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## ABSTRACT

We studied the causes of recurrent geomagnetic activity by analyzing interplanetary magnetic field and plasma data from earth-orbiting spacecraft in the interval from November 1973 to February 1974. This interval includes the start of two long sequences of geomagnetic activity and two corresponding corotating interplanetary streams. In general, the geomagnetic activity was related to an electric field which was due to two factors: 1) the ordered, mesoscale pattern of the stream itself, and 2) random, smaller-scale fluctuations in the southward component of the interplanetary magnetic field $B_z$. The geomagnetic activity in each recurrent sequence consisted of two successive stages. The first stage was usually the most intense, and it occurred during the passage of the interaction region at the front of a stream. It was related to a $\underset{\sim}{V} \times \underset{\sim}{B}$ electric field which was large primarily because the amplitude of the fluctuations in $B_z$ was large in the interaction region. It is suggested that these large amplitudes of $B_z$ were primarily produced in the interplanetary medium by compression of ambient fluctuations as the stream steepened in transit to 1 A.U. The second stage of geomagnetic activity immediately following the first was associated with the highest speeds in the stream. It was, among other things, related to a $\underset{\sim}{V} \times \underset{\sim}{B}$ electric field which was large mainly because of the high speeds.

## I. INTRODUCTION

The large-scale pattern of geomagnetic activity in the interval 1973 through 1975 is shown in Figure 1, where the black areas indicate the times when the daily average, C9 index was $\gtrsim 5$ for two or more days in succession. The most striking features are two sequences of recurrent activity from 1974 to mid-1975, one to two years before solar minimum. In one sequence, which will be called sequence 4, the activity persists for a few days on each rotation, while in the other sequence the activity persists for several days on each rotation. The occurrence of such pairs of recurrent sequences lasting as much as a year is known to be a general characteristic of the years just prior to solar minimum (Allen, 1943, Abdel-Wahab and Goned, 1974).

Maunder (1905) presented a plot similar to Figure 1, with solar longitude instead of time on the abcissa, and he noted "a striking and most important relation. The disturbances are not distributed irregularly with regard to solar meridians, but chiefly affect two or three regions". He describes these as "definite and restricted areas rotating with a synodic period corresponding to latitudes between $0^{\circ}$ and $30^{\circ}$". He suggested that recurrent geomagnetic activity is caused by "a stream which, continually supplied from one and the same area of the Sun's surface, appears to us, at our distance, to be rotating with the same speed as the area from which it arises". He also concluded that the streams have "an average diameter of $20^{\circ}$ supposing them to be circular in section", and that the "streamlines... are not necessarily truly radial in direction".

The recurrence of geomagnetic activity was known long before Maunder's paper in 1905. Brown (1858) was one of the first to notice it. Prior to

Maunder's concept that streams are the cause of geomagnetic activity, it was believed by some that geomagnetic activity was caused by "magnetic waves spreading out from the Sun equally in all directions through space". This hypothesis was criticized by Lord Kelvin and others on the basis of energetics. Maunder's concept of a restricted beam of particles was important, because it provided a way out of this difficulty. We now know from in situ measurements in interplanetary space (e.g., Neugebauer and Snyder, 1966a, b) that recurrent geomagnetic activity is indeed associated with non-radial streams from restricted areas on the Sun. However, we shall show that "magnetic waves" also play an important role in geomagnetic activity, although these magnetic fluctuations are very different from those considered and rejected by Lord Kelvin. The principal new results to be presented below concern the importance of these magnetic fluctuations and their interaction with streams in determining geomagnetic activity.

The nature and sources of the streams have been reviewed by Chapman and Bartels (1940), Akasofu and Chapman (1972), Gulbrandsen (1975), and Roelof (1974). Their nature is now well understood, but their sources have been controversial until now.

Bartels (1932) called the solar sources of interplanetary streams M-regions, and suggested that they might not be visible features on the Sun. Maunder (1905), on the other hand, considered that the sources are active regions, although he recognized that sunspots or flares need not be visible in the source region. This view was given prominence by Mustel and his colleagues in a long series of papers. Others, including Allen (1943), Saemandson (1961), and Lapointe and Vallee 1970), argued with Bartels that M-regions were not active regions, but rather some unidentified region. Allen (1943) identified M-regions with coronal streamers that are deflected away from plumes, which are usually associated with sunspots, and he inferred that they generally lie to the north and south of the solar equator because M-disturbances are most intense in March and September when the Earth is farthest from the equatorial plane. Billings and Roberts (1964) suggested that magnetic field lines diverge in M-regions, whereas they are generally closed in active regions. The importance of diverging field lines has been stressed by Hundhausen (1972) and shown in models by Pneuman and Kopp (1971) and others. Observations by Skylab in 1973 revealed the existence of regions called coronal holes in which the density is low and the magnetic field lines diverge. These are found to be correlated with solar wind streams (e.g., see Nolte et al., 1976, Sheeley et al., 1976, Neupert and Pizzo, 1974). The prevailing view at present is that M-regions are in fact coronal holes, but this should be viewed as a preliminary result. The problem is under intensive study.

Even now, some authors discuss solar-terrestrial relations as though streams were the sole or primary intermediary between the Sun (coronal holes) and recurrent geomagnetic activity, essentially following Maunder's line of thought. It is known, however, that the interplanetary magnetic field is also of prime importance in regulating geomagnetic activity, although magnetospheric physicists generally take this as a given input function and do not inquire about the nature and origin of this field. Alfven (1950) suggested that the basic cause of geomagnetic activity is the interplanetary electric field, $\underset{\sim}{E} = -\underset{\sim}{V} \times \underset{\sim}{B}$, i.e., both the streams and the magnetic field, acting together determine the behavior of geomagnetic activity. Dungey (1961) proposed that it is the southward component of $\underset{\sim}{B}$ which is most important; he imagined that a southward interplanetary magnetic field line could reconnect with a northward geomagnetic field line, and that geomagnetic activity was produced by the motion of the new field line. Alfven dismisses reconnection as a colloquialism, and he stresses the importance of thinking in terms of currents driven by the electric field, bu. he agrees that it is basically the southward component of the interplanetary magnetic field, $B_z$, that is important. Current theoretical ideas about the cause of geomagnetic activity (Vasyliunas, 1975; Svalgaard, 1973, 1975; Holzer and Reid, 1975; Gonzalez and Mozer, 1974) also consider $B_z$ and V to be essential factors. The observations support this view. A high correlation between $B_z$ and geomagnetic activity has been demonstrated by Fairfield and Cahill (1966), Wilcox et al. (1967), Tsurutani and Meng (1972), Patel and Desai (1973), and by many others. Arnoldy (1971), Foster et al. (1971), Kane (1972), Meng et al. (1973) and Hirshberg and Holzer (1975) have discussed a very high correlation between $B_z$ and the AE index, which measures activity in the auroral zone. The correlation between geomagnetic activity and the interplanetary electric field has been discussed by Rostoker and Falthammer (1967), Alfven and Fathammer (1971), Foster et al. (1971), Garret (1974), Garrett et al. (1974), Russell et al. (1974), and Bahnsen and D'Angelo (1976).

