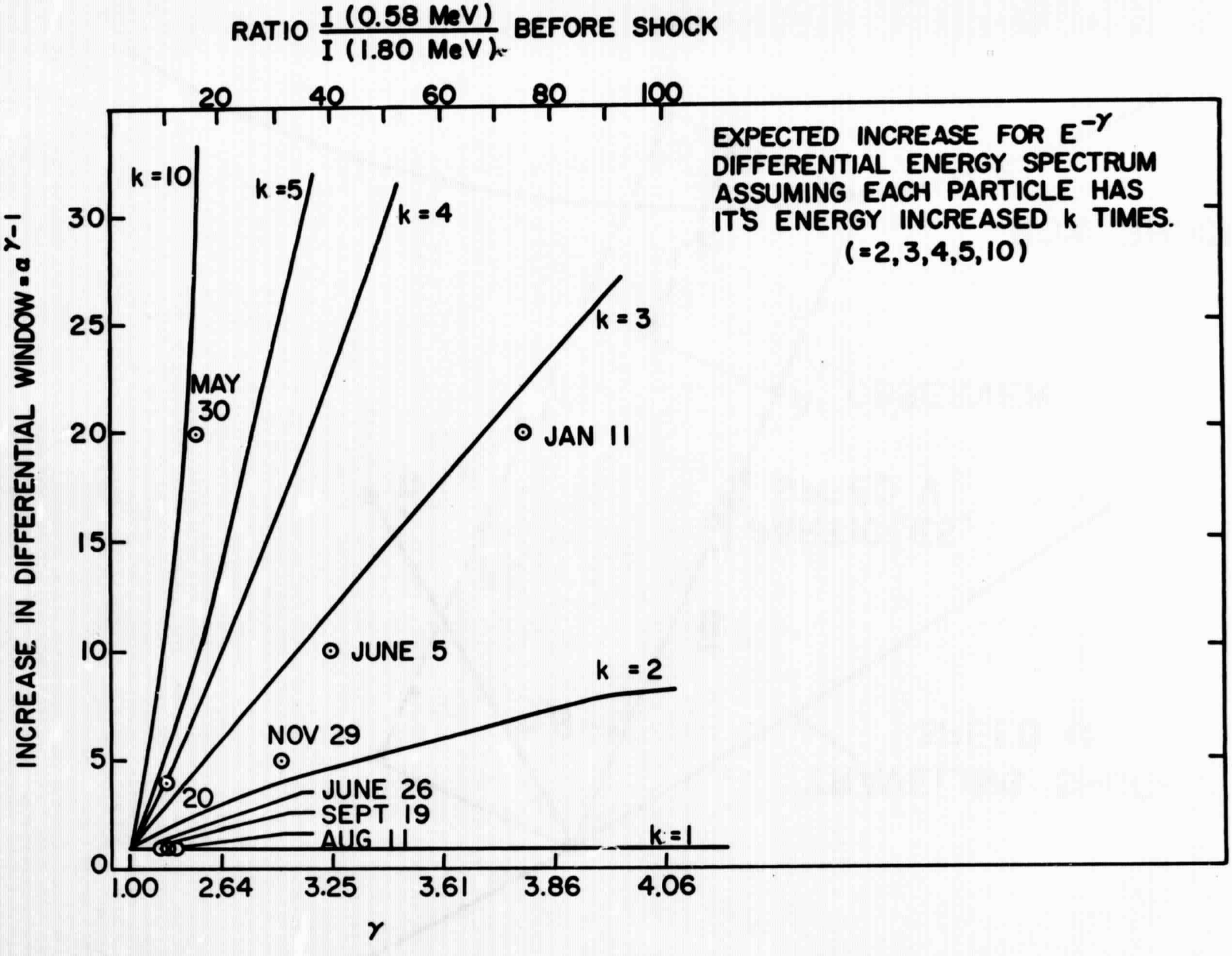

RATIO $\frac{I\ (0.58\ MeV)}{I\ (1.80\ MeV)}$ BEFORE SHOCK
20
40
60
80
100
EXPECTED INCREASE FOR $E^{-\gamma}$ DIFFERENTIAL ENERGY SPECTRUM ASSUMING EACH PARTICLE HAS IT'S ENERGY INCREASED k TIMES. (=2,3,4,5,10)
k =10
k =5
k = 4
k = 3
k = 2
k = 1
MAY 30
JAN 11
JUNE 5
NOV 29
20
JUNE 26
SEPT 19
AUG 11
INCREASE IN DIFFERENTIAL WINDOW = $a^{\gamma-1}$
0
5
10
15
20
25
30
1.00
2.64
3.25
3.61
3.86
4.06
γ

