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CAUSES OF FORBUSH DECREASES AND OTHER COSMIC RAY VARIATIONS

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Abstract

The relationship between neutron monitor variations and the intensity variations of the interplanetary magnetic field is studied, using Deep River data and IMP-series satellite data. In over 80% of the cases studied in 1968, identifiable depressions of the cosmic ray intensity are associated with magnetic field enhancements of several hours duration and intensity above 10 gamma. Conversely, each magnetic field enhancement has an identifiable effect (though not necessarily a marked depression) on the cosmic ray intensity. Long lasting Forbush decreases are found to be the consequence of the successive action of several such features. An explanation is presented and discussed.

1. Introduction

Sharp temporary decreases of the galactic cosmic radiation of duration several days and amplitude of a few percent have been observed and studied for many years. The field has been reviewed by Lockwood (1971), Sandstrom (1965) and Quenby (1967), and recent work has been summarized by Cini-Castagnoli (1973). Although it is generally agreed that these Forbush decreases are caused by magnetic field variations associated with interplanetary disturbances, there remains considerable disagreement as to the configuration responsible. For example, among those considered are (1) Intense magnetic fields in a bottle configuration (Gold, 1959), (2) High magnetic fields created by a shock wave (Parker, 1963) (3) A single discontinuity of large extent (Quenby, 1971; Barnden, 1973a) (4) Irregularities in the magnetic field (Morrison, 1956; Parker, 1963; Laster, et al., 1962) and (5) A series of directional discontinuities (Barnden, 1973b). In most previous papers only a few events, usually those with very large intensity depressions, are considered. In this paper we consider all cosmic ray depressions with a scale of a day or more and seek a common cause to all events. It is found that for the period analysed (1967-1968) each Forbush decrease results from the passage of a region in which the magnetic field intensity is high - a magnetic blob, or simply, a blob. We advance the hypothesis that each blob drags a wake of low cosmic ray intensity behind it. Conversely, every magnetic blob either depresses the cosmic ray intensity or, in the case of two successive blobs, decreases the recovery rate. Most, but not all, high field regions occur at the leading edge of high speed streams, and can be explained by interplanetary plasma dynamics. Both corotating streams and flare-associated streams give rise to field configurations causing Forbush decreases, but it seems that the largest F.D.'s are the result of strong compressions ahead of fast, flare-associated streams.

Although the relation described above between cosmic ray intensity and magnetic blobs is basically simple and very general, at times the phenomena may present a complex appearance. For this reason, an in order to illustrate the basic concepts involved, we begin in Section 3 with a detailed discussion of a simple type of cosmic ray decrease. Section 4 discusses all C.R. depressions during 1968 and relates them to the corresponding magnetic field intensity variations possible models for these events. Section 5 describes and interprets more complicated types of Forbush decreases. Section 6 deals with a period when the interplanetary medium was very disturbed and recoveries were very sl :. Finally in Section 7 plasma data are also used to show the relationship between the primary cause, the interplanetary solar wind variations, its effect, the magnetic field variations, and the cosmic ray effect caused by the magnetic field.

2. Data: Source and Treatment

The results to be presented in later sections are derived from data from three sources: neutron monitors at earth, satellite measurements of the interplanetary magnetic field, and satellite measurements of the interplanetary plasma. For each of these data sets certain problems must be overcome before meaningful relationships can be found. These problems are discussed below.

Neutron Monitor Data. As we wished to include small amplitude Forbush decreases in our study, we were led to remove the diurnal variation from the neutron monitor time record. This can be done in two ways: either one averages over a number of stations or one uses numerical filterin echniques over a single station. Each of these methods presents its own particular advantages. We have found that numerical filtering of the data from a single station was simpler and more convenient for our purpose, while conserving the essential characteristics we wished to display. The filtering technique used has been previously described (Barouch, 1965). The major disadvantage of this method is its dependence on the particular directional properties of the station, which combines with the anisotropic character of the decrease to give different F.D. profiles from different stations, as discussed by Lockwood (1971), for instance. This effect must be kept in mind when comparing the detailed time history of the magnetic field and cosmic ray intensity, as it leads to an uncertainty of a few hours on the onset time. Another effect of the smoothing technique used is to limit the maximum rate of variation of the smoothed data. These disadvantages are of secondary importance in this paper. Most of the data used in this paper, then, will be smoothed Deep River neutron monitor data. The main features we are interested in are variations with a time constant of the order of one day. Even in the smoothed data these variations are not always very prominent. We have therefore carried the treatment one step further, and performed a crude numerical differentiation of the data by simply taking the difference between consecutive data points of the smoothed data. For esthetic reasons we changed the sign of the resulting time series, and normalised, obtaining the logarithmic derivative by dividing this quantity by the corresponding C.R. intensity, so that a <u>positive</u> derivative corresponds to a Forbush <u>decrease</u>.

<u>Magnetic Field</u>. To relate the cosmic-ray intensity time profile, N(t), with the magnetic field time profile B(t), one

obviously needs continuous time series for both B(t) and N(t) measured at the same point. So as to get a time series for B(t) near earth with as few data gaps as possible data from GSFC instruments aboard Explorer 28, 33, 34 and 35 were combined. One hour averages are used for the magnetic field computed from the averages of the field components.

In order to determine the nature of a blob, i.e. whether it is corotating or not, it is necessary to have simultaneous measurements from another spacecraft at some distance from the earth. Since we use hourly averages, the corotation time delay must be at least a few hours, say ten hours, if we are to resolve it. On the other hand, the separation must not be too great, for features can evolve appreciably in ten hours, The corotation rate is approximately 0.5 deg/hr, corresponding to angular separations between 20^{o} and 40^{o}. Such data are available from the GSFC and GSFC/Rome experiments aboard Pioneer 7 and 8 for January-February 1967 and June-December 1968 respectively. These are times when we have good coverage of B(t) both at Pioneer and at earth.

Plasma Data . To study the formation mechanism of the blobs we need plasma data giving at least the bulk speed, and preferably also the proton density and temperature, in addition to the data mentioned previously. During the period June-December 1967, the GSFC instrument aboard Explorer 34 was monitoring the solar wind almost continuously at a time when measurements of B(t) were available. This also happens to be a very disturbed period with an exceptionally large number of streams. We have used three hour averages for the plasma parameters measured aboard Explorer 34.

3. Simple Forbush Decreases

By a simple C.R. decrease we mean a smooth, definite decrease followed by a smooth recovery to the original intensity. Such events are rather rare. An event displaying some of these characteristics is the event of February 3 - February 13, 1967, which is shown in Figure 1. The decrease began on February 2nd, more or less coincident with the arrival of an extensive magnetic blob marked A. The passage of this feature lasted approximately 7 days, and the C.R. intensity decreased throughout this interval. As soon as it passed, the C.R. intensity began to recover, and the recovery lasted for about 7 days, during which no large magnetic blobs were observed. This event was not associated with a shock or a large flare.