The aim of this paper is to better understand the role of the interplanetary medium in connecting solar conditions (coronal holes) and the geomagnetic activity measured by AE. In particular, we examine the following: 1) the characteristics of the magnetic field in corotating streams that influence AE, 2) the relations between this magnetic field and corotating streams, and 3) the dynamical processes within the streams that reconfigure the interplanetary electric field and thereby impress a characteristic pattern on geomagnetic activity. Our results are based on interplanetary magnetic field measurements from IMP-8 and HEOS and on plasma measurements from the MIT instruments on IMPs-7 and -8.

## II. A CONCEPTUAL MODEL FOR THE CAUSES OF RECURRENT GEOMAGNETIC STORMS

In this section, we consider one geomagnetic storm, and we examine the interplanetary stream and magnetic field configurations which caused it. The results and concepts illustrated in this case study have general significance, as will be shown in the next section.

We consider a geomagnetic storm that occurred in the sequence labled 2 in Figure 1. Figure 2 shows the AE index during one passage of sequence 2, from November 3 to November 13. Note that the variation of AE consists mainly of a series of pulses, each lasting a few hours. In this case, the largest pulses occurred on November 4 and November 7, and correspondingly the C9 index was high ( $\geq$ 5) on those two days in BR 1918. Hourly averages of the $B_z$ component of the interplanetary magnetic field (in solar ecliptic coordinate's) are shown above AE in Figure 2. One sees a striking correlation between the bursts in AE and large southward values of $B_z$. There can be no doubt that $B_z$ is an essential factor in causing the geomagnetic activity. A similar correlation was shown by Arnoldy (1971) between geomagnetic storm activity and a flare-associated stream. A general statistical correlation between AE and $B_z$ was also shown by Arnoldy (1971) and confirmed by Kane (1972) and Garret (1974). They point out that the correlation is better if one uses solar magnetospheric coordinates, but this is a detail as far as our aims are concerned.

Although the pulse-like nature of geomagnetic activity shown in Figure 2 is due to the fact that the interplanetary magnetic field is highly variable on a scale of a few hours, each AE pulse is basically a D-C effect, there being one AE pulse per peak in plots of the hour average of $B_z$ rather than two. Garrett et al. (1974) looked for an effect of the higher frequency variations in $B_z$, following a suggestion of Dessler and Fejer (1963), but this effect was found to be very small. Thus, the geomagnetic activity in a moderate recurrent storm lasting several days is associated with fluctuations in $B_z$ with apparent (Doppler-shifted) periods in the range of one to several hours. The fluctuation pattern is to first approximation the result of convection of a spatial pattern of the field past the spacecraft.

Figure 2 shows that the geomagnetic activity on November 3-13, was also associated with a stream. This stream has been associated with a coronal hole near the solar equator (Nolte et al., 1976, Sheeley et al., 1976), which is shown in Figure 3a. It is generally agreed that such streams are accelerated within 25 solar radii of the Sun and move through the interplanetary medium with little change in speed. However, as such a stream moves through the interplanetary medium, the fast plasma overtakes the slow plasma in the stream, causing an enhancement of density and magnetic field in the interaction region in front of the stream (e.g., see Neugebauer and Snyder, 1966b; Davis et al., 1966; Burlaga et al., 1971; Hundhausen, 1972; Burlaga, 1975; and Burlaga and Barouch, 1976). Such enhancements are seen in Figure 2.

Neither a stream alone, nor fluctuations in $B_z$ alone cause a storm. Both V and $B_z$ are important in influencing geomagnetic activity, through the electric field, $\underset{\sim}{E} = -\underset{\sim}{V} \times \underset{\sim}{B}$, as suggested by Alfven (1950). This is shown by the bottom panel of Figure 2, which is a plot of $E_y = VB_z$, where velocity is assumed radial. The electric field pattern is very similar to the $B_z$ pattern, with one essential difference. The amplitude of the fluctuations in $B_z$ is much larger in the interaction region (where n and B are high) than in the high-speed region, whereas the amplitude of the fluctuations in $E_y$ tends to be the same in these two regions. In the interaction region, $B_z$ is high but V is low, while in the high-speed region $B_z$ is low but V is high. This leads to the concept of two stages in a geomagnetic storm. The first stage is associated with the passage of the interaction region, where $E_y$ is large mainly because $B_z$ is large. The second stage is associated with the passage of the high speed region, where $E_y$ is large mainly because V is large.

