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**IONOSPHERIC RADIO WAVE ABSORPTION EVENTS
AND THEIR RELATION TO SOLAR PHENOMENA**

**A
DISSERTATION**

**Presented to the Faculty of the
University of Alaska in Partial Fulfillment
of the Requirements
for the Degree of
Doctor of Philosophy**

**by
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July, 1964**

IONOSPHERIC RADIO WAVE ABSORPTION EVENTS
AND THEIR RELATION TO SOLAR PHENOMENA

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ABSTRACT

A six-year series of high latitude radio wave absorption data is examined in the context of the general subject of solar-terrestrial relations. The data show that the two well-known types of absorption, polar cap absorption (PCA) and auroral absorption, are caused by different types of solar particle emissions. On the one hand, particle streams which are ejected from the sun during flares with energies ranging from hundreds of Mev down to a few kev produce great nonrecurring magnetic storms and auroral effects, PCA events, and, in extreme cases, ground level cosmic ray increases. The typical sequence of events following a flare is the onset of PCA after one or two hours followed by a magnetic storm and auroral activity commencing after one or two days. On the other hand, long lived streams of particles with energies of only a few kev and attributed to solar M-regions give rise to recurring magnetic storms, aurora, and auroral zone radio wave absorption, but not to PCA or other high energy phenomena.

A list of 135 PCA events from January 1957 through September 1963 is compiled from the published literature and also from a study of the records of various high latitude ionosondes and riometers. This list, combined with a superposed epoch analysis of the riometer data from College, Alaska, shows no significant 27-day recurrence tendency in PCA but does reveal an unexpected recurrence with a period of about 32-35 days. Assuming this long period not to be fortuitous, it is suggested that an explanation might lie in disturbances contained within the sun and which slip backwards relative to the photosphere.

Using the daily average absorption at College as an index of solar corpuscular bombardment, auroral absorption is shown to exhibit a well-defined 27-day recurrence tendency and so is interpreted as an M-region effect. On the basis of the absorption data several conclusions are reached about the nature of solar M-regions: 1) M-regions are detectable within a year after sunspot maximum; 2) M-type particle streams subtend an angle of about 66° , on the average; 3) M-regions are contained in the sunspot zones and follow the characteristic migration toward the equator during the sunspot cycle; 4) M-regions are definitely not identified with centers of activity; and 5) M-regions show a statistical association with unipolar magnetic (UM) regions although there is not a one-to-one relationship between the two phenomena. It is suggested that M-regions should possibly be identified with old UM regions which are a minimum of two or three solar rotations beyond the final bipolar magnetic (BM) stage. Thus, a new concept is suggested for the life history of a center of solar activity. In its youth it produces flare associated plasma clouds and PCA protons; in middle age its violent activity has disappeared and it is a BM region which inhibits the escape of matter from the sun; and finally, in very old age, as a mature UM region, it permits an enhanced outflow of solar plasma.

The Mariner 2 plasma velocity measurements and the daily average absorption are found to have a correlation coefficient of 0.71, thus providing some justification for the assumption that the daily average absorption is a suitable index for studies of solar-terrestrial relations. Some of the terrestrial features of absorption, in particular the daily and annual variations and the latitude variation, are interpreted as solar plasma effects. Absorption is expressed as a linear function of the angle

between the earth's dipole moment and the sun-earth line, and is discussed as an effect of the Kelvin-Helmholtz instability of the magnetospheric boundary.

PREFACE

During the past decade, especially since the beginning of the International Geophysical Year, considerable attention has been devoted to the problems of solar and terrestrial physics in general, but with particular emphasis on the earth's reactions to the sun's corpuscular radiation. Included in these reactions are geomagnetic storms, auroras, perturbations of the Van Allen radiation belt, cosmic ray variations, and radio wave absorption events. This latter category consists of two separate phenomena which are observed at high magnetic latitudes: the polar cap absorption (PCA) and the auroral absorption event. PCA and its production by protons which are accelerated and ejected from the sun during flares have been intensely studied by numerous investigators, but relatively little effort has heretofore been made to trace the auroral absorption phenomenon to its ultimate source on the sun. The evidence presented in this work for the interpretation of auroral absorption as an effect of solar M-regions and the consequent new insight into the nature of M-regions will hopefully serve to open a new and fruitful approach to the study of solar-terrestrial relations.

Although both polar cap and auroral zone absorption events are treated in this work, the greater emphasis is placed on the solar control of auroral absorption since this subject has never before been investigated in detail. Much of the energy expended on the PCA problem was devoted to compiling a list of events which was made as extensive as possible in order to insure that most PCA contamination was removed from the data when studying the auroral absorption problem. The list of PCA events proved useful for the study of the recurrence tendency of PCA and it should likewise serve other needs for many sectors of the scientific community.

To a great extent this work can be considered a study of absorption since it examines several of the basic absorption properties including occurrence as a function of intensity, the relation to the Kp index, the recurrence tendencies, and the relationship to solar processes. But in a larger sense, it can also be viewed as a general study of the solar-terrestrial relationships involving the effects on the earth of particles from the sun. The overall organization of the work has therefore been devised in an attempt to treat the absorption phenomena in this perspective. Chapters 1 and 2 are of a review nature providing background information and establishing a framework into which is fitted the analysis program described in the later chapters. Thus, the informed reader may wish to omit the two introductory chapters and proceed directly into Chapter 3 which sets forth the methods of analysis. Anyone familiar with cosmic noise absorption data and the superposed epoch technique may also wish to skip Chapter 3 and read only the results and conclusions presented in Chapters 4, 5, and 6.

To a great extent, the success of this work has depended on the availability of data collected by numerous other people. The College riometer program was initiated by Dr. C. Gordon Little and carried on for many years under the direction of Dr. Harold Leinbach. It was only because of their efforts that I had at my disposal a sufficient quantity of data for the type of study presented here. In addition to the utilization of various sources of published data, I have also profited from the generosity and cooperative spirit of several individuals who supplied me with unpublished information. Thus, I gratefully acknowledge the contributions of Dr. Robert Howard of the Mt. Wilson Observatory, Sara Smith and Harry Ramsey of the Lockheed Solar Observatory, Dr. Conway Snyder and

Marcia Neugebauer of the Jet Propulsion Laboratory, and A. J. Masley of the Douglas Aircraft Company.

For first suggesting that I investigate the question of how riometer data is related to occurrences on the sun and for maintaining a keen interest throughout the project, I am indebted to Dr. Leif Owren. Without his moral support and professional endorsement, I would never have been able to carry the work to completion. I also acknowledge the helpful discussions with staff members of the Geophysical Institute, including in particular those with Dr. Syun-Ichi Akasofu, Ronald N. DeWitt, and J. Roger Blake.