An example of a more classical Forbush decrease is shown in Figure 2. This the well-known event of February 15, 1967 which has been extensively studied. Hirshberg et al. (1970) showed that the high field region followed a shock associated with a 3+ flare at E11° and found that it was followed by a region of high He/H ratio, which they considered to be the front of a piston. Pioneer 7 was monitoring the magnetic field at 25° ahead of earth at $\approx$1.1 A.U., but saw a broad region of high fields rather than a spike (Fig. 2). Scudder and Burlaga (1974) showed that the geometry was probably such that the flare ejecta which passed the earth at 0° could have originated from the flare site at 10°E but probably were not of sufficient angular extent (30° at 1 A.U.) to reach Pioneer 7. A magnetic bottle associated with this event will be described in a later publication (Barouch and Burlaga, to be published). Despite these differences from the event discussed in the preceding paragraph, one sees the same correspondence between the C.R. profile and the magnetic field intensity; the decrease occurs during the passage of an intense magnetic blob, marked A in Figure 1. For 9 days after the passage of this feature, the magnetic field intensity is relatively low and the C.R. intensity recovers. This recovery is not smooth, because it is interrupted briefly by the passage of small blobs. Again, the observations are consistent with our model. The smoothed data shown here smear out an important detail discussed by Barnden (1973a) viz, that the decrease occurred in two steps, the first coincident with the passage of a shock and the magnetic blob behind it, and the second near the time that the helium "piston" boundary passed, when the magnetic field intensity decreased. This second decrease is perhaps due to entry in to a magnetic bottle, with closed field line configurations, since B is not high in the bottle. These effects are not resolved in the data handling technique we use. It may well be that there is more than one mechanism for decreasing cosmic ray intensity, but as we shall show, magnetic blobs are probably the major cause of most C.R. decreases.

In the two examples above, there is a rough coincidence between the beginning of the cosmic ray decrease and the beginning of the increase in B; similarly the minimum flux is reached approximately at the end of the blob. This will be shown to be a general and important characteristic of almost all the cosmic ray events studied.

The thickness, or radial cross-section, of the blob which cause cosmic ray decreases varies. On February 7, 1967 the blob is about 1 A.U. in thickness, whereas on February 15 its thickness is 0.2 A.U. There appears to be a corresponding variation in the interval over which the cosmic ray intensity decreases, February 15, being very abrupt while February 3, is much less so. As has been noted in the introduction, the use of a single neutron monitor may introduce some uncertainty in the time scales involved, so that care must be exercised in carrying this correlation too far, but the general effect is probably real.

4. General Cause of Large C.R. Intensity Decreases

Let us consider the relation between the interplanetary magnetic field intensity measured near earth and C.R. intensity measured by the Deep River neutron monitor during 1968, a period of moderate activity. In order to identify with objectivity the C.R. intensity decreases, we use the logarithmic derivative of the smoothed neutron monitor data, as described in Section 2. Very small fluctuations in the logarithmic derivative, below 0.1 percent/hour, may be due to statistical fluctuations residual daily variation,or the round off errors of our filtering technique, and we consider only decreases (in our figure, where the negative of the logarithmic derivative is shown, peaks) above 0.1 percent/hour. Figure 3 has vertical lines drawn through these selected peaks. The following conclusions can be deduced:

a). There were 40 C.R. intensity decreases in 1968 satisfying the condition $(1/N)(dN/dt) \geq 0.1$ percent/hour as recorded by the Deep River neutron monitor.

b) Only one of these 40 events was not associated with a large enhancement of B. ($B \geq 10\gamma$). c). For six events a comparison between B and N cannot be made because of data gaps in B. For 33 of the 34 remaining events the depression in cosmic ray flux was associated with a region of high magnetic field intensity. d). The width (duration) of the magnetic field intensity regions is generally of the order of the duration of the interval during which the C.R. intensity decreases, and is much shorter than the recovery time, indicating that the low intensities during the recovery phase are not the consequence of immersion in a blob, but seem rather more like the consequence of a "wake" of C.R. depletion behind the blob.

In view of the high correlation between the C.R. depressions and the magnetic field enhancements, and because (as we shall show later) it is possible to imagine a plausible mechanism for [illegible] depression by high magnetic fields, we conclude that the high field regions are the cause of the C.R. decreases. However, we cannot yet state that it is the high field intensity which causes the decrease rather than an accompanying shock or fluctuations embedded in the high field region.

Generally, the magnetic fluctuations are high when B is high (Hirshberg and Colburn, 1969; Davis et al., 1966, Sari, 1972) so that it is difficult to separate the effects of these two features, although an investigation in this direction is in progress (Barouch and Sari, to be published).

The effects of shocks can be examined using SSC observations, since an SSC is a good indicator of the passage of a shock (Hundhausen, 1972, Chao and Lepping, 1974). Sudden commencements during 1968 are indicated by arrows on the time scale in Figure 1. Twenty SSC's were reported by J. Virgina Lincoln in JGR for 1968. Sixteen of these were associated with C.R. decreases; four were not associated with such a decrease, and only 18 of the 40 C.R. decreases could be associated with an SSC. Thus most (80%) of these "shocks" were associated with a C.R. decrease, but only half (~47%) of the C.R. decreases were associated with SSC's. This confirms a detailed study by Bachelet et al., (1960). (Some of the SSC's were not caused by shocks but tangential discontinuities, as discussed in the references). On the other hand, all the SSC's associated with C.R. decreases were also associated with high magnetic fields. Ockam's Razor leads us to conclude that the high magnetic fields themselves cause the C.R.'s rather that the shocks.

We now turn to the problem of determining whether the C.R. decreases are due to corotating, stream-induced, blobs or to spherically expanding shells. Observations from two widely separated spacecraft can give clues to answering this question. For the period January through June 1968, Pioneer 8 was too close to earth for this data to be useful - the corotation time is less than 15 hours. From July to December 1968 the corotation time varied from 15 hrs to 1.5 days. (Mariani et al.,1971, present a graph of the trajectory and corotation time). An examination of the Pioneer 8 data for this period shows that indeed the magnetic field intensity profiles at Pioneer 8 is generally similar in form to that obtained aboard Explorer spacecraft, but there are significant differences, indicating either temporal evolution over times of 15-60 hours or spatial inhomogeneities over distances of 6 million to 10 million km. There are also many data gaps which make unambiguous statements impossible. The somewhat subjective result is as follows. There are 20 blobs in this period: six appear to be corotating, six appear not to be corotating, and in 8 cases the data does not permit an unequivocal determination. Only one of the corotating events was associated with a SSC. Three of the six non-rotating events were associated with an SSC. We conclude that CR depressions are caused by both corotating and non-corotating magnetic blobs and only a small fraction of the events are caused by non-corotating, shock associated blobs.

In other words, one does not require a shock-associated blob (as one might expect from flare-associated C.R. decreases) to produce a Forbush decrease.

4. A Model for C.R. Decreases

Our conclusion from the preceding section is that a C.R. decrease is generally the result of the passage of a region of high magnetic field intensity. Later it will be shown that most such regions are produced in the interplanetary medium by the steepening of streams. However the presence of a stream is not a necessary condition, nor is it necessary that streams or blobs be long lived. For simplicity we shall consider a blob which has just passed 1 A.U. This avoids the problem of blob evolution beyond 1 A.U.