To understand the cause of the first stage of a geomagnetic storm, one must understand why $B_z$ is high in the interaction region. It is well known (Davis et al. (1966); Hirshberg and Colburn (1969)) that the fluctuations in $\underset{\sim}{B}$ tend to be high where $|B|$ is high (i.e., in the interaction region). Dessler and Fejer (1963) and Coleman (1968) proposed that such fluctuations are generated within 1 A.U. by the Kelvin-Helmholz instability, but Burlaga et al. (1971) have argued against this proposal. A simpler and more direct explanation for most of the enhanced fluctuations in the interaction region is this: fluctuations in the direction of $\underset{\sim}{B}$ are always present and occur throughout a stream, but they are compressed (amplified) in the interaction region as the stream steepens in transit to 1 A.U. If we assume that the stream in Figure 2 was symmetric near the Sun and that the asymmetry seen at 1 A.U. is due to kinematic steepening, we find that the volume between the low speed at the beginning of the stream and the maximum speed (i.e., the interaction region) is diminished by a factor of $\approx 2.5$ as the stream moves from the Sun to 1 A.U.; hence, the amplitude of $B_z$ in the interaction region increases by approximately this amount. The amplitude of the fluctuations in $B_z$ in the body of the stream is not much affected by the kinematic changes. This agreement applies to all types of fluctuations insofar as propagation affects can be neglected. The amplication of one type of nonlinear fluctuation, transverse Alfven waves, has been treated in more detail by Hollweg (1975) and Richter and Olbers (1974) with similar results.

The cause of the second stage of a geomagnetic storm is primarily the high solar wind speed. High speeds contribute directly to geomagnetic activity through the electric field. They probably also contribute via another mechanism such as viscous drag (e.g., Svalgaard, 1975; Murayama and Hakemada, 1975; and Kane, 1974).

We thus arrive at the following conceptual model for the processes that lead to recurrent geomagnetic activity in general, and to the results in Figure 2 in particular: random, small-scale waves and convected structures are always introduced into the interplanetary medium from all longitudes near the Sun, and they are convected outward with the solar wind. Fast streams are generated above coronal holes, and they steepen kinematically as they move to 1 A.U. The fluctuations in $\underset{\sim}{B}$, which occur throughout the stream (as well as the ambient field intensity and the solar wind density), are compressed in the interaction region as a result of the steepening of the stream. This produces large amplitude fluctuations in $B_z$ and hence, large fluctuating electric fields in the interaction region which in turn produce bursts of geomagnetic activity that constitute the first phase of a geomagnetic storm. Moderate amplitude magnetic field fluctuations in the body of the stream (i.e., where V is high) cause bursts of geomagnetic activity lasting a few to several days.

Our model explains the statistical result of Hirshberg and Colburn (1973), Sawyer and Haurwitz (1976), and others that geomagnetic activity is highest following sector boundaries which tend to occur on the day preceding the maximum speed in the high-speed stream. These times correspond to the passage of the interaction region, where the amplitude of fluctuations in $B_z$ is highest, as described above. Hirshberg and Colburn (1973) previously suggested that this might be the case, but they did not have the observations needed to prove it.

Bobrov (1973, 1975) also suggested that a geomagnetic storm has two phases, but he was referring to $K_p$ (t) and Dst (t). Perhaps this is why he found that rapid fluctuations in the magnetic field intensity are more important than $B_z$ during the second stage, whereas the example in Figure 2 shows the opposite to be the case. Recurrent storms measured by the am index have been studied by Svalgaard (1975), who concluded that viscous drag is important as well as merging. Muragama and Hakamada (1975), Kane (1974), and others have concluded the same. One must carefully distinguish between the cause of AE changes and the causes of $K_p$, Dst, am, etc., during the second phase of a storm. The results in this paper refer to the causes of AE, which are more directly related to interplanetary conditions than $K_p$, etc.

The model that was just presented to describe and explain recurrent geomagnetic storms is conceptual, and so far we have considered only one storm. Actually, the model was arrived at inductively by considering many recurrent storms and some hypotheses of earlier workers. It remains to show that the model is generally applicable and to make it more quantitative. Specifically, several questions remain to be answered:

1) Does the model apply throughout a given sequence of recurrent geomagnetic activity and to different kinds of sequences?

2) What is the nature of the fluctuations in $B_z$, and how do they originate?

3) What is the two-dimensional pattern of the fluctuations in the ecliptic plane, and how does the amplitude of the fluctuations increase with distance from the Sun as the result of steepening of a stream?

4) How does one mathematically describe the growth of fluctuations in $B_z$ due to the steepening of the stream and their radial development in the absence of such effects?

In addition, of course, it remains to be shown how streams are accelerated at coronal holes near the Sun, and how the electric field at 1 A.U. produces geomagnetic activity in the magnetosphere, but such matters are beyond the scope of this paper. The remainder of this paper is concerned with the first point.

## III. DISCUSSION OF OTHER RECURRENT STORMS

The geomagnetic activity that was discussed in the previous section occurred on Bartels Rotation 1918 (BR 1918), and it was associated with a coronal hole that is designated CH2 (see Figure 3a from results in Nolte et al. (1976). On the next rotation, BR 1919, there was again a moderate storm associated with CH2. The AE index, plotted versus time in Figure 4, showed a few prominent peaks lasting several hours, and several smaller bursts. A large burst on December 4, 1973, occurred during the passage of an interaction region, where the density and field intensity were high and the speed was increasing. This event differs from the corresponding one on BR 1918 in a few details. Note that the density was high and increasing well ahead of the increase in speed and the enhancement in magnetic field intensity. This effect has been observed before (Belcher and Davis, 1971), but it is still not understood. The large AE burst on December 4, was associated with large southward $B_z$ and large B, but in this case there is a period of several hours at the time of the 'anomalous' increase in density when $B_z$ is always southward with no north-south oscillations. There are a few possible explanations for the persistent southward field at this time: a) boundary conditions near the Sun, b) a flow induced by the stream which carried the field along and produced a net negative $B_z$ ($\phi$ was in the second and third quadrants predominately at this time), c) a chance configuration. We cannot sort out these and other possibilities. In the interval with the largest values of AE on December 4, $B_z$ was in fact fluctuating, with the largest southward oscillations occurring near the peak in B and giving corresponding peaks in AE, consistent with our conceptual model.