I am grateful to Sharon Dean for her assistance with many of the details of the data reduction and analysis and to Patricia Andresen for her assistance in programming and operating the computer. I also want to thank Dr. Leif Owren, Dr. Syun-Ichi Akasofu, Dr. Sydney Chapman, and Dr. Russell Carr for reading and commenting on the manuscript.

Credit for drafting the figures goes to Dan Wilder and to Anne Dupere for supervising the typing and printing of the manuscript.

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CHAPTER 1

SOLAR PHENOMENA

1.1 INTRODUCTION

In this chapter solar phenomena will be examined in so far as they are or might be related to the emission of particles from the sun. All of the information and conclusions presented are taken from the publications of other authors, and so they represent knowledge which has been acquired without any first hand experience in solar physics. Realizing the danger in this situation a disclaimer is entered here that there is no attempt at completeness or at a balanced presentation. Emphasis has been given to those aspects which are believed to be most relevant to a study of polar cap and auroral absorption events, namely flares (and their associated radio bursts) and M-regions. Thus, this chapter is a selective review of previous investigations of corpuscular emissions from the sun; the investigations of solar problems which are original to this work are all described in Chapters 4, 5, and 6.

The approach in this review is descriptive and historical in general. To some extent there has been an arbitrary selection of the interdisciplinary papers (i.e. those studying the relation of solar and terrestrial phenomena) to be discussed in this chapter instead of in the next. Chapters 1 and 2 could be combined quite naturally under the single heading of "solar corpuscles and their terrestrial effects", but they have been divided for the sake of convenience of presentation and to emphasize the two separate sets of observations involved, pertaining to the sun on the one hand and the earth on the other. Those papers which are particularly concerned with auroral and polar cap absorption have been treated mostly

in Chapter 2, whereas most of the solar-geomagnetic studies are included here.

In addition to the specific publications referenced, use is made of the general references by Kiepenheuer (1953, 1959), Ellison (1959, 1963), Athay and Warwick (1961) and de Jager (1959, 1963).

1.2 SUNSPOTS

Sunspots, which are areas on the solar disk that are cooler and thus darker than the surrounding photosphere, are the longest recognized and most studied manifestation of solar activity. They consist in general of two distinct regions; a darker umbra which is completely surrounded by a less dark and slightly structured penumbra. Sunspots tend to occur in groups, and they are associated with other forms of disturbance including faculae (or plages), the bright regions usually observed in the light of calcium or hydrogen; prominences and filaments, which appear as great protrusions above the photosphere or as elongated dark chains depending on whether they are viewed at the limb or against the disk; and flares, the sudden brightenings usually observed in the $H\alpha$ line of hydrogen. Individual sunspots have lifetimes which range from a few hours to as much as five rotations (135 days) and their numbers wax and wane in a characteristic cycle with an average period of about 11 years.

Sunspot number has long been recognized as an index of solar corpuscular emission because of its relation to geomagnetic disturbance. However, the relationship is not straightforward, as can be seen from the discussion in Chapman and Bartels (1940). There is quite good correlation between the annual means of relative sunspot numbers and of various magnetic activity measures, the correlation coefficient being 0.88 in one

case (using the u_1 geomagnetic index defined by Chapman and Bartels in their section 11.8), but the monthly means are decidedly less correlated, the coefficient mentioned before now being only 0.65. On individual days there is an almost complete lack of correlation even taking into account the travel time for the particles from sun to earth. There is, however, some association of large magnetic storms with large sunspots. Thus, although particle emission as evidenced by magnetic activity on the earth follows closely the main trend of the 11-year cycle, sunspots themselves are probably not the source of the particles but are only related to another process (or processes) which is responsible for the ejection of the particles from the sun.

It seems likely that the local magnetic fields on the sun, of which sunspots are one visible expression, exert the most direct control over the corpuscular emission processes. The magnetic fields of sunspots have been measured for many years by utilizing the Zeeman effect which produces a magnetic splitting of photospheric emission lines. A review of the early work on sunspot magnetic fields can be found in Kiepenheuer (1953). Sunspots have been classified at the Mount Wilson Observatory according to their magnetic properties into three basic types consisting of unipolar (α), bipolar (β), and complex (γ) groups. The α group is subdivided according to the position of the group in its calcium plage, and the β group is subdivided according to whether the leading spot is larger or smaller than the following spot. The descriptions and per cent occurrences of the various classes are given in Table 1 which is taken from Kiepenheuer (1953), Ellison (1959), Bell and Glazer (1959), and NBS Solar-Geophysical Data.

Table 1. The Magnetic Classification of Sunspots

Symbol	Per cent 1915-24	Occurrence 1937-53	Description through Dec. 1958	Description since Jan. 1962
α	14.0	9.3	Single spot or group of spots with same polarity symmetrically surrounded by plages.	
αp	20.4	24.7	Same, but with spots in preceding part of elongated plage.	All spots in group have polarity of preceding spots in that hemisphere for that cycle.
αf	4.0	3.9	Same, but with spots in following part of elongated plage.	All spots have polarity of following spots in that hemisphere for that cycle.
β	20.9	27.3	Groups with preceding and following spots about same size.	Magnetic measures indicate a balance between preceding and following spots.
βp	29.2	23.5	Groups with preceding spot larger.	Magnetic measures indicate preceding spots dominant.
βf	7.9	8.0	Groups with following spot larger.	Magnetic measures indicate following spots dominant.
βy	3.0	2.7	Bipolar characteristics but no marked north-south division between spots of opposite polarity.	General β characteristics but at least one spot out of place as far as polarity concerned.
γ	0.8	0.7	Complex distribution of polarities.	Group in which polarities are completely mixed.

The Mount Wilson magnetic observations of sunspots, including latitude and central meridian passage (CMP) date along with the field strength were listed in the Publications of the Astronomical Society of the Pacific from 1920 through 1958. Starting in January 1962 the observations, including the time and heliocentric coordinates, are listed in the NBS Solar-Geophysical Data. As can be seen from Table 1, the definitions of the $\beta\gamma$ and γ groups are unchanged, but the other symbols have been slightly redefined.

Bell and Glazer (1958) have made a detailed study of the relation of sunspot characteristics to particle emission as evidenced by geomagnetic conditions. They found that complex (γ) sunspots are the most consistently disturbing geomagnetically and semicomplex ($\beta\gamma$) spot groups are moderately disturbing, but unipolar and bipolar spots produce no significant geomagnetic deviations. They also found that the flare productivity of a spot group is moderately important, whereas spot area is relatively unimportant in determining the ability of sunspots to produce magnetic storms.