As the blob moves outward, it "sweeps away" the C.R. particles ahead of it, by a mechanism yet to be elucidated. Since one only occasionally observes enhancements before a Forbush decrease, it is possible that the particles are deflected out of the ecliptic. One possible deflection mechanism is a gradient drift. Since the scale length of the cross section of a blob is $L \simeq 0.25$ A.T. to 0.5 A.U., particles with rigidities to up $\sim$100GV can be deflected. Since the magnetic field intensity increases from $\simeq 5\gamma$ to $\simeq 20\gamma$ to 30γ in a blob, the gradients are on the order of 100γ/A.U. Such a gradient causes a drift given by

$$v_D = (c/e)\, w_\perp / B^3 \, (\underline{\underline{B}} \times (\underline{\underline{\nabla B}}))$$

(Northrop, 1963). Let $L = \ell R$ where R is the gyroradius. For a 1 Gev proton in a 20γ field, $R \simeq 0.01$ A.U., and for L=0.25 A.U., $\ell \simeq 25$. Noting that $\omega_\perp$ = eP and P = BR, where P is the rigidity, one finds that $v_o \simeq$ c/25. This drift velocity is much larger than the rate at which the blob advances (v_o/v_ω=c/25 $v_\omega \simeq$ 30, where v_ω is the solar wind speed), so blobs will effectively sweep away particles by gradient drifts. Other mechanisms may, of course, be operating simultaneously.

One should study the number of particles affected in this way. This depends in part on the distribution of perpendicular velocities, $\omega_\perp$, previous to the passage of the blob, and on the particular configuration of field gradients in the blob. We have not attempted to analyze this complex question. Qualitatively, we can say that as the blob moves radially outwards from the Sun it leaves a "wake" or region of depressed cosmic ray intensity. For the configuration shown in Figure 4 this wake is confined to the disturbed region. One can present arguments from two different viewpoints to explain why the wake fills up slowly.

If one takes the viewpoint that there are numerous irregularities along the field lines then we know that the cosmic rays will tend to close the wake at the diffusion rate, v_{Diff} = D/t_{Diff}, while the blob advances at speed v_ω. The recovery time is typically a few days, corresponding to a wake length of 1 A.U., and the azimuthal extent of the blob at 1 A.U. is also $\simeq$ 1 A.U.; so the observed geometry implies that $v_{Diff} \approxeq v_\omega$, i.e. $\frac{D}{t_{Diff}} = v_\omega$. Thus $D = v_\omega^2\, t_{Diff}$, where t_{Diff} = 1 A.U./v_ω. This gives $D \simeq v_\omega$ x 1 AU $\sim 6\text{x}10^{20}\text{cm}^2\text{sec}$ as an order of magnitude estimate for the diffusion coefficient near 1 A.U. This agrees reasonably well with the accepted value of the diffusion coefficient obtained from flare events, magnetic power spectra calculations, etc.

If one takes the opposite viewpoint of adiabatic motion of cosmic rays between large angle scattering interactions, the picture is somewhat different. In this representation, the C.R. intensity at any point A along a field line is the sum of three parts. One part is cosmic rays coming from the anti-sunward direction. Another is cosmic rays which have gone past the point A and mirrored in the converging magnetic field, and are now returning to A. The third part consists of particles which have been scattered on to the field line from other field lines, close to the sun where the fields are too disturbed for the adiabatic approximation to hold.

From the moment of formation of the blob the C.R. intensity behind the blob is sealed off from further injection except for the part scattered across the solar surface at the foot of the field line. Thus as the blob moves outward the C.R. density behind it should continue to decrease indefinitely. That this does not happen indicates that presumably diffusion across the solar surface is fairly important, or that the blob loses its effectiveness as a barrier with the passage of time.

Finally a word should be said about the effect of successive blobs. The particles remaining after a blob has deflected some of the particles away are of higher than average rigidity, since it deflects the low rigidity particles more efficiently. Thus, a second, identical in all respects to the first should cause a much smaller intensity depression.

6. Complex Events and Events with Long Recovery Times

Figure 5 shows a single cosmic ray intensity depression lasting from August 30 to September 27, 1968. Close inspection of the figure shows that the form of the depression is closely related to the sequence of blobs associated with it.

Five magnetic blobs passed the earth during this time. The main decrease in C.R. intensity appears to occur in three steps, corresponding to the passage of the first three blobs, A, B, and C, each causing a moderate C.R. intensity depression, and, all together, they cause a large decrease. Only the third C, is associated with an SSC, so the main part of the decrease is not caused by shocks or shock-like flow. Pioneer 7 data shows that A and B were corotating: because of a data gap one cannot tell whether C was corotating. After the passage of C, the recovery begins again after the passage of D. Blob E appears to have little effect on this recovery, (although it may have retarded it somewhat), and after the passage of E the recovery continues to the original intensity, no further blobs interrupting this process. In summary, the September 1968 C.R. decrease can be divided into several stages, each of which is related to the passage of a magnetic blob. Each blob has the effect of either reducing the C.R. intensity or retarding the rate of increase. The total C.R. profile can be regarded as the collective result of the effects of these five blobs. Note that the multiple depressions occur because the separation between the pairs of blobs A, B, and B, C is smaller than their wakes. In other words, there is a multiple depression because the times between successive blobs are smaller than the recovery times for these blobs. One can compare this to the behavior of a pulsed RC circuit where the time constant is larger than the separation and width between pulses. We believe this behavior to be general.

A more complicated event caused by several shock-associated blobs is shown in Figure 6. The sudden commencements which we assume are due to shocks, are indicated by arrows on the abscissa. The derivative of N shows 8 large decreases; all are associated with blobs, and six follow shocks, In addition, there are two blobs which do not cause CR decreases, detectable in our data handling scheme, but these occur during the recovery of the largest depression. Again, the basic concepts which we have described give a natural phenonenological description of this complex event.

Long Recovery Times. Lockwood (1971) in his review paper stresses the particular difficulty of explaining Forbush decreases with very long recovery times (≥10 days). Here we show how such C.R. decreases are a natural consequence of our model, for certain interplanetary magnetic field configurations.

A cosmic ray decrease with a recovery time of 23 days, between November 21, 1967 and December 15, 1967, is shown in Figure 7, where the Deep River neutron monitor data are shown together with the Explorer magnetic field data. The reason for the long recovery time is at once evident: there is a steady succession of blobs throughout most of this time interval, and these blobs follow closely on the heels of one another. Further insight is gained by examining the profiles in more detail. Five regions are identified in Figure 8 labelled A, B, C, D, and E. The C.R. decrease begins abruptly with the arrival of A, where there is unfortunstely a data gap. Before the C.R. intensity can recover from A, B arrives and causes a small decrease. This is followed immediately by a large, irregular blob which again prevents a recovery, even causing the intensity to decrease somewhat further.

When the magnetic field intensity drops near the average value towards the rear of C, the C.R. intensity begins to recover, but this is stopped very soon by the passage of D, which depresses the intensity again. After the passage of D there are no further blobs for several days and accordingly the C.R. intensity recovers, regaining its previous value on November 21.

One sees that long recovery events are not particularly different from complex events. There is just a sufficiently rapid and prolonged succession of blobs to prevent the recovery from any single blob.

7. Causes of Magnetic Blobs

We have examined a relatively short interval where fairly complete observations of the neutron monitor counting rate N, the magnetic field intensity B and the plasma bulk speed V were available. The data, covering July 1967 to October 1967, are shown in Figure 8. The most prominent blobs are indicated by vertical lines. The correlations between B and N discussed earlier are also evident here. Incidentally, one may note that the recovery from the C.R. decrease which occurred at the end of July lasted three months because of the unusually large numbers of blobs. The main point of interest in this section is the relation between blobs and the bulk speed. If we exclude features for which no data is available, there are seventeen blobs in Figure 8 and twelve of them are followed by distinct streams. Only two are not followed by streams. We conclude that most, but not all, blobs are caused by streams. This is not too surprising, as it has been observed often that the magnetic field is high ahead of streams, which comes as a natural consequence of the compression arising from the steepening of interplanetary streams (e.g. Hundhausen, 1972, Burlaga, 1974 who reviewed this topic).