Between BR 1919 and 1921, there was an evolution of the equatorial coronal hole that produced the events which we have been discussing, and a new hole was formed (designated CH2′) which extended from the south polar regions of the Sun to near the solar equator, as shown in Figure 3b. This polar hole produced a broad, high-speed stream, as shown for BR 1921 in Figure 5, beginning on January 25, 1974. Here again one sees the pattern that we described above. In the interaction region ahead of the stream, the density and field intensity are high, presumably due to compression by the steepening stream. Random fluctuations in $B_z$ are found throughout the 27-day interval, and peaks in AE are associated with large, southward fluctuations in $B_z$. The amplitudes of the $B_z$ fluctuations are largest in the interaction region, causing the first and most intense phase of the storm, which is indicated by the large AE burst. Numerous AE bursts occur in the main body of the stream, following the interaction region. They are apparently produced by the southward oscillations in $B_z$ and the high speeds, the large amplitude of AE being due mainly to the large values of V and the sporatic nature of AE being due to the fluctuations in $B_z$. Thus, the interplanetary magnetic field pattern and the relation to geomagnetic activity is essentially the same for this event as it was for the other events that were discussed above. Conversely, the generally low AE indices over January 22 (mid-day), 23, and 24, 1974, are consistent with a low solar wind speed, even though for part of this time the $B_z$ component is as large and as frequently negative (by hourly average count) as it was from January 26 through 31, where the AE indices were high and the speed was high, strengthening our case for this model further.

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The magnetic storms considered above were associated with just one large sequence of geomagnetic activity, due to coronal holes 2 and 2'. We now ask whether or not the conceptual model presented in Section 2 applies to other sequences as well. In particular, let us consider a storm in sequence 4 (Figure 1), which was related to a stream from coronal hole 4 (see Figure 3c).

Figure 6 shows the plasma density and speed, the field intensity and $B_z$, and AE for the storm in the interval November 24-30, 1973, which occurred in sequence 4 on BR 1919. In this case, the stream does not persist as long as that from CH2 , but otherwise the features of the two streams are similar. There is the familiar enhancement in n and B in front of the stream (although note that again the density is high even ahead of the interaction region). Fluctuations in $B_z$ occur throughout the stream, and they are largest in the interaction region which produces the first and most intense stage of the storm, indicated by the high AE and C9. There is a second stage of geomagnetic activity following the interaction region, which is presumably due mainly to high speeds in the body of the stream, but there is a gap in the magnetic field observations.

## V. SUMMARY

We have examined the causes of two sequences of recurrent storms in the period November 1973 to February 1974. One of these sequences was associated with a stream from coronal hole CH2 , while the other was associated with a stream from hole CH4. Generally, each magnetic storm could be viewed as the result of a series of geomagnetic disturbances, which appeared as a series of pulses in the AE index, separated by a few hours to several hours. Each of these pulses was associated with a southward fluctuation in $B_z$. Such fluctuations occurred throughout the stream and the storm, with an apparent period of a few to several hours. In most cases, a storm consists of two stages of geomagnetic activity. The first stage, which is usually the most intense, is associated with the largest amplitude fluctuations of $B_z$ and the largest magnetic field intensity, which occur in the interaction region of the stream, where V is increasing. The second stage of a recurrent geomagnetic storm lasts longer and is predominately associated with the high speeds.

The observations just described suggest the following physical model for recurrent geomagnetic storms. Mesoscale stream configurations are produced by processes associated with coronal holes at the Sun, and they recur as long as the holes persist (which may be nearly two years), although they are not exactly stationary and may change in detail from one solar rotation to the next. Smaller scale fluctuations in the magnetic field, probably both waves and convected structures, are also produced near the Sun and occur in all parts of a stream. As a stream moves from the Sun to 1 A.U., it steepens and compresses the ambient field, the density, and the magnetic field fluctuations in the interaction region where V is increasing. Thus, when the stream arrives at 1 A.U. the ambient fluctuations in $B_z$ have been amplified in the interaction region. These large amplitude, small-scale fluctuations in $B_z$, together with slowly increasing speeds in the stream, produce a non-uniform, quasi-stationary electric field which causes the bursts of geomagnetic activity that are observed in the first stage of a recurrent storm. The fluctuations of $B_z$ in the main body of the stream are not particularly intense, and they are not modified very much by interplanetary dynamical processes, but the speed there is high for a few to several days. This mesoscale, high-speed pattern together with the small-scale fluctuations of $B_z$ produce a quasi-stationary electric field which is non-uniform on a scale of several hours, but which has high amplitudes for several days. This field causes the bursts of geomagnetic activity that are observed in the second phase of a geomagnetic storm. Another mechanism such as viscous drag might also be operative during the second state, but this was not studied here.

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## FIGURE CAPTIONS

Figure 1 Recurrent geomagnetic storms prior to solar minimum arranged by Bartels' rotations. Dark areas indicate times when the daily C9 index was $\gtrsim 5$ for two or more days in succession.

Figure 2 Relation between the interplanetary magnetic field, a corotating stream, and geomagnetic activity. The AE index is related to fluctuations in $E_y$ (= $B_z$ V). These fluctuations occur throughout the stream but are largest in the interaction region, where ambient fluctuations have been compressed.

Figure 3 Some coronal holes that produced recurrent streams which caused recurrent geomagnetic storms.

Figure 4 Another recurrent storm associated with a stream from coronal hole 2.

Figure 5 A recurrent storm associated with CH2′. Notice that $B_z$ is plotted on a more sensitive scale than B. The basic features of all the storms associated with CH2 and CH2′ are the same although there are differences in detail.

Figure 6 A recurrent geomagnetic storm due to magnetic fields in a stream from coronal hole 4. Notice that $B_z$ is plotted on a more sensitive scale than B. The basic features are the same as those related to streams from CH2.