In searching for a criterion by which to pick out the geomagnetically effective sunspots from the hundreds of spots which are ineffective in generating corpuscular streams, Simon (1956), following the lead of Denisse (1952), distinguished between quiet (radioélectriquement inactives) and noisy (radioélectriquement actives) sunspots on meter wavelengths. He found that the noisy spots were also geomagnetically active since their central meridian passage was followed within a few days by an increase of geomagnetic activity, whereas the quiet spots were geomagnetically inhibiting since their CMP was followed by a period of less than average disturbance on the earth. He found from a systematic study of the optical

properties, that the radio classification of sunspots was unrelated to their area, magnetic type, Zürich classification, or eruptive properties, and he concluded that geomagnetic activity is more closely correlated with radio features than with optical features on the sun.

Finally, a few words should be said about the sunspot cycle, number 19, during the latter half of which the data for this project were collected. This cycle was remarkable in many respects. The maximum annual number of sunspots, which occurred in 1958, was the greatest maximum ever recorded, and 1957 and 1959, though not maximum years, had higher numbers than were recorded even during the peaks of previous cycles. The spot activity in the higher latitudes was exceptional, especially above 40° where a total of 34 groups was observed. The high spot numbers were, however, caused principally by numerous small and middle-sized groups, large spots being much less frequent than during the previous cycle, although there was a considerable increase in the number of large spots in 1959 and 1960. There was a less than normal frequency of long-lived sunspots with only about 14% of the spots in the maximum years surviving the passage from east to west limb. There was also a subnormal occurrence of spots with large magnetic fields, the percentage of spots with $H \geq 2000$ gauss being lower than ever before observed. A more detailed discussion of these points can be found in Cragg (1958, 1959, 1960, 1961) and Bell (1959).

1.3 FLARES

A few of the disturbances associated with sunspots were mentioned in the preceding section, but the most cataclysmic and spectacular of solar phenomena, the flare, will now be discussed in some detail. Flares are

rarely visible in white light and are best observed in the lines of hydrogen or calcium using either a spectrohelioscope or a Lyot filter. Since these instruments have been in use for only the last 30-40 years, and flare patrols have only in the past few years begun to operate continuously all over the world, flare data are not nearly so numerous nor as thoroughly investigated as sunspots.

Flares occur in the chromosphere, and in European publications they are frequently referred to as "chromospheric eruptions". They are variously described as similar to explosions, thunderstorms, or lightning flashes, and they cover great areas of the sun's disk in the neighborhood of sunspots. They show up as sudden increases of light intensity, blazing up very quickly to reach a maximum within a few minutes and then decaying slowly back to the normal intensity over the next hour or two. They always occur within the faculae surrounding a spot group, beginning as bright specks and expanding to cover large portions of the facular region, sometimes even including the spot umbras.

Flares are classified according to area and brightness into three groups which give the importance of a flare as 1 (smallest), 2, or 3 (largest). Subdivisions of these groups are indicated by + or - following the number. The area, brightness, line width, and duration of flares all increase with importance, so that class 3⁺ flares, the largest observed, last for about 2 1/2 hours, cover more than 1200 millionths of the visible disk, and have a brightness greater than 2.4 times the level of the continuous spectrum.

Although flares are basically a visible phenomenon, their characteristics being described on the basis of H α observations, about half the flares are observed to be accompanied by an ejection of matter. The most

conspicuous of these ejections are called surges, and they are observed to spew out matter at radial velocities of the order of 500 km/sec. When viewed at the limb, surges have the appearance of fountains or geysers spouting matter to heights of hundreds of thousands of kilometers. Sometimes the ejected material fades into invisibility in the corona, but on other occasions it is seen to return to the sun, retracing its outgoing path. When viewed against the disk, surges usually appear as dark blobs because of their absorption of $H\alpha$, and they are again frequently known to fall back into the sun because of observations of a doppler shift to the red. Surges are almost always associated with flares, and the probability of their occurrence increases with the importance of a flare so that over three quarters of the importance 3 flares generate surges.

Flare phenomena which eject matter at higher velocities have also been observed. Dodson, Hedeman and Chamberlain (1953) presented observations of hydrogen and ionized calcium moving away from the sun at velocities up to at least 750 km/sec at the time of the onset of flares near the solar limb. After each ejection some material was seen to fall back to the solar surface, but they stated that the fall was not comparable to the rise. Moreton and Ramsey (1960) reported that major flares which were characterized by a distinct phase of pre-maximum intensity "explosive" development sometimes initiated disturbances which traveled outward to distances of half a million kilometers at velocities ranging between 500 and 2000 km/sec. The study of the effects of flares with explosive phases was extended by Athay and Moreton (1961) to include a treatment of filament activations. They interpreted the sudden disappearances of dark filaments from the vicinity of "explosive" flares in terms of corpuscular streams ejected from the flare and traveling at velocities of the order of

1500 km/sec. Their quantum mechanical explanation for the disappearance, requiring that protons from the stream depopulate the $N = 2$ level of hydrogen in the filament and thus render it transparent to $H\alpha$, has been criticized by Malville (1961). However, for the present study, it is significant to note that they selected the PCA flares of May 10, July 16, and September 1, 1959 as producing distinctive effects on dark filaments. The study of PCA flares with explosive phases was extended by Athay (1961).

The mechanism by which flares are generated is not known although several theories have been advanced which involve electrical discharge, the magnetic pinch effect and thermonuclear reactions, and hydromagnetic waves. The most commonly held opinion is that flares result from a release of magnetic energy, that is a conversion of magnetic energy into radiant and kinetic energy, from the local magnetic fields which exist in sunspot regions. Gold and Hoyle (1960) present a good discussion of the role of magnetic fields in generating flares. In support of this opinion there have been observations of a rearrangement and an overall reduction of the field intensity in active regions after the occurrence of a flare, (Evans, 1959; Severnyi, 1958, 1961). However, other observers have reported no such changes in the magnetic field during the progress of a large flare (Howard and Babcock, 1960).

Many investigators have given their attention to the study of the effectiveness of solar flares in producing magnetic storms on earth. In important early works Newton (1943, 1944) found that over 80% of the intense (3^+) flares located not more than 45° from the center of the disk were followed about a day later by magnetic storms. He found that the mean interval between flare and storm onset, the travel time of the corpuscular stream, was about 20 hours. His data included 37 great flares

observed between 1859 and 1942. The analysis was extended to include class 3 and 2 flares, but, although there was a slight increase of geomagnetic activity following class 3 flares, there was no perceptible rise following class 2. Using magnetic data from 1906 to 1942, Allen (1944) also concluded that flares cause great magnetic storms and found in addition that they cause a few smaller storms after a delay of about 2 1/2 days, but he reported that sudden commencements were not produced by flares except in the case of great storms. However, van Sabben (1953) and Watson (1957) found no significant increase of geomagnetic activity after flares during the years from 1949 to 1954, but, as pointed out by Warwick and Hansen (1959), these negative results seem to be characteristic only of years near sunspot minimum.