There are perhaps other interplanetary phenomena which can give rise to these features. Some possibilities which come to mind are driven shocks, massive ejection of magnetised material from the sun, and bottle configuration. We propose to study some of these possibilities in another paper, but we must stress here that it seems likely that the most frequent phenomenon, at least in the part of the solar cycle which we studied, is the stream steepening mechanism. For the years 1967-1968 a preliminary investigation has shown that only four or five candidates for bottle-like configurations are likely - although we were not using as complete a set of plasma observations as one could hope for. Shocks are indeed often associated with Forbush decreases, and may be considered probably as the next important blob generator. Sector boundaries are not in general associated with either blobs or Forbush decreases, although some noteworthy exceptions have been found in the data set studied (in fact we have magnetic field angular data for all the time intervals presented in this paper, and have not presented it in the interest of keeping the figures as clear as possible).

8. Conclusions

Evidence has been presented conclusively showing the association of regions of high magnetic field with cosmic ray intensity depressions. The hypothesis that these depressions are caused by the magnetic blobs has been shown to explain complex Forbush decreases and long-lived depressions in a qualitative way in those cases examined. The mechanism by which this is achieved has not been unambiguously identified, although we feel that our preliminary model presents several attractive features.

Further insight into the Forbush decrease phenomenon may be achieved in a number of ways, some of which are under investigation in this laboratory.

Fundamentally, two directions may be pursued: the study of the extent and properties of magnetic blobs, and the detailed study of cosmic ray phenomena associated with the Forbush decreases.

Precise quantitative predictions of the intensity of the decrease, time constants of the decrease and recovery phase, and anisotropy properties of the F.D. phenomenon cannot, in our view, be made without a full three-dimensional mapping of the magnetic field intensity in the vicinity of earth. It does not seem possible to achieve this in the near future.

We hope to obtain some better idea of the gross features of the magnetic field configurations from three sources: multi-space craft observations, theoretical predictions of interplanetary dynamics, and, indirectly, from the study of the path of moving type III bursts throughout the solar system. Such data should be available with the next year or two. The key to the mechanism of the decrease may lie in the study of the directional anisotropy as a function of time in those cases where the geometry can be at least roughly estimated - isolated blobs observed by two or more spacecraft. The implications regarding the anisotropy inherent in our model have not been worked out as yet and further work on this is in progress.

The general thesis presented in this paper allows us to make some predictions as to the rigidity dependence of F.D.'s. The rigidity dependence of a complex F.D. caused by a succession of blobs should vary markedly from the first to the second blob passage. The higher the field in the blob the harder the rigidity dependence should be. As we do not have a meson telescope data set we were unable to verify these predictions.

It is clear that the type of structure of the interplanetary magnetic field here revealed implies important effects in other cosmic ray phenomena besides the Forbush decreases. These cannot be detailed here, but cosmic rays will surely move about differently in an ensemble of blobs such as is depicted here than in the usual homogeneously turbulent magnetic field assumed in the current theories of cosmic ray propagation.

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Figure Captions

Figure 1 Hourly averages of the smoothed neutron monitor data and magnetic field intensity at earth and Pioneer 7 respectively - Feb. 3-15.

Figure 2 As in Figure 1, Feb. 16-22.

Figure 3 Hourly averages of the smoothed Deep River neutron monitor data, logarithmic derivative of this curve, and magnetic field intensity close to earth as measured by Explorer series spacecraft.

Figure 4 Idealised magnetic blob, (black region) moving radially outward with velocities indicsted by the arrows. Two hypothetical spiral magnetic field lines are shown. The dots represent the conjectured cosmic ray intensity.

Figure 5 Five successive magnetic blobs and their effect on the smoothed neutron monitor intensity.

Figure 6 Complex Forbush decrease showing the effect of a succession of blobs. The negative of the logarithmic derivative of the neutron monitor intensity tracks the magnetic field quite closely.

Figure 7 A very long-lived Forbush-like decrease caused by four magnetic blobs of long duration.

Figure 8 Three hour averages of the plasma bulk velocity, one hour averages of the magnetic field intensity and smoothed neutron monitor data, illustrating the formation of blobs at the head of high-speed streams.