Figure 3

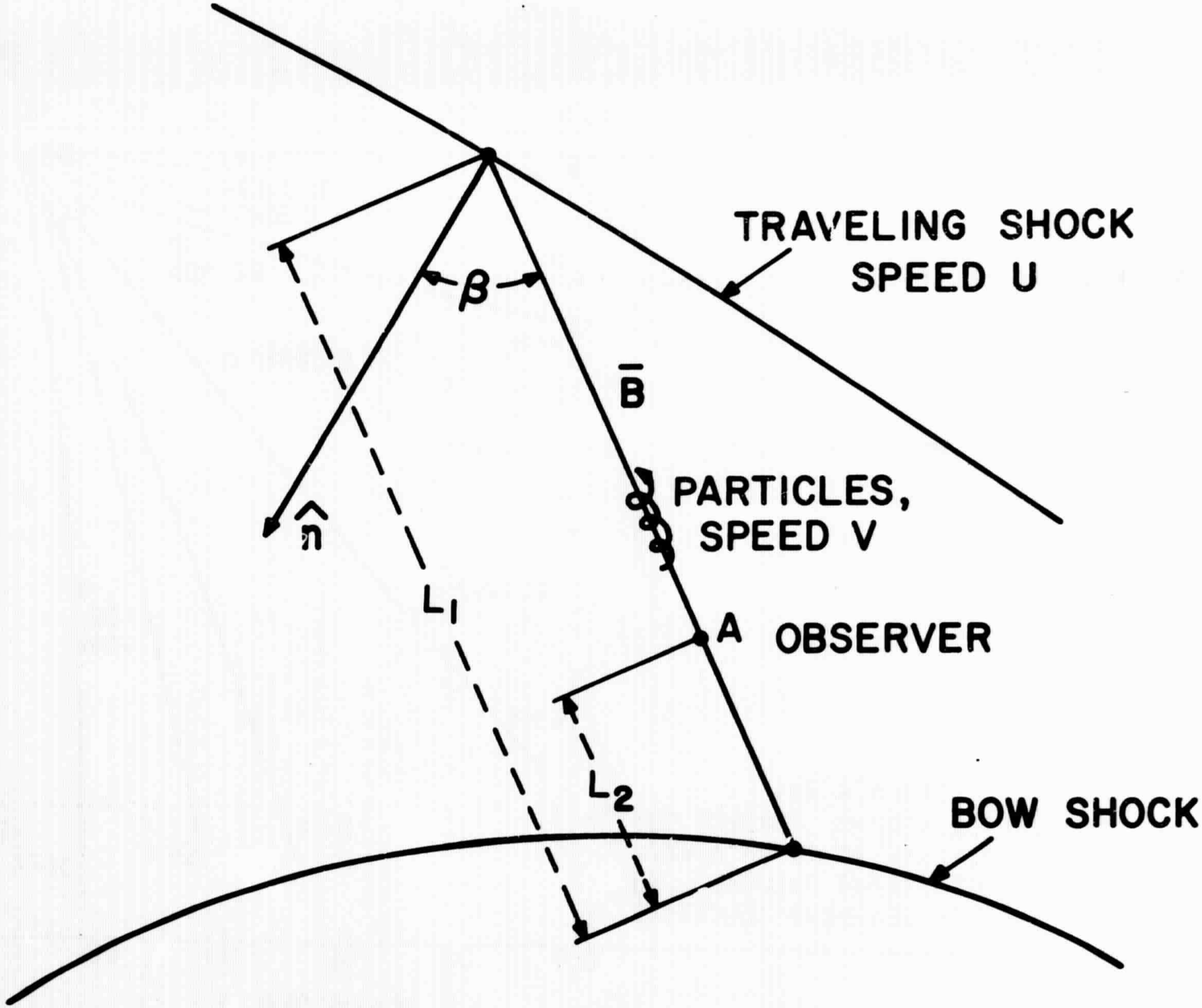
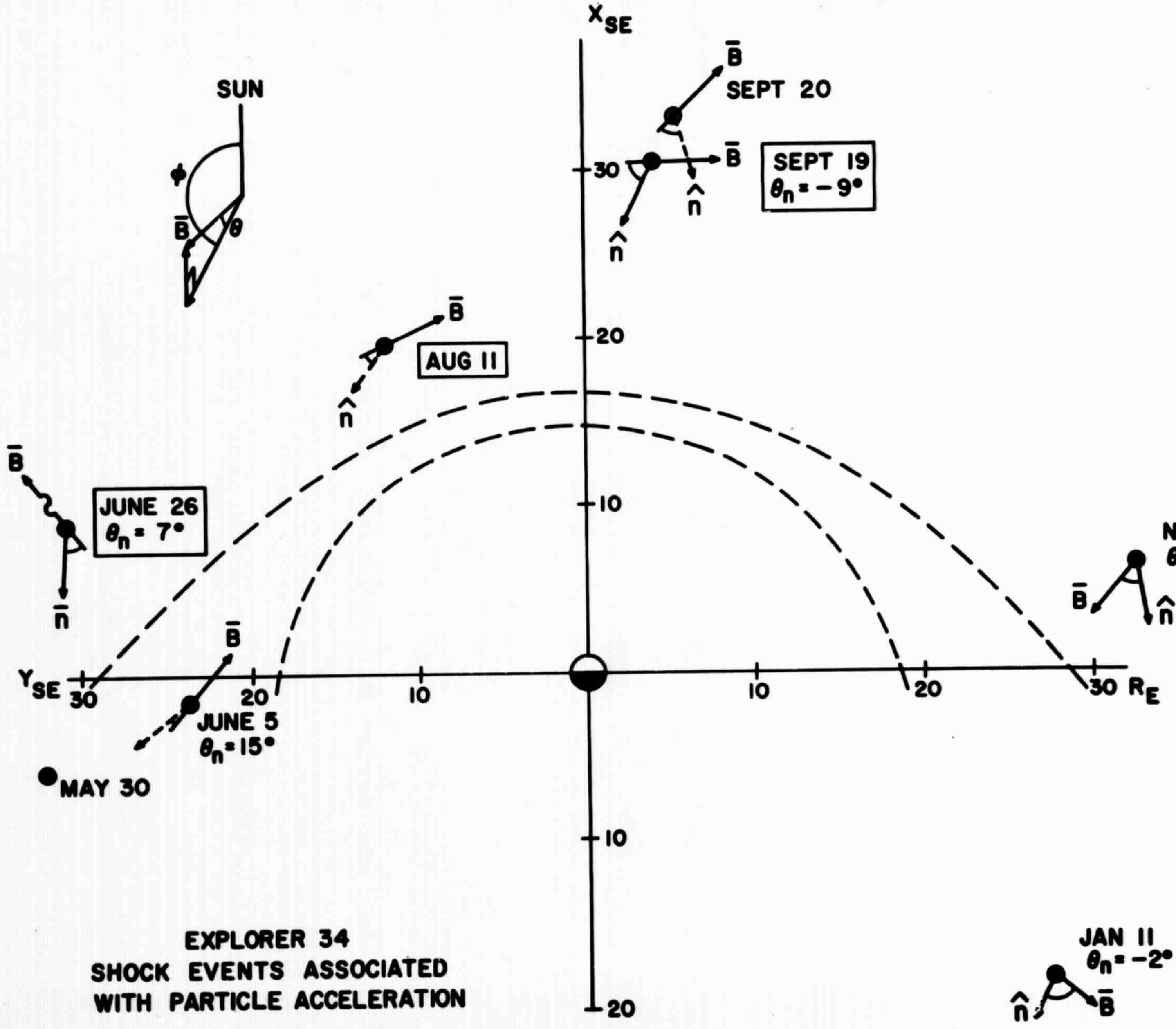

TRAVELING SHOCK
SPEED U
β
B̄
PARTICLES,
SPEED V
n̂
L1
A
OBSERVER
L2
BOW SHOCK

Figure 4



X_{SE}
SUN
ϕ
$\bar{B}$
θ
$\bar{B}$
SEPT 20
$\bar{B}$
SEPT 19
$\theta_n = -9°$
$\hat{n}$
$\hat{n}$
$\bar{B}$
AUG 11
$\hat{n}$
$\bar{B}$
JUNE 26
$\theta_n = 7°$
$\bar{n}$
NOV 29
$\theta_n = -47°$
$\bar{B}$
$\hat{n}$
$\bar{B}$
Y_{SE}
30
20
10
10
20
30 R_E
30
20
10
10
20
JUNE 5
$\theta_n = 15°$
MAY 30
EXPLORER 34
SHOCK EVENTS ASSOCIATED
WITH PARTICLE ACCELERATION
JAN 11
$\theta_n = -2°$
$\hat{n}$
$\bar{B}$

Figure 5