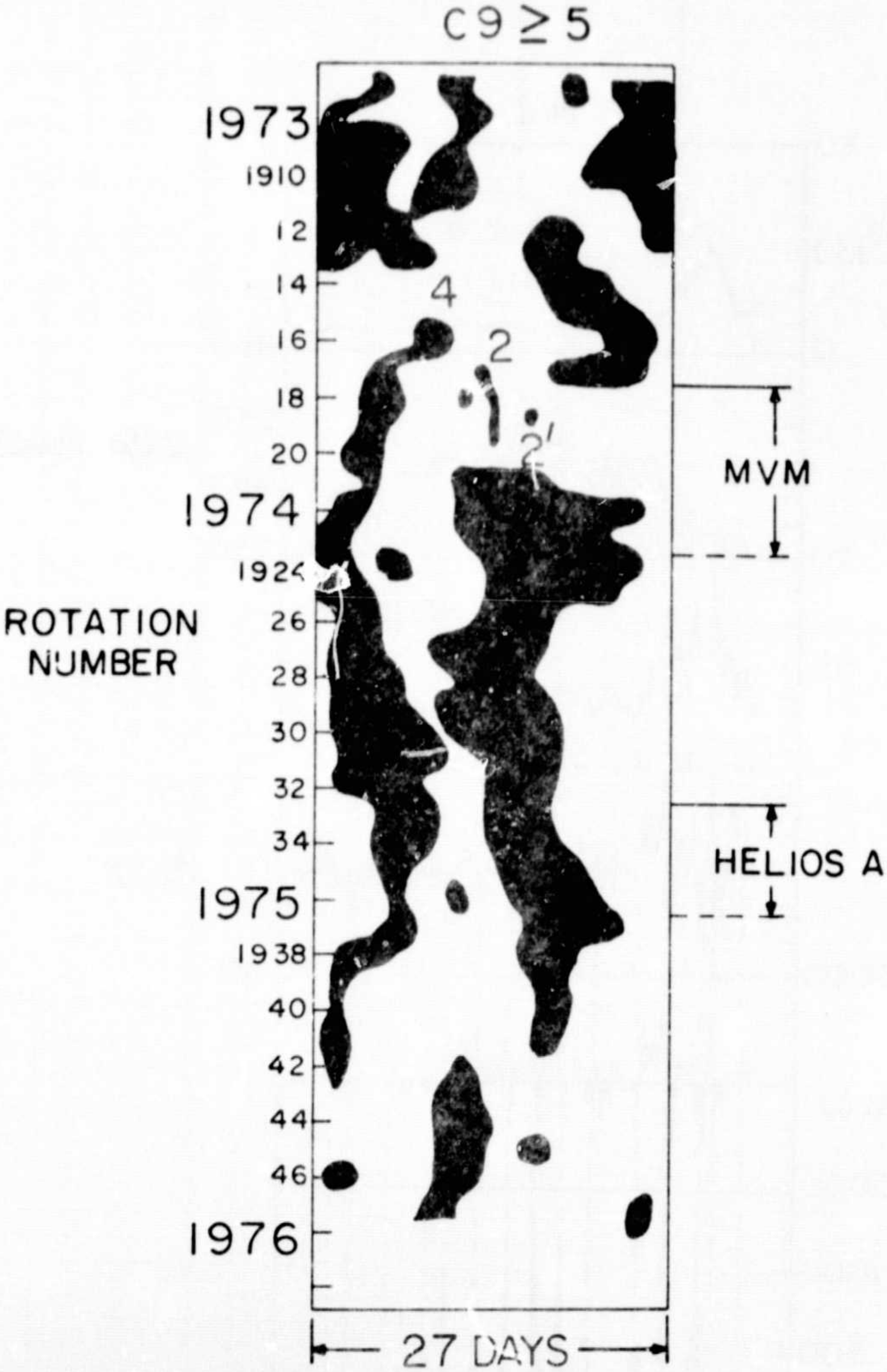

C9 ≥ 5
1973
1910
12
14
16
18
20
1974
1924
26
28
30
32
34
1975
1938
40
42
44
46
1976
ROTATION NUMBER
4
2
2'
MVM
HELIOS A
27 DAYS