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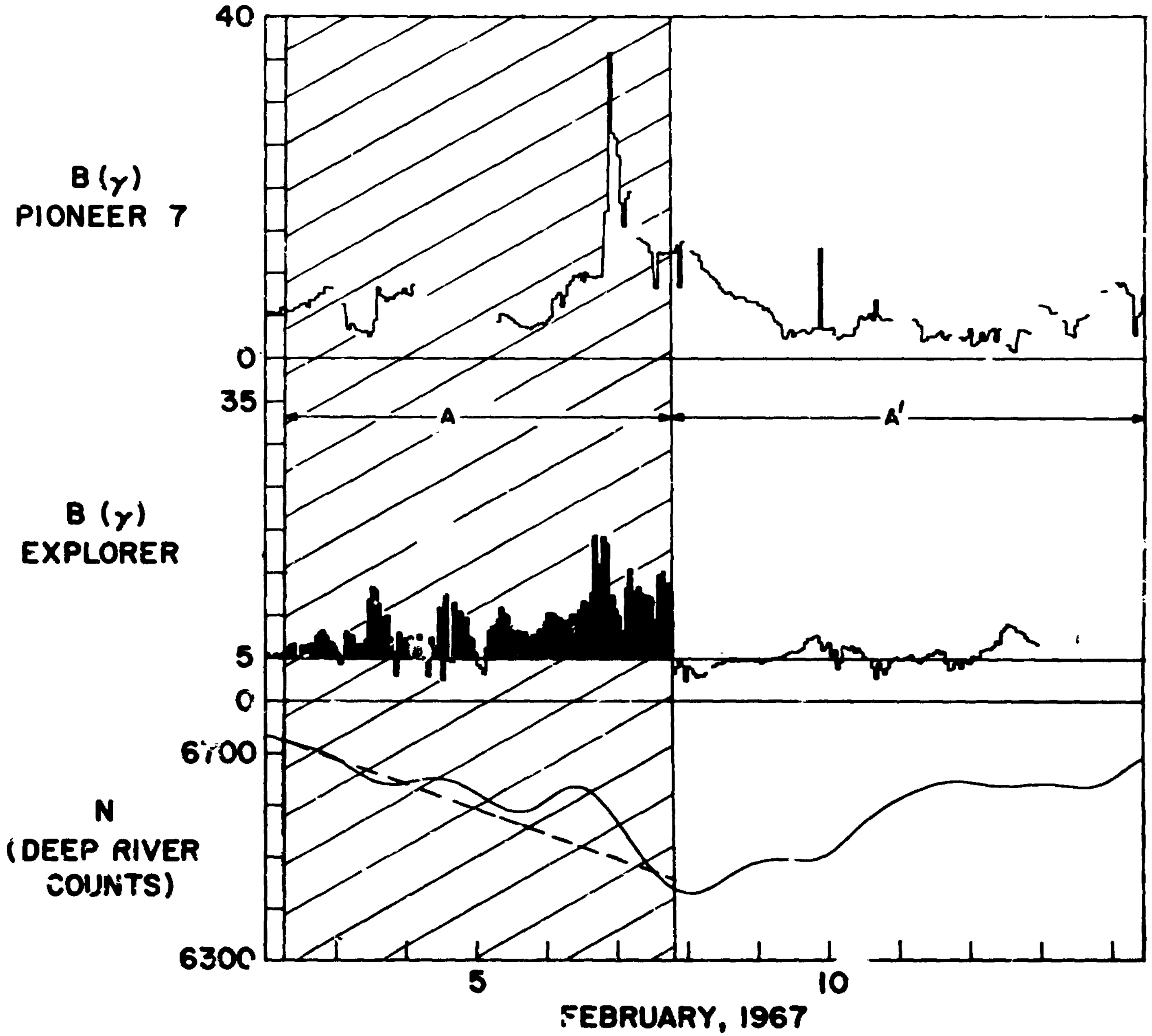
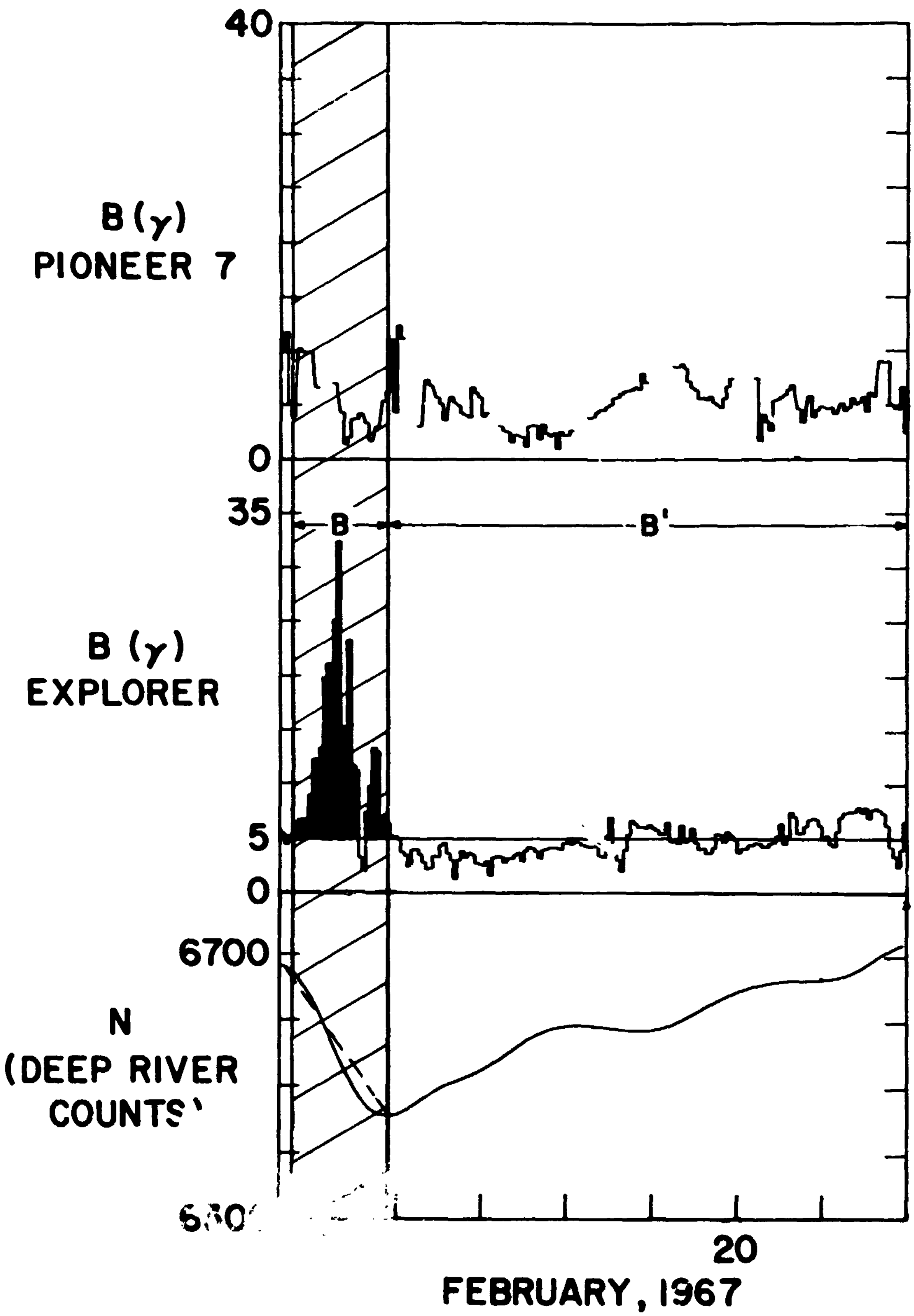