In a more recent study Bell (1961), using data on 580 flares of importance $\geq 2^+$ for the years 1937-1959, found that a major flare occurring in association with a magnetically complex (γ or $\delta\gamma$) sunspot group is much more likely to be followed by a major geomagnetic storm than is a similar flare in a unipolar (α) or bipolar (β) group. In studying the distribution of flares over the solar disk, she found a striking preference of great-storm flares for the northern hemisphere. Eighty-six per cent of the flares which were followed within 3 days by a great geomagnetic storm occurred north of the solar equator, and the northern preponderance was found in all 3 of the solar cycles examined (No. 17-19). She also confirmed what is now generally regarded as true, that the emission of a corpuscular stream is associated with the occurrence of a major flare rather than with the CMP of a sunspot region.

Hartz and McAlpine (1961) showed that during the four years 1956-1959 all major ($\geq 2^+$) flares which were accompanied by radio bursts at

200 mc/s or less were followed by magnetic storms whereas those without bursts were not. They also found that storm producing flares are distributed asymmetrically over the disk, occurring preferentially in the western hemisphere.

The most important recent work on the optical characteristics of flares which eject corpuscular streams has been that of Dodson and Hedeman (1959, 1960). They have found in examining H α records that flares which produce polar cap absorption events exhibit the unusual property of covering large portions of the umbras in the associated sunspot group during some stage in their development. They have also come to significant negative conclusions about the properties of flares which produce solar cosmic rays. In particular, they point out that it is not just a matter of size and brightness of the flare or of the suddenness of its rise to maximum, nor is it necessary to have very wide hydrogen emission in order for a flare to produce particles which bombard the earth's atmosphere. Their work has been extended by Malville and Smith (1963) who have statistically confirmed that solar radio emissions at both centimeter and meter wavelengths are related to the percentage of the total umbral area of a sunspot covered by a flare. Wolback (1963) has also verified that large scale umbra coverage is a unique characteristic of cosmic ray flares. He found that only 10% of non cosmic ray flares covered some part of a spot umbra, and then only a small part and usually around the edges.

In another recent effort to define the distinctive properties of flares which eject particles, Krivsky (1963a,b,c) has suggested that flares which exhibit a Y or V shape in the course of their development are effective in generating cosmic rays. According to his interpretation the acceleration and expulsion of high energy particles takes place during

the transient connection of a secondary filament to the primary emission filament giving the brief appearance of the shape of a Y.

One of the most important aspects of flare phenomena, emission at radio frequencies, will be discussed in the next section.

1.4 RADIO EMISSIONS

A distinctive symptom of the solar upheavals which spew corpuscular clouds into the interplanetary medium has proved to be the emission of radio waves. These were first detected only about 20 years ago, and since then they have been studied intensely by several groups all over the world. The early observations at fixed frequencies were generally interpreted as related to the ejection of particles, but it was only with the introduction of sweep frequency techniques and the subsequent spectral definitions that appreciation of the dynamic character of the various phenomena began. The following discussion will thus begin with a brief description of the five spectral types and their physical interpretation, and finally reference will be made to the findings of some of the more important studies of the relationship of radio bursts to particle bombardment of the earth. In addition to the specific references cited use is made of Steinberg and Lequeux (1963, Wild and McCready (1950), and Ellison (1963).

Type I solar radio emissions consist of short (1-20 sec) high intensity bursts with a narrow frequency spectrum at meter wavelengths which are superimposed on a high, slowly varying, background continuum which is referred to as a noise storm. These solar noise storms typically last for a few hours although they sometimes continue for a number of days. The type I or storm bursts are observed more commonly than the other types, but the mechanism of their generation is not known. They are found to

occur over some optical centers of activity but not others, and they are sometimes but not always associated with type-IV bursts (Avignon et Pick, 1959).

Type II bursts, descriptively referred to as slow drift bursts, occur at meter and decimeter wavelengths with a bandwidth of about 50 mc/s. Their onset is observed a few minutes after the maximum of some flares, and their emission gradually drifts from high to low frequencies at a rate of about 1 mc/s in 4 seconds. Type II bursts usually show a harmonic structure and they are thought to be generated by plasma oscillations induced by the passage of a shock wave upwards through the corona at a velocity of 1000-1500 km/sec.

Type III bursts, called fast-drift bursts, often occur in groups lasting for only a few seconds each. Their name is derived from their observed drift from high to low frequencies at a rate of around 20 mc/s per second. They are usually associated with flares, beginning nearly simultaneously with the optical emission. Their precise emission mechanism is unknown, but they are generally thought to be produced by clouds of electrons or shock waves which travel upward through the corona at velocities of the order of 100,000 km/sec. Type III bursts are very numerous, with thousands being recorded in a single year. A very complete discussion of Type III bursts and their associated solar and geophysical phenomena has been given by Malville (1961).

Type IV, a continuum emission which sometimes lasts for several hours, was distinguished as a separate spectral type by French radio astronomers (Boischot, 1957) whereas all the other types were first described and classified by Australians. Type IV events were originally defined at meter wavelengths, but the extended definition which is now accepted states

that a type IV burst is a long-period continuum event which follows a flare in any part of the radio spectrum. These are complex events which are found to have several components that are not yet completely resolved or understood and which are thought to be generated by a variety of physical mechanisms including synchrotron, Cerenkov, and bremsstrahlung (Wild, 1962; Fokker, 1963a). Type IV is the most important of all solar radio events in the sense that it has the closest association with geophysical phenomena. Some of the details will be discussed later, but in general all ground level cosmic ray increases and most PCA events and SC geomagnetic storms are related to type IV outbursts.

Type V bursts were defined by Wild, Sheridan, and Trent (1959)—as broad-band enhancements occurring at meter wavelengths, following very closely after type III bursts, and lasting for up to 3 minutes. They are a continuum emission, distinguished from type IV by their short duration and close association with type III, and are ascribed to synchrotron-radiation. Smith (1962) found that almost all type V bursts could be attributed to specific flares, but that only a small fraction of flares produced type V events.