Figure 1

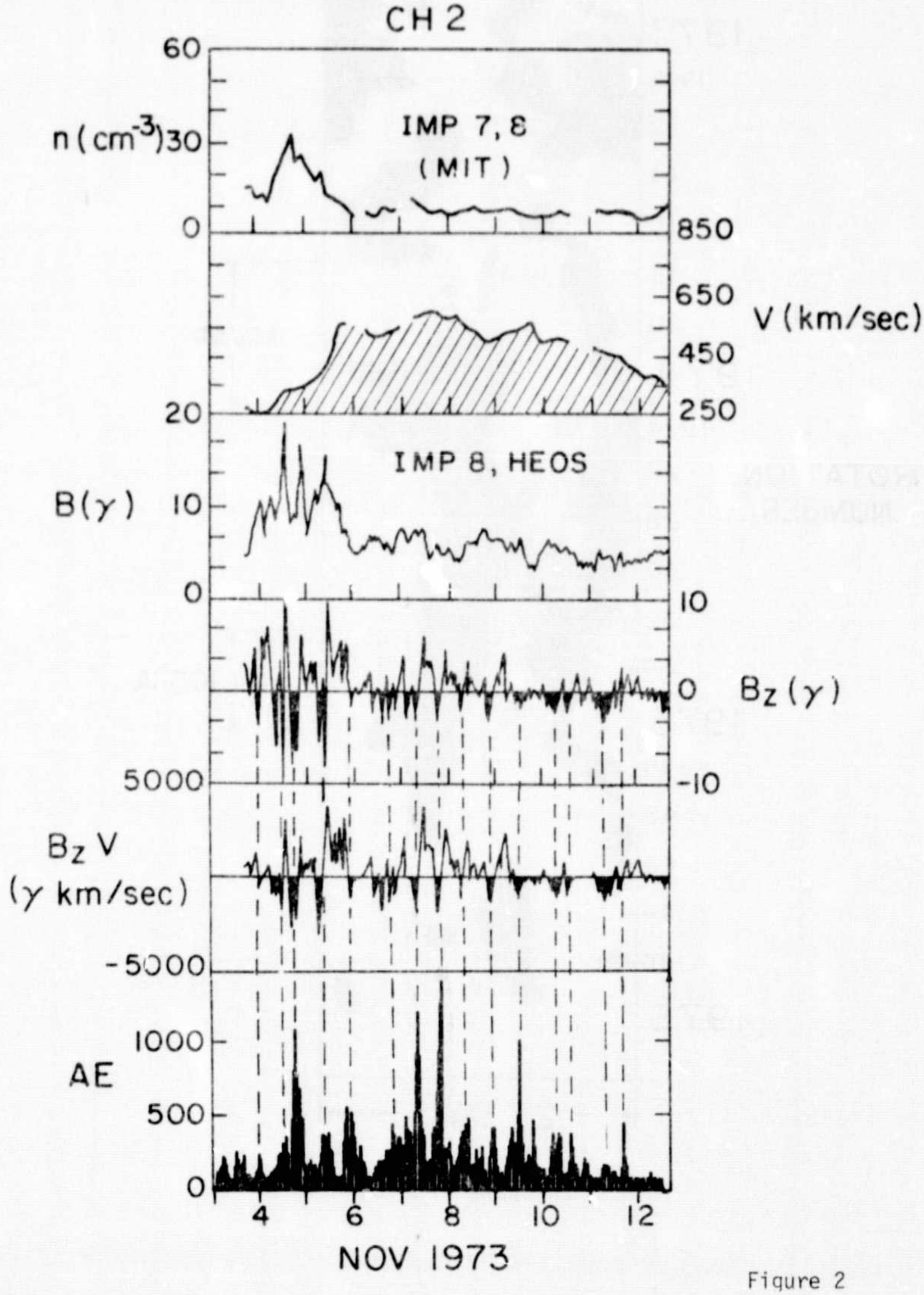

CH 2
60
n(cm$^{-3}$)30
0
IMP 7, 8
(MIT)
850
650
V(km/sec)
450
250
20
B(γ) 10
0
IMP 8, HEOS
10
0
Bz(γ)
-10