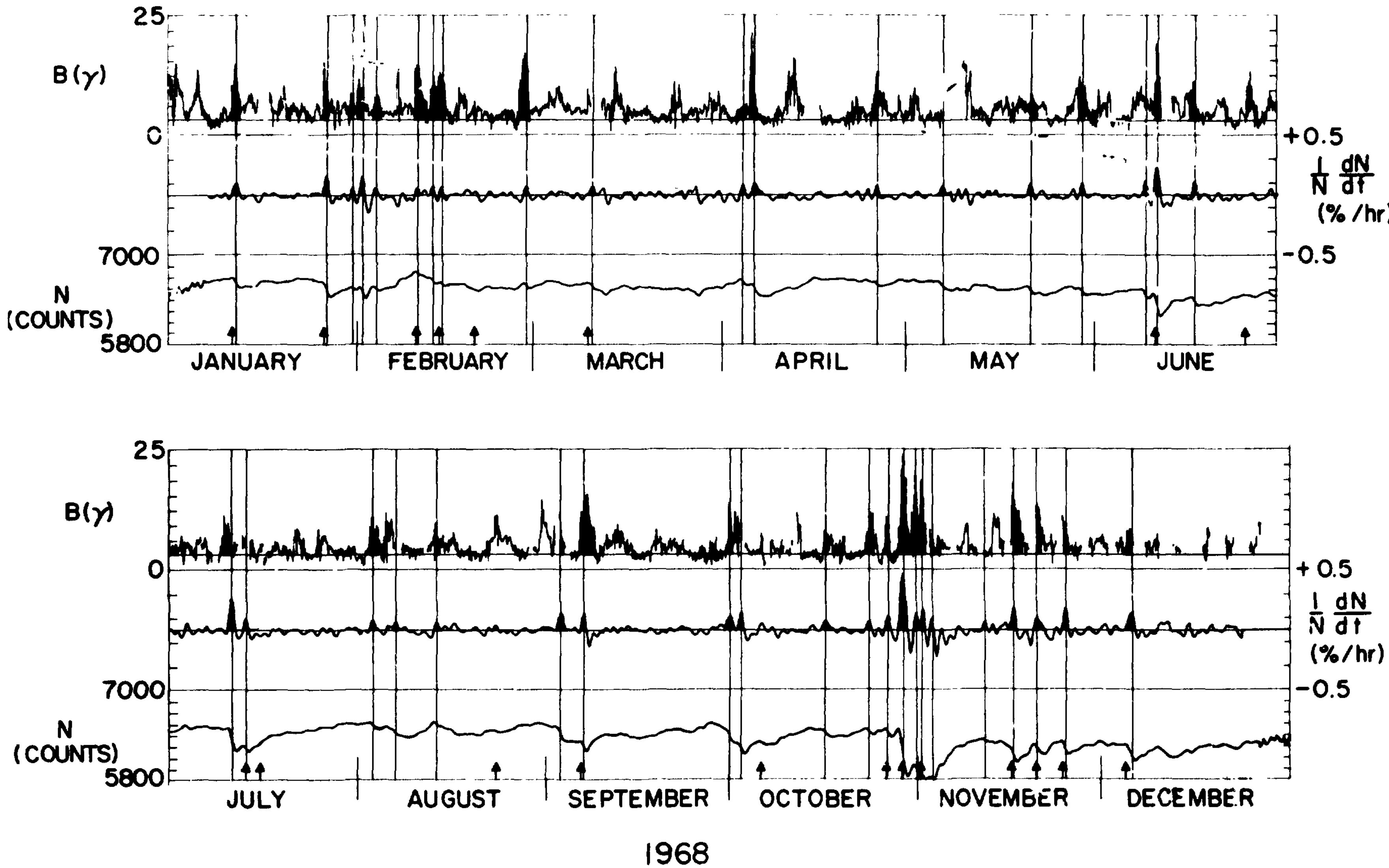
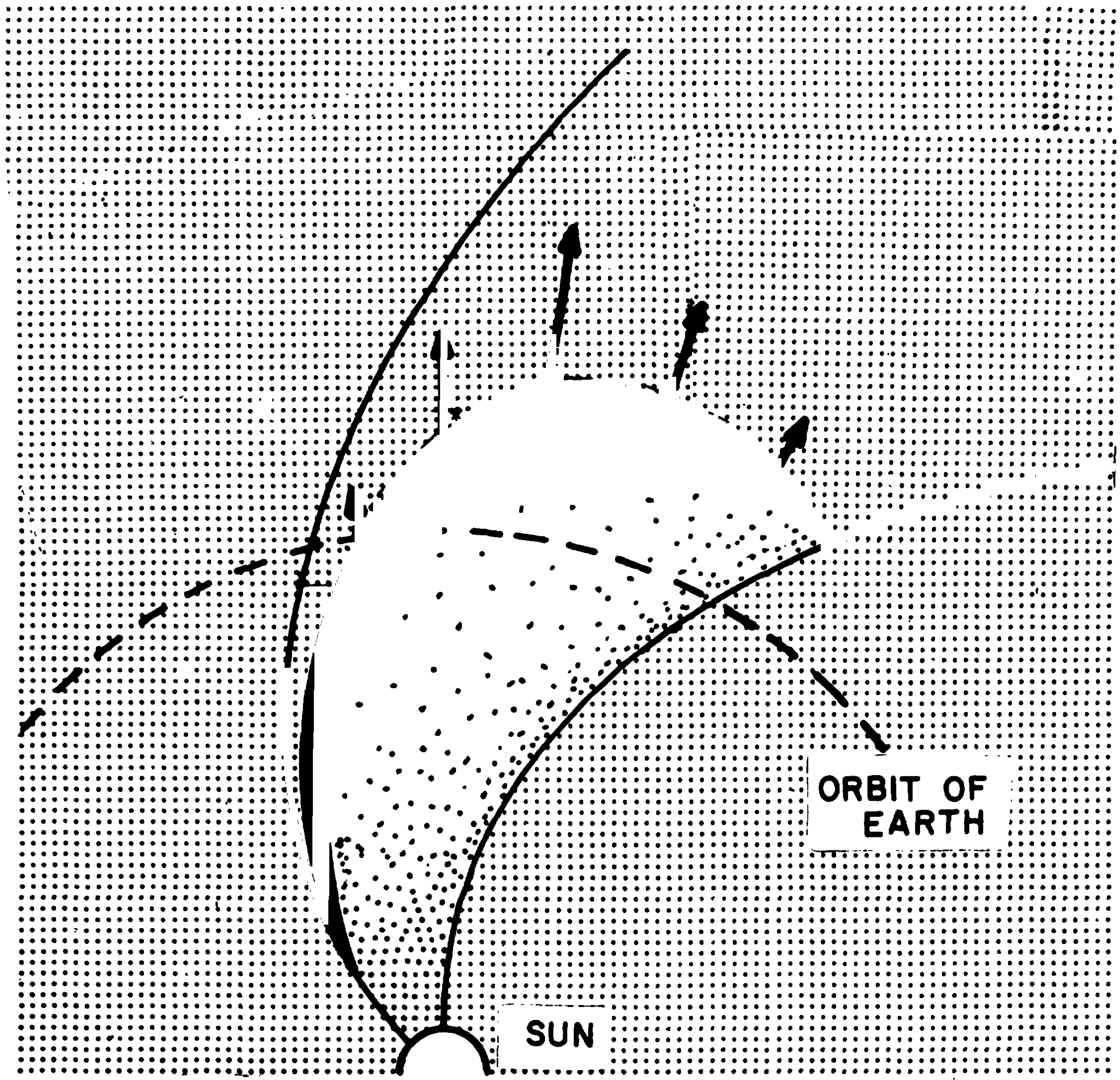
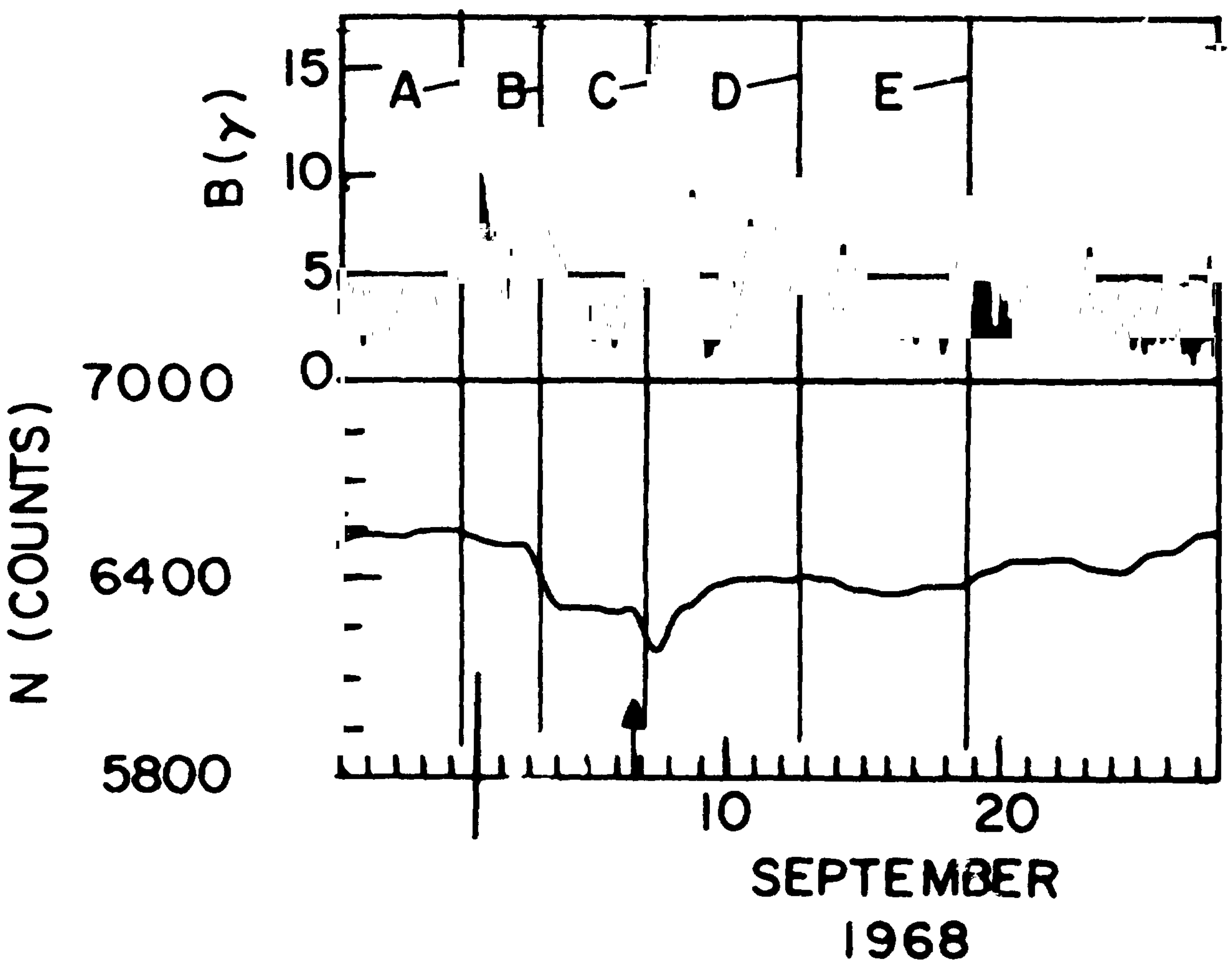