The characteristic sequence of radio events accompanying large optical flares has been recognized by Wild (1962, 1963) and interpreted in terms of disturbances propagating upward through the corona. He envisages the flare as resulting from the pinch effect in a magnetically neutral plane between two spot groups. At the time of the sudden expansion of the H α flare a cloud of relativistic electrons is ejected generating type III and V bursts, and a magnetohydrodynamic shock wave is produced which travels upward at a speed of about 1000 km/sec. This shock front is responsible for the second phase of the flare sequence which begins 2 to 5

minutes later with the onset of a type II burst. The characteristic type II frequency drift results because the shock front in passing through the various coronal layers excites them to radiate at their critical plasma frequencies which diminish as the electron density of the corona decreases outwards. The particles in the ionized cloud behind the front radiate the type IV continuum emission, and because of the close relation observed between type IV outbursts and terrestrial effects, this cloud is thought to contain the cosmic rays and geomagnetic storm particles which reach the earth after the appropriate travel time delay. It should be emphasized that this is a description of a model event. The full sequence of these occurrences is observed only with very large flares.

French radio astronomers were among the first to recognize the importance of radio emissions as indicating the ejection of particles from the sun. Denisse, Steinberg, and Zisler (1951) found that noisy and quiet (radioélectriquement actifs et inactifs) centers of solar activity have opposite effects on the earth's magnetism, the noisy centers producing an increase of geomagnetic activity while the quiet centers produce a decrease. This original work was followed up by several studies (Denisse, 1952, 1953; Becker and Denisse, 1954; Simon, 1956). This latter reference was discussed in section 1.2.

Maxwell (1952) found that a series of recurring magnetic storms was preceded 27 days earlier by an intense radio noise storm at meter wavelengths, so he identified the region of radio emission as an M-region. This subject will be discussed in detail in section 1.7.

One of the earliest suggestions that solar radio events mark the time and place of emission of auroral particles was made by Payne-Scott, Yabsley, and Bolton (1947). Payne-Scott and Little (1952) later identified

outbursts of radio noise at 97 mc/s as another manifestation of disturbed regions on the sun which are the source of geomagnetic storm particles. They measured the velocity of the corpuscular stream rising through the corona as from 500 to 3000 km/sec. Dodson, Hedeman, and Owren (1953) noted that outbursts of solar radiation at 200 mc/s were observed at the start of flares which were accompanied by an ejection of material at high velocity. It was subsequently verified that a close association existed between flares with these "major early bursts" and sudden commencement geomagnetic storms (Dodson and Hedeman, 1958; Dodson, 1958). They found that this type of radio emission occurred with only about 4% of all flares, but it was followed within 5 days by a geomagnetic storm in 92% of these cases. The average time interval between the flare and the start of the resulting magnetic storm was about 2 1/2 days.

Many investigators have commented on the close relation between type IV emission and the subsequent corpuscular effects on earth (Boischot et Denisse, 1957; Sinno and Hakura, 1958; Avignon et Pick-Gutman, 1959; McLean, 1959; Hakura and Goh, 1959; Thompson and Maxwell, 1960a; de Feiter et al., 1960; Roosen and de Feiter, 1962). Thompson (1962) found that about 40% of the observed type IV bursts are followed by polar cap absorption and 75% by magnetic storms. Kundu and Haddock (1960, 1961) presented the first evidence that PCA events are associated not only with meter-wave type IV bursts but also with broad-band outbursts at centimeter wavelengths which would now be classified as type IV under the extended definition.

Investigations at the Harvard Radio Astronomy Station (Thompson, 1959; Maxwell, Thompson, and Garmire, 1959; Thompson and Maxwell, 1960b) have led to the conclusion that type II bursts are emitted by auroral

particles which reach the earth after a mean delay of 33 hours, that type III bursts are not related to particle bombardment of the earth and that type IV radiation is directly related physically to the emission of protons in the energy range 30-300 Mev which are observed on earth.

1.5 CORONAL EMISSION LINES

Superimposed on the continuous light from the corona, which is only photospheric light scattered by free coronal electrons (the K-corona) and by zodiacal dust particles (the F-corona), are several bright lines emitted by elements which are highly ionized at the coronal temperature of around 10^6 K. These emission lines are called the L-corona. The brightest of these lines are radiated by iron atoms which have lost varying numbers of their electrons, but other commonly observed emissions are given off by ionized calcium and nickel atoms. The green line at 5303 Å (FeXIV), arising from iron atoms with 13 electrons gone, is by far the most intense of the coronal emission lines, but other important emissions are the 6374 Å (FeX) red line and the 5694 Å (CaXV) yellow line. Radiation intensity from the corona increases markedly, thus indicating increased density, above sunspot regions, and it is only above such active regions that the CaXV yellow line is observed at all. Because of the relatively high ionization potential of the ion, this latter observation is interpreted to mean that temperatures are higher above activity centers than in the surrounding corona.

The relation of coronal line emissions to geomagnetic disturbances has been the subject of several investigations; however, the results have not been consistent and the interpretations have varied from one author to another. Since the corona is not visible against the disk, the coronal

line intensities at CMP must be estimated from observations made at the east and west limbs, taking into account the sun's rotation. This restriction of course precludes the possibility of studying anything but relatively stable and long-lived features, and consequently coronal emissions have been related to M-region disturbances rather than to the great non-recurring storms which are produced by ephemeral and cataclysmic events such as flares.

Waldmeier (1942) introduced the term C-region to describe those parts of the inner corona which show strong 5303 Å emission but which overlies undisturbed and spot free portions of the photosphere. He found that the CMP of C-regions were correlated with geomagnetic disturbances, and he suggested that they are identical with M-regions. His study pertained to 1939-1940, years of declining sunspot numbers following the maximum of 1937. Denisse and Simon (1954) examining the period 1946-1952 found that CMP of the 5694 Å yellow line was accompanied by an augmentation of geomagnetic activity lasting 5 to 6 days whereas a diminution occurred during CMP of regions where the emission was absent.

However, the results of other investigations have demonstrated the reverse association to be true, namely that CMP of regions of high and low intensity coronal emission respectively produce low and high geomagnetic activity (Shapley and Roberts, 1946; Smyth, 1952; Bruzek, 1952; Müller, 1953; Tanden, 1956; Sinno, 1957; Warwick, 1959). Kiepenheuer (1947) also found this inverse relationship for 1943, but noted that it disappeared completely with the beginning of the new solar cycle in 1944 and 1945. This disappearance he attributed to the sudden change of the distribution of coronal intensity over the heliographic latitudes from an equatorial maximum in 1943 to a double maximum at about 30° north and south of the

equator in 1944 and 1945. This latitude shift of course followed the characteristic latitude migration of sunspots and confirmed Waldmeier's (1942) observation that C-regions are restricted to sunspot zones although they avoid the spots themselves. Lincoln and Shapley (1948) also noted that the coronal-geomagnetic correlation became weaker during 1944-1946 and exhibited a different time relationship from that observed earlier by Shapley and Roberts (1946). Actually, Shapley and Roberts (1946) interpreted the maximum they observed in magnetic activity 4 days after east limb passage (ELP) of bright coronal regions as the significant feature of their results, indicating that particles, assumed to come from the C-regions, were ejected from the east half of the sun's visible disk at an angle of roughly 45° forward with respect to solar rotation. However, another interpretation which would be more plausible in the light of subsequent investigations could be that the C-regions were responsible for the minimum observed 10 days after their ELP while the maximum at 4 days was the result of the CMP of quiet regions adjacent to and preceding the C-regions.