5000
Bz V
(γ km/sec)
-5000
1000
AE
500
0
4
6
8
10
12
NOV 1973

Figure 2

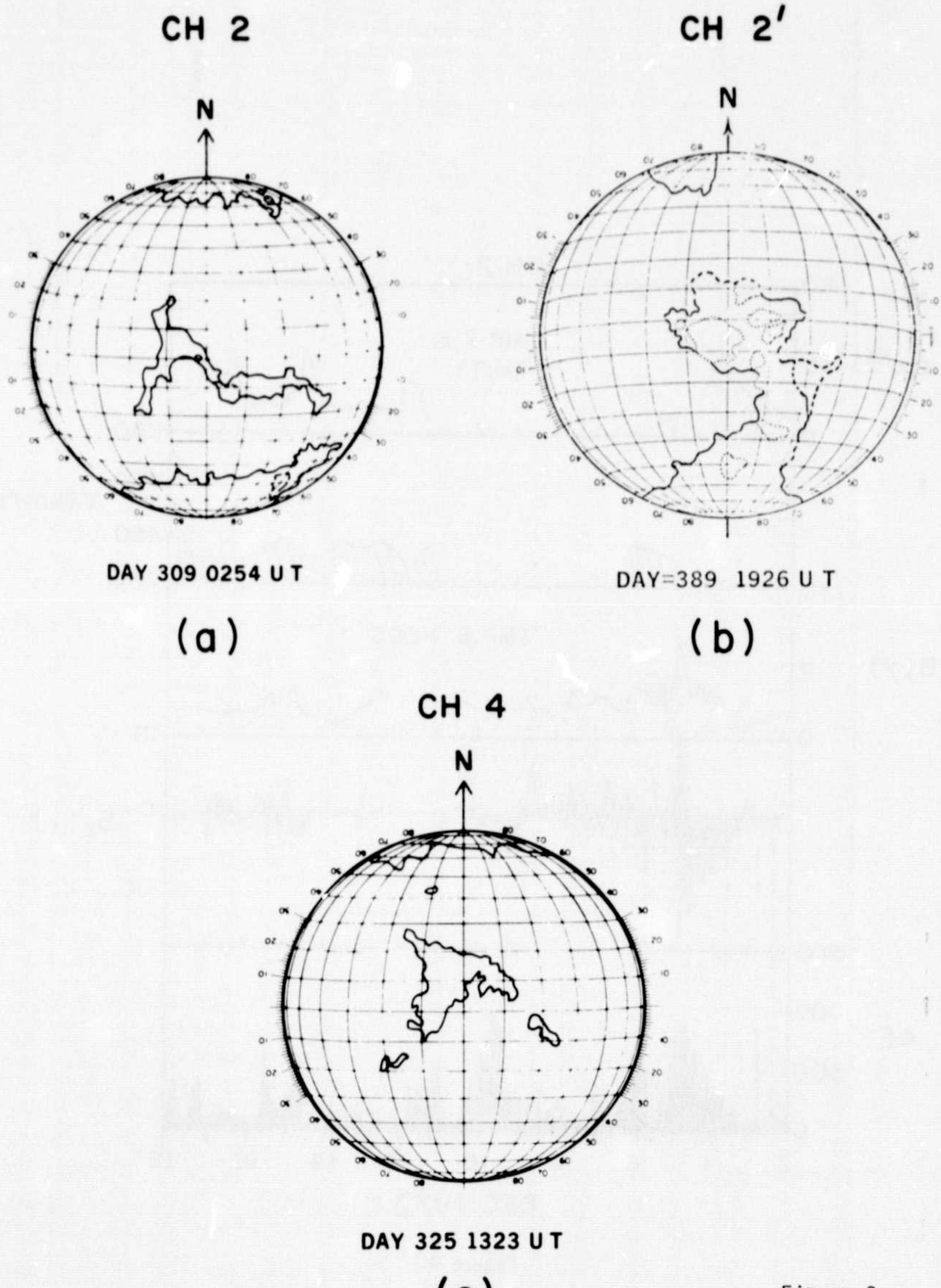
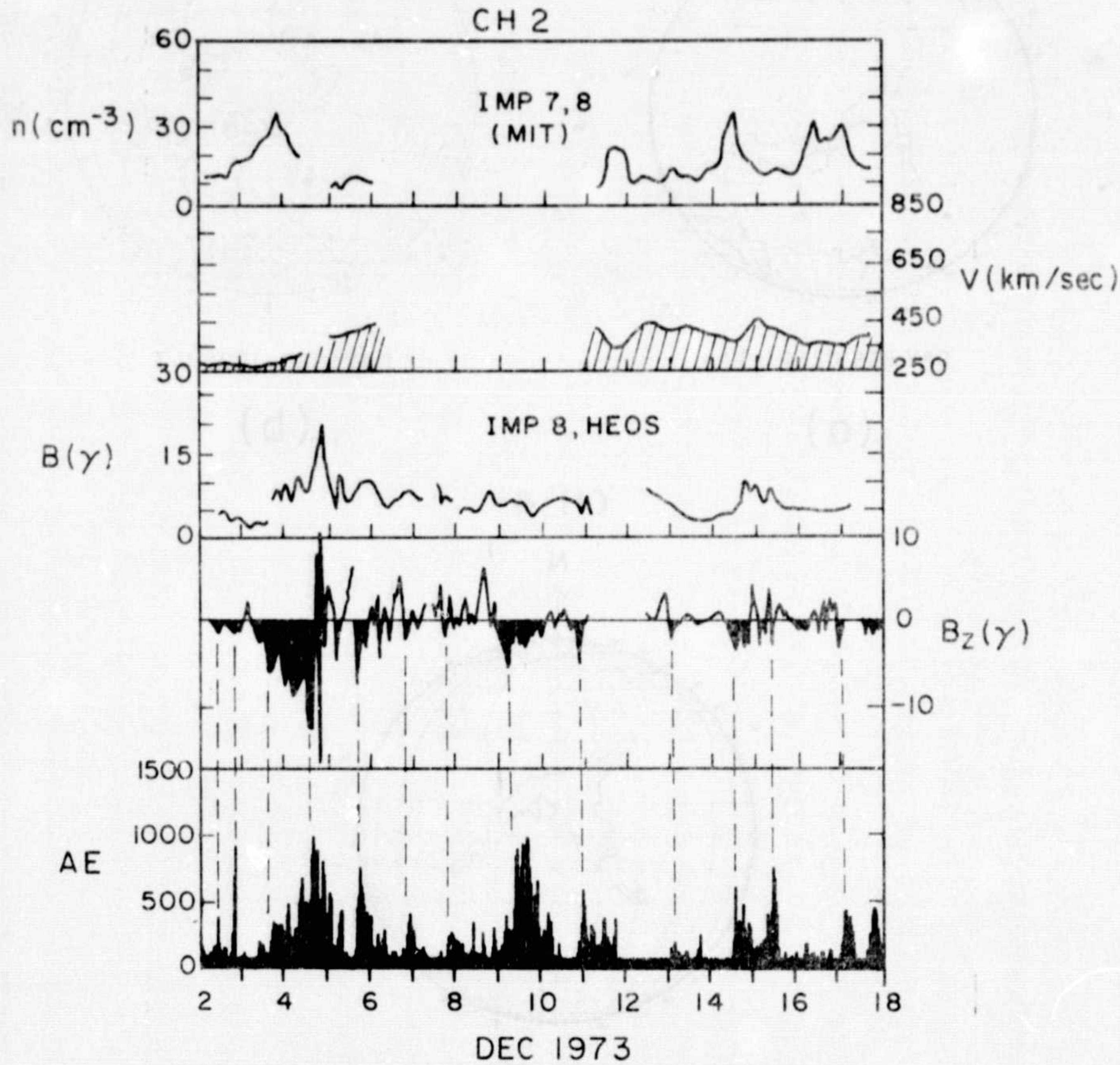