B (γ)
PIONEER 7
B (γ)
EXPLORER
N
(DEEP RIVER
COUNTS)
40
0
35
5
0
6700
6300
A
A′
5
10
FEBRUARY, 1967



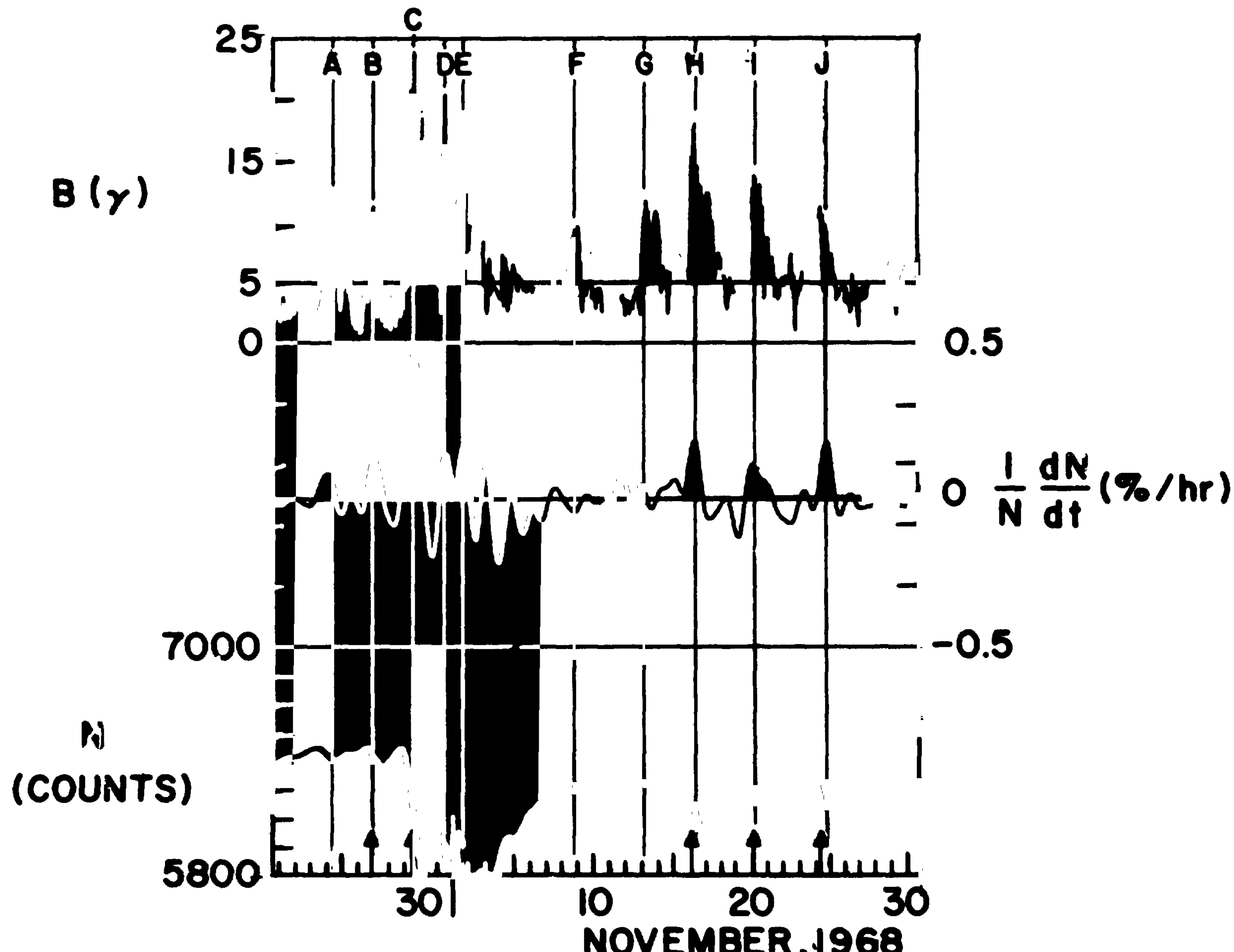
40
B (γ)
PIONEER 7
0
35
B
B'
B (γ)
EXPLORER
5
0
6700
N
(DEEP RIVER
COUNTS)
20
FEBRUARY, 1967