In the most extensive study ever made on the subject of the relation of geomagnetism to coronal emission lines, Bell and Glazer (1957) came to the conclusion that M-regions were not C-regions, but, to the contrary, were regions of unusually weak 5303 Å coronal emission. This relation was found to be enhanced when only coronal intensities in the favorable solar hemisphere were considered, the favorable hemisphere being on the same side of the solar equator as the earth. In discussing the work of others, they pointed out that there were no discrepancies in the results of studies covering the same time interval. The relationship between geomagnetic and coronal features does, however, seem to change during the solar cycle.

1.6 CENTERS OF ACTIVITY

The various occurrences discussed in the preceding sections of this chapter are not independent phenomena but are all manifestations of what is classified under the general heading of "solar activity" or "solar disturbance." The spatial, temporal, and physical interrelations of these phenomena have been touched on sufficiently to indicate that they occur in localized centers of activity covering great areas of the solar surface and extending through the chromosphere and well into the corona. These centers are believed to appear when submerged magnetic fields come to the surface of the sun and disrupt the normal processes of energy release. Of course, the size, shape, and development of individual centers vary over a wide range, but Kiepenheuer (1953) has described the life history of a typical center, starting with the appearance of a small bright facular speck, continuing through the formation and dissolution of spots and their surrounding faculae, and ending with the filament's migration to the pole. Some centers have lifetimes of only a few days, but the evolution of others is carried on through several rotations of the sun. Activity centers are characterized by strong magnetic fields, ranging from thousands of gauss in some sunspots to about 5 gauss in the overlying coronal region, which is also characterized by abnormally high temperature and density. Active regions are so plentiful on the sun's disk during the maximum years of the solar cycle that as many as three or four commonly cross the central meridian in a single day. Their number decreases rapidly, however, toward solar minimum.

A detailed description of all observed centers of activity is given in the IAU Quarterly Bulletin on Solar Activity. This description includes the coordinates of the center, the date and its age at the time

of CMP, its duration in rotations, its importance, and the number of its associated flares. The importance is assigned in the range from 1 to 10 on the basis of the extent and mean intensity of the plage as well as the number and dimensions of the associated spots.

The concept of "center of activity" will be seen in the next section to play an important role in the discussion of M-regions.

1.7 M-REGIONS

From a large scale statistical study of magnetic data collected during the period 1906-1931, Bartels (1932) recognized the 27 day recurrence pattern of minor disturbances as a persistent solar influence which he was unable to identify with any visible feature on the sun's surface. To account for this apparent paradox, he hypothesized the existence of regions on the sun, for which he proposed the name "M-regions", which, although they were not observable by direct astrophysical methods, could be detected by their effectiveness in producing recurrent magnetic storms on the earth. Attempts to discover the physical properties of these hypothetical M-regions have been made by numerous investigators for over 30 years now, but some confusion and disagreement about their basic nature still exists in spite of a vast quantity of observational evidence. There are currently two opposing schools of thought, one of which contends that M-regions are contained in centers of activity while the other identifies them with quiet and undisturbed areas on the sun.

In an important early work Allen (1944) studied the relation of sunspots to magnetic storms and concluded that M-regions tend to avoid the area within about 40° of sunspot groups and that the appearance of a sunspot in an M-region would bring it to an end. He also found that a mean

period of about 3 days is required for M-region particles to travel from sun to earth, and he suggested that they were associated with coronal streamers.

The relation of M-regions to other aspects of activity centers has also been investigated. Kiepenheuer (1947) found for the sunspot minimum years 1922-1924 that M-regions were characterized by filaments which passed the central meridian 3-4 days before the onset of a storm. This result was not confirmed, however, by Roberts and Trotter (1955) who studied the years 1951, 1953, and 1954. Shapley (1946) found that the CMP of large palges was followed after 3-4 days by a minimum in the American magnetic character figure, which of course shows that M-regions are not characterized by plages. Maxwell (1952) gave evidence that a strong meter wavelength radio noise storm heralded a preliminary stage of the development of an M-region that was to become an effective particle source during the next solar rotation. The majority of the results on coronal emission lines already given in section 1.5 show that M-regions are marked by low intensity 5303 A emission. The most definitive conclusions in this respect were those of Bell and Glazer (1957) who found that M-regions are distinguished by unusual weakness of the green coronal line emission, which permits a fairly definite localization in solar longitude. They inferred that M-regions underlie portions of the corona with relatively low density and possess weak unipolar magnetic fields. They also found that the effectiveness of an M-region in disturbing the earth's magnetic field was greatest when it was favorably located on the sun, that is when it was on the same side of the solar equator as the earth.

In their study of the sun's magnetic field Babcock and Babcock (1955) identified bipolar magnetic (BM) and unipolar magnetic (UM) regions with

centers of activity and M-regions respectively. They described BM regions as contiguous areas of opposite magnetic polarity formed as if rising material had brought submerged toroidal fields to the surface, and they found that the life history of a BM region followed closely the evolutionary sequence of an activity center as it was described in the last section. They suggested that the disintegration of some BM regions leave UM regions as remnants having low magnetic intensity and covering a rather large area with ill-defined limits. These UM regions were revealed by the magnetograph but were not observable by other means. They were identified with M-regions because of an observed close relation between the CMP dates of a UM region with a sequence of recurrent magnetic storms. The Babcocks concluded their paper by offering an explanation for the characteristically different properties of M-regions and activity centers. They suggested that corpuscles arise from transient chromospheric jets or spicules which are distributed more or less uniformly over the entire solar surface. Over a BM region particles accelerated upward are guided by the arching lines of force until they collide and condense over the region at a considerable height, thus accounting for the generally increased density observed over active regions. Over a UM region on the other hand, corpuscular streams accelerated outward are expected to proceed more or less radially for an indefinite distance. If the geometry determined by the position of the M-region on the sun and the earth in its orbit is favorable, these particles encounter the earth and generate a magnetic storm. The north and south polar regions of the sun, which are reasonably permanent UM regions of a special class, are expected by this theory to be copious sources of particles. Bell and Glazer (1957) have elaborated on this model, and they contend that a "polar source" theory is fully

capable of explaining the observed relations of geomagnetic activity to M-regions and activity centers. In their view, centers of activity guide particles and trap them in their own neighborhood, whereas undisturbed regions in the spot zone allow the polar corpuscles to be deflected only by the general magnetic field of the sun which is capable of guiding them to the vicinity of the earth. Thus the M-regions are necessary to storm production even though they are not the source of the particles.