CH 2
N
DAY 309 0254 U T
(a)
CH 2′
N
DAY=389 1926 U T
(b)
CH 4
N
DAY 325 1323 U T
(c)

Figure 3



CH 2
60
n(cm$^{-3}$) 30
0
IMP 7,8
(MIT)
850
650
V(km/sec)
450
250
30
B(γ) 15
0
IMP 8, HEOS
10
0
$B_Z(\gamma)$
-10
1500
1000
AE
500
0
2
4
6
8
10
12
14
16
18
DEC 1973


Figure 4

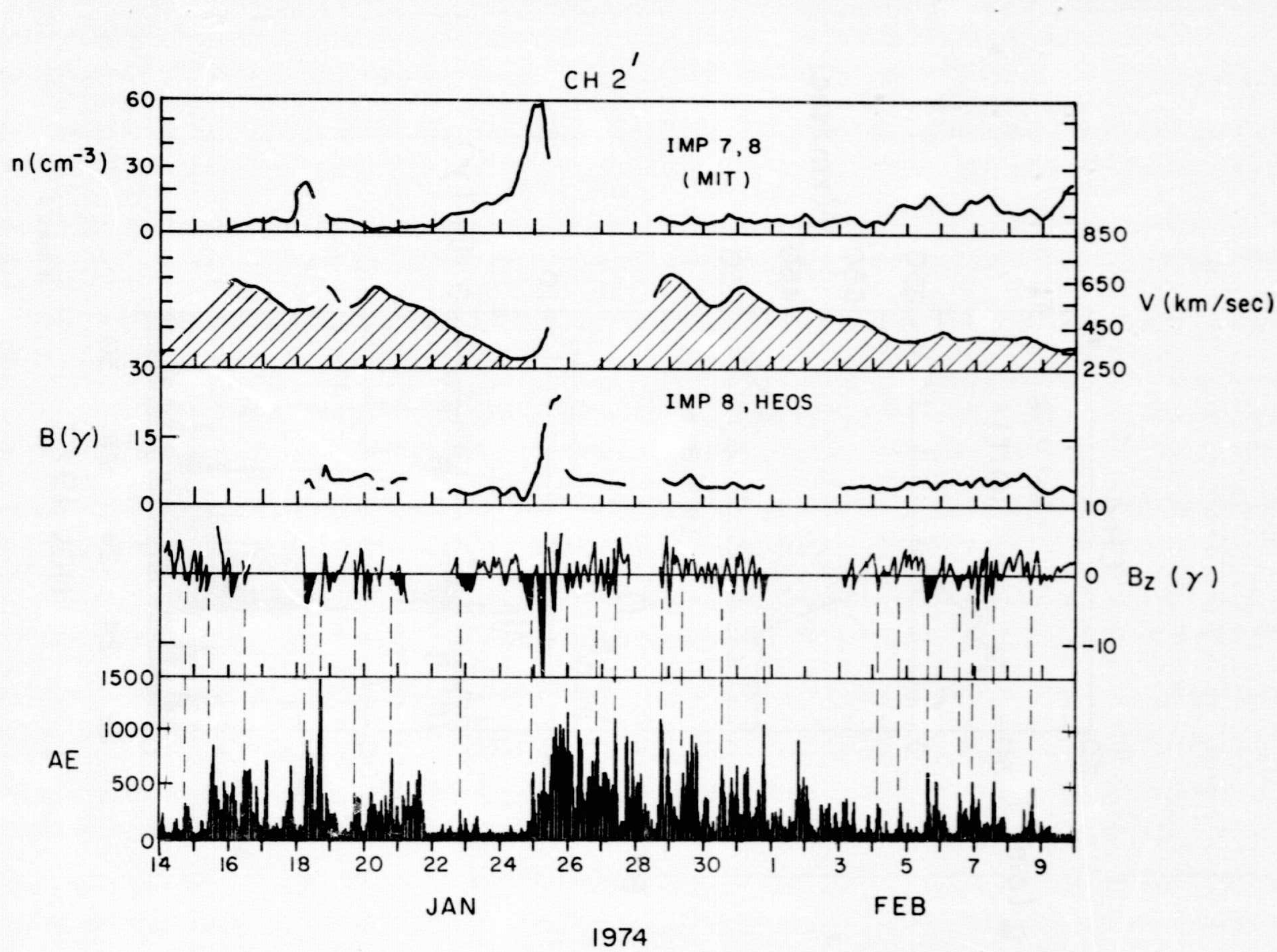
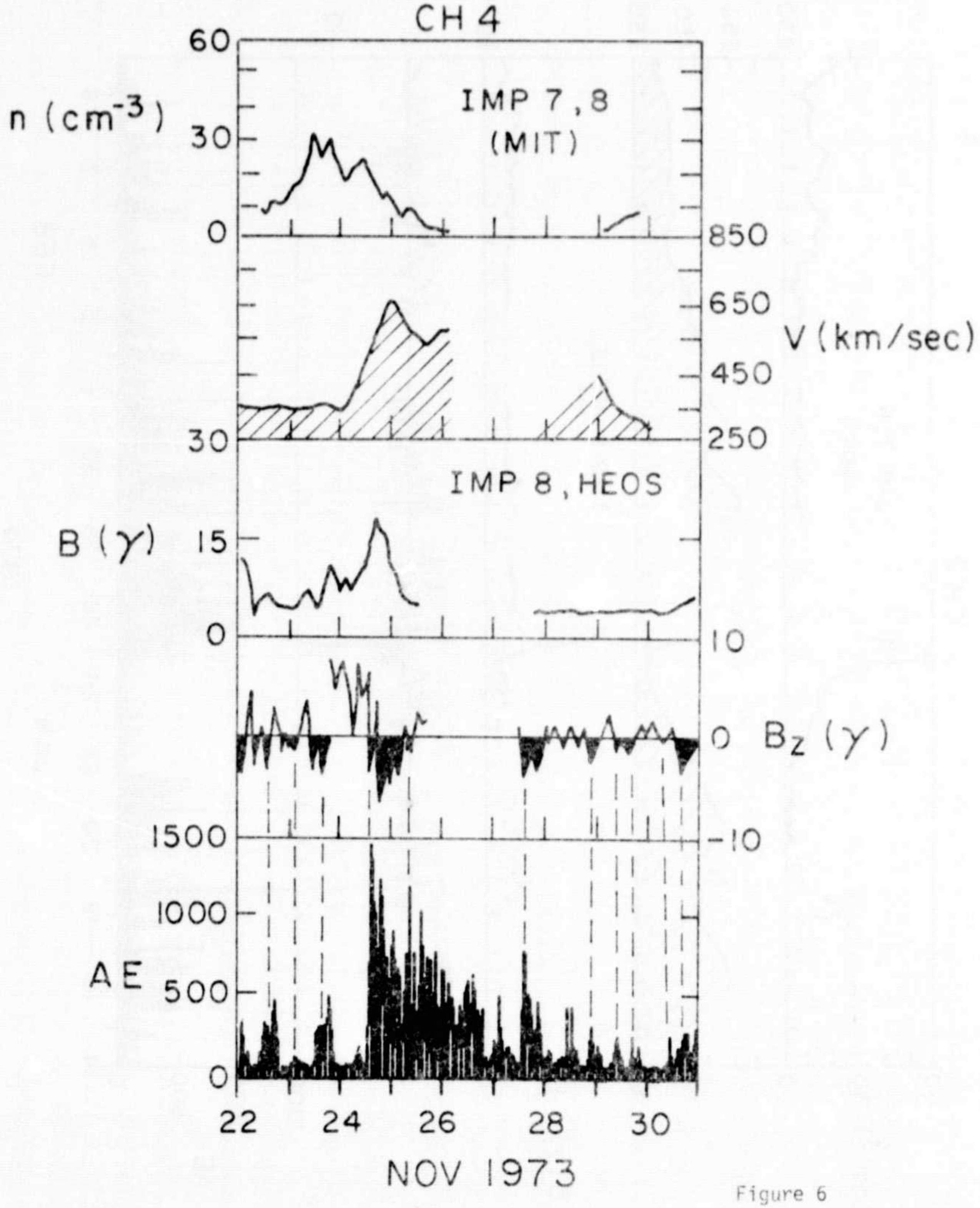

CH 2′
IMP 7, 8
(MIT)
IMP 8, HEOS
n(cm⁻³)
B(γ)
AE
V (km/sec)
Bz (γ)
60
30
0
15
1500
1000
500
850
650
450
250
10
-10
14
16
18
20
22
24
26
28
30
1
3
5
7
9
JAN
FEB
1974

Figure 5



CH 4
n (cm$^{-3}$)
IMP 7, 8
(MIT)
V (km/sec)
IMP 8, HEOS
B ($\gamma$)
$B_Z$ ($\gamma$)
AE
60
30
0
850
650
450
250
30
15
0
10
0
-10
1500
1000
500
0
22
24
26
28
30
NOV 1973


Figure 6