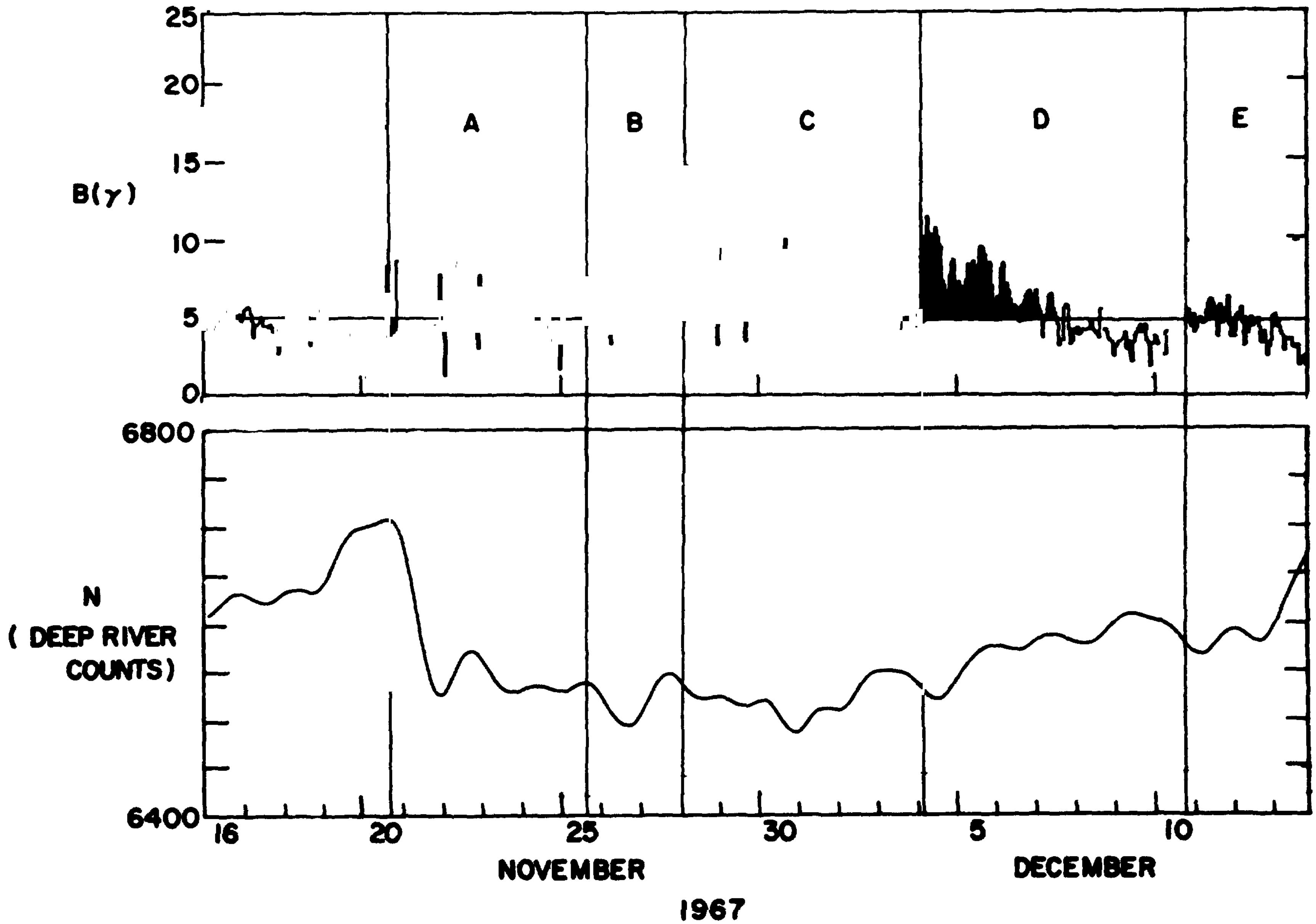

25
B(γ)
0
7000
N
(COUNTS)
5800
+0.5
1/N dN/dt
(%/hr)
-0.5
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
1968


ORBIT OF
EARTH
SUN

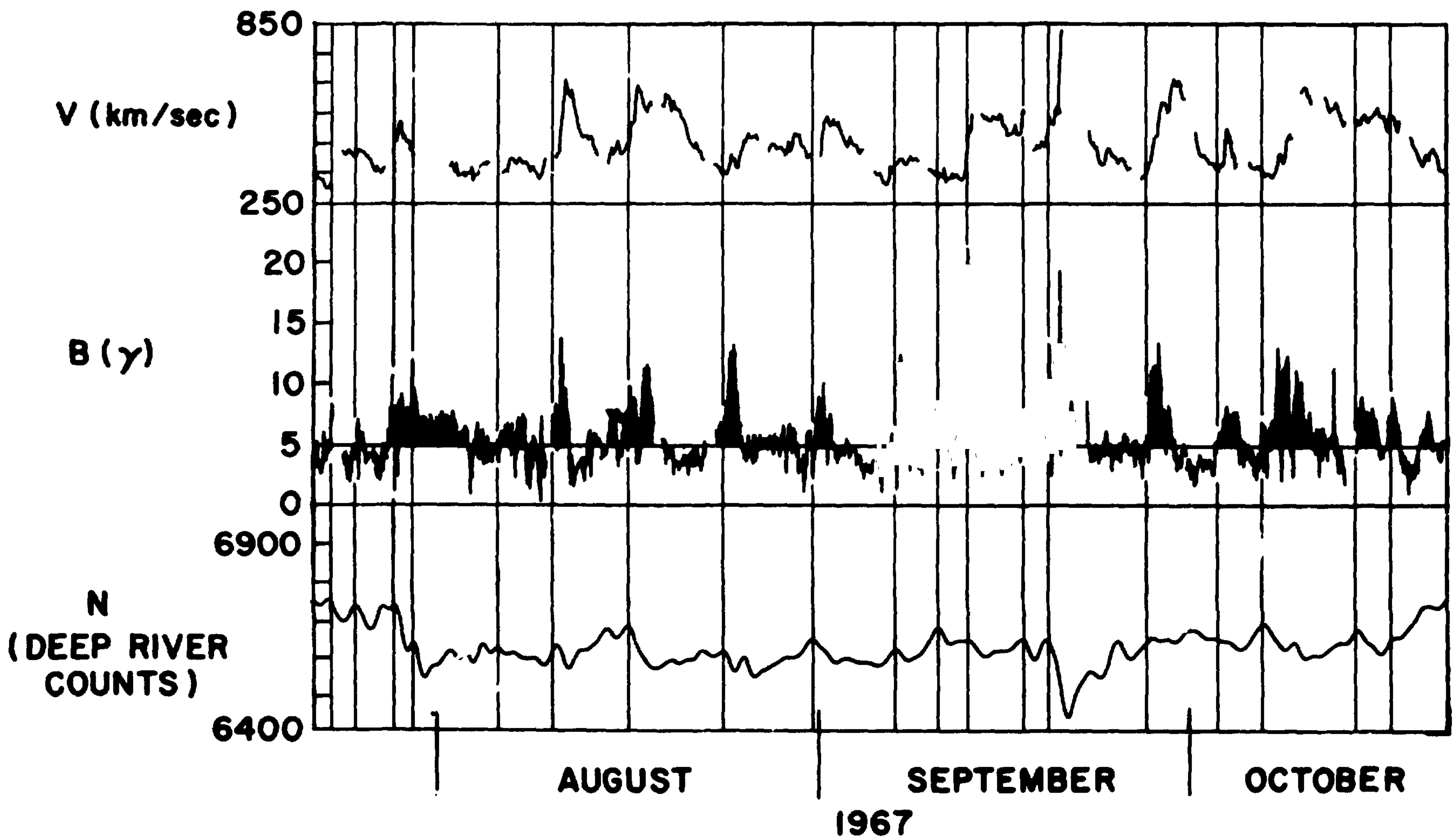


15
10
5
0
B(γ)
A
B
C
D
E
7000
6400
5800
N (COUNTS)
10
20
SEPTEMBER
1968


B (γ)
N
(COUNTS)
25
15
5
0
7000
5800
A
B
C
DE
F
G
H
I
J
0.5
0
-0.5
$\frac{1}{N}\frac{dN}{dt}$ (%/hr)
30
1
10
20
30
NOVEMBER, 1968



B(γ)
25
20
15
10
5
0
A
B
C
D
E
N
(DEEP RIVER COUNTS)
6800
6400
16
20
25
30
5
10
NOVEMBER
DECEMBER
1967


850
V (km/sec)
250
20
15
B (γ)
10
5
0
6900
N
(DEEP RIVER
COUNTS)
6400
AUGUST
SEPTEMBER
OCTOBER
1967