Pecker and Roberts (1954, 1955) recognized that the particle streams which are responsible for geomagnetic storms are of two basically different types depending on whether they emanate from activity centers or M-regions. They postulated that small jets, which they identified with chromospheric spicules or photospheric granules, send out radial streams of corpuscles from all over the solar surface. The presence of a center of activity disrupts this uniform outflow by deflecting the particles, by means of magnetic fields, so that they are excluded from a cone of $55-80^\circ$ (4-6 days) above the center. Thus the CMP of a single activity center should be marked on earth (after allowing for travel time) by a period of magnetic quiet preceded and followed by days with increased activity resulting from bunching the excluded particles at the periphery of the "cone of avoidance".

In a rather novel approach to the problem of M-regions Wulf and Nicholson (1948, 1950) developed the hypothesis that the east limb passage of bright hydrogen and calcium flocculi caused the onset of magnetic activity through the action of ultraviolet light. However, Richardson (1941) had previously concluded that the apparent relation of some flocculi to M-regions was accidental, and since a decline of magnetic activity followed the CMP of their flocculi, Wulf and Nicholson's

results are not inconsistent with the idea of a negative effect from activity centers.

Waldmeier (1942, 1946, 1950, 1962) deserves special attention since he has a somewhat different view of M-regions. That he identified them with C-regions was already mentioned in section 1.5, and he has also reported them to be closely correlated with stable prominences. He contends that they develop in the vicinity of large sunspot groups after the disappearance of the spots and providing no new spots are formed. This condition is likely to be met only during years immediately preceding sunspot minimum, which he believes explains the preference of M-region storms for this portion of the solar cycle. He states that coronal emission line studies which have not supported his results have failed to make the necessary distinction between emissions occurring in conjunction with spots and those observed over spotfree regions. It is only the latter which qualify as C-regions under his definition. His basic tenet is that M-regions are very old and dead centers of activity which are still covered by filaments and intense 5303 Å coronal emission and which underlie the long coronal streamers observed during eclipses near sunspot minimum. The suggestion that coronal rays are a manifestation of corpuscular streams from M-regions has also been made by others, for example, von Klüber (1952), but it should be noted that Bell and Glazer (1957) have criticized this suggestion as being geometrically unacceptable.

In a proliferation of papers dealing with solar M-regions, Mustel (1958; 1960a,b,c; 1961a,b; 1962a,b; 1963) has rejected the conclusions of previous investigators who have regarded quiet regions on the sun as the source of long-lived particle streams, and has championed instead the opposite point of view that activity centers are responsible for the

production of M-type disturbances. In his opinion, the maximum of geomagnetic activity which appears 6 days after the CMP of plages is the significant feature in the results of his superposed epoch analysis. He discounts the significance of other maximums as well as the minimum which occurs at +3 days saying that they result from the superposition of effects from adjacent centers of activity. He contends that no hypothesis involving the "destroying" effect of activity centers can consistently explain his results, and he labels the concept of cone of avoidance as completely meaningless since the corona is considerably more dense above active regions than above other parts of the sun. He interprets his results in terms of the spatial structure of the solar corona. According to his model there are two fundamentally different types of rays which extend for great distances in the corona: 1) streamers above active regions which he calls "R-rays" (or sometimes "AR-streamers"); and 2) streamers associated with quiescent prominences and thus referred to as "P-streamers". The P-streamers reach outward to (at most) 30-50 solar radii, and he believes them to be ineffective in producing magnetic storms. However, R-rays are thought to consist of particles traveling in long elastic magnetic tubes which emerge from active regions and extend even beyond the earth's orbit. Mustel contends that M-type disturbances are generated when these R-rays encounter the earth.

A refutation of Mustel's hypothesis that active regions are the source of recurring-storm particles was published by Saemundsson (1962). He recognized two different kinds of solar corpuscular emission: one which is emitted sporadically and transiently from active areas and gives rise to non-recurrent magnetic storms, and the other which is produced independently of active areas and causes M-type storms. For sporadic

storms he finds a maximum frequency of occurrence from 1 to 6 days after the CMP of calcium flocculi with the mean travel time of the particles being 3 1/2 days. For M-storms he finds a minimum 3 days after the CMP of flocculi, preceded and followed by maximums at 0 days and +6 days. He disputes Mustel's interpretation of similar results which relies on a particular longitudinal separation of adjacent activity centers. Saemundsson shows that this proposed explanation breaks down because the flocculi do not conform to the peculiar distribution required. Although his results support the general concept of a cone of avoidance, he points out that M-regions occur independently of activity centers (but of course shunning their immediate vicinity) and so are not necessarily dependent on the deflecting properties of these centers as is required by the cone of avoidance hypothesis.

Dessler and Fejer (1963) have criticized the concept that M-region magnetic storms are due to narrow streams of solar plasma that are continuously emitted from the sun and which cause storms when they strike the earth. They propose instead that the M-region magnetic storm is due to a stream of turbulence and irregularities in the solar wind. They suggest further that this turbulence arises from velocity discontinuities in the plasma stream which result from a longitudinal gradient in coronal heating. However, Snyder, Neugebauer, and Rao (1963) have observed that M-region streams are characterized by higher than usual plasma velocities rather than by turbulence, although they could not rule out the possible effectiveness of irregularities with scale sizes too small to be detected by their instrument.

In a recent review of the conflicting opinions on the nature of M-regions, de Jager (1963) states that in his opinion a final decision on

the identification of the source of M-particles can not yet be made. The problem is therefore considered further in Chapters 5 and 6 in the light of the observed relations between solar phenomena and aurorally associated radio wave absorption.

CHAPTER II

TERRESTRIAL EFFECTS OF SOLAR PARTICLES

2.1 INTRODUCTION

As has been described in the preceding chapter, the sun emits charged particles which in the course of their flight through interplanetary space sometimes encounter the earth and interact with its atmosphere and magnetic field. This interaction is observed on the earth by numerous techniques which lead to its description in terms of auroras, magnetic storms, cosmic ray variations, and radio wave absorption events. However, in spite of these varied manifestations there are apparently only two basic phenomena involved, and these are believed to arise from characteristically different solar processes. In general, the observing techniques are sensitive to different particle energies and so are dependent on the energy spectrum of the incident stream of particles. On the one hand, particle streams which are ejected from the sun during solar flares with energies ranging from hundreds of Mev down to a few kev produce great nonrecurring magnetic storms and auroral effects, polar cap absorption (PCA) events, and, in extreme cases, ground level cosmic ray increases. The typical sequence of events following a flare is the onset of PCA after 1 or 2 hours followed by a magnetic storm and auroral activity commencing after 1 or 2 days. On the other hand, streams of particles with energies of only a few kev and having no clearly recognized association with solar disturbances give rise to aurora, recurring magnetic storms, and auroral zone radio wave absorption but not to PCA or other high energy phenomena. The following sections will describe these various terrestrial effects and discuss their relation to solar particles. Because of the

voluminous literature which would have to be treated, no attempt will be made to give a complete account of these subjects. The references cited will be for the most part either of a general review nature or will pertain to specific problems to be discussed in later chapters.

The preceding chapter was concerned with corpuscular streams leaving the sun, but before discussing the consequences of their arrival on earth, it is appropriate to consider what is known of them en route. It was thought at one time that radiation pressure was responsible for the accelerations observed in the tails of comets, but the current opinion, as reviewed by Biermann (1953), is that "friction" with solar ion streams best accounts for the orientation of the tails. Prior to magnetic storms, abnormal absorption on the ultraviolet side of solar emission lines has been observed, corresponding to the Doppler displacement due to particles traveling toward the earth from the sun at speeds of about 1000 km/sec. These two pieces of indirect evidence have now been supplemented by Mariner 2's direct observations of solar plasma streaming through interplanetary space. According to a summary by Snyder (1963), the data showed velocities to be in the range of about 320-840 km/sec. Distinct sets of velocity peaks that recurred every 27 days were observed, and there was some suggestion that these were associated with the CMP of calcium plages, but the relation was not clear. The velocity of the solar stream was also found to correlate strikingly well with geomagnetic activity. A recent account of this work was given by Snyder, Neugebauer, and Rao (1963).

The solar wind, which is considered to be the result of a continuous emission of particles from the undisturbed sun, is not treated in

this work since it is believed to arise from processes distinctly different from those already described for M-regions and activity centers. Parker (1963) has given a comprehensive treatment of the problem of the continuous presence in interplanetary space of plasma streaming from the quiet sun, and the subject has been reviewed recently by Lüst (1962).

In this chapter it is important to keep in mind the distinction between solar cosmic rays (including polar cap protons), all of which are positively charged; solar plasma, which is ionized but macroscopically neutral; and neutral (unionized) particles, which are mostly hydrogen atoms. In general, solar streams (or clouds) will contain all three of these, the relative proportions determining the nature of the terrestrial consequences of the stream impact. The main problem in relating most terrestrial phenomena to solar particle streams concerns the mechanism of the energy transfer from the stream to the earth, or in other words, the injection of particles into the magnetosphere. The injection is straightforward for cosmic rays, or for neutral hydrogen, but the problem is difficult for streams of plasma. For the most part, this problem is not treated here. The approach adopted is to discuss relations between occurrences on the sun and the earth with only superficial regard for the mechanisms of interaction. This limitation is dictated of course by the scope of the present study rather than by the importance of the problem. A discussion of some of the physical aspects of the interaction of the plasma with the earth's magnetic field is given in section 6.3.

2.2 MAGNETIC STORMS

The main geomagnetic field is generated within the earth, but it is subject to a great variety of perturbations which arise from processes taking place in the atmosphere and surrounding space. The gravitational influence of the sun and moon account for some of the variations, but the most dramatic effects are produced by particles from the sun. The fundamental theory for the production of magnetic storms by streams of solar particles was developed by Chapman and Ferraro (see Chapman and Bartels, 1940, ch. XXV). According to this theory, when the neutral stream of ionized gas reaches the outer limit of the earth's magnetic field, currents are induced on the surface setting up a field which retards the forward motion. The stream surface then advances around the earth forming a hollow on whose opposite surfaces positive and negative charges tend to build up. As the stream face flows on beyond the earth and closes in behind it, a ring current may be established encircling the earth in a westerly direction, opposite to the earth's rotation. This ring current superimposes its magnetic field on that of the earth causing the variation observed during magnetic storms. The present day concept of the ring current involves protons and electrons trapped in the Van Allen radiation belt and migrating in opposite directions around the earth, but the basic idea that the sun as the source of these particles is responsible for magnetic storms has remained unchanged.

The relations between geomagnetic activity and particular solar phenomena were discussed in the preceding chapter. However, certain aspects of the temporal behavior of magnetic storms reflect on the general nature of the solar streams. For instance, as discussed by McIntosh (1959), the 27 day recurrence tendency and the lag of average

magnetic disturbance behind relative sunspot number in the solar cycle strongly suggest that particles are emitted nearly radially over long periods from localized regions on the sun having a solar cycle latitude variation closely in phase with that of sunspots. Assuming a radial emission from the sunspot belts, the equinoctial maximums in magnetic activity can be interpreted as arising from the systematic variation of the earth's heliographic latitude between about 7° north and south of the solar equator. This "axial theory" for the semiannual component of geomagnetic activity (Priester and Cattani, 1962), although not accepted by everyone (see McIntosh, 1959), indicates that the preferred mean latitude of emission is always greater than 7° in each hemisphere. In a similar vein, M-regions show up in the declining and not in the ascending phase of the solar cycle because they depend on sunspots, or at least on the location of the sunspot zones, and during the ascending phase these are too high in latitude to be effective. During minimum years when sunspots are nearest the equator, the geometry of the M-region streams is optimum for encountering the earth.

Jenkins and Paghis (1963) have investigated the criteria for the association of geomagnetic disturbances with solar flares. Their results have confirmed those of earlier investigations which were given in section 1.3. In a statistically significant number of cases, they found that days in the years 1949-61 on which the linear planetary magnetic index A_p increased by an amount ≥ 50 within 12 hours were preceded 1 to 3 days earlier by solar flares with importance $\geq 2+$. This association of flares and storms was controlled by flares accompanied by major radio bursts and was found for both SSC and non-SSC A_p rises,

indicating that active region storms are not necessarily of the sudden commencement type, as is sometimes assumed. They found the association between major burst flares and geomagnetic disturbances to be very dependent on the heliographic location of the flares, with storm flares being dominantly in the northern hemisphere and having a preference for the western side of the disk in both northern and southern hemispheres.

The problem of east-west asymmetry in storm flare location has also been dealt with by Dvoryashin, Levitskii, and Pankratov (1961) with very interesting results. They discovered that the intensity of a storm was dependent on the position of its flare on the solar disk, with the strongest storms being produced by flares in the region $10-30^\circ$ west of the central meridian. When plotted as functions of flare longitude, the average Kp index and the amplitude of the main phase of the storms both were shown to increase systematically toward the central meridian from east to west, reaching a maximum for flares in the $10-30^\circ$ W range, and then decreasing again toward the west limb. They interpreted the effectiveness of centrally located flares ($\pm 30^\circ$) as indicating that the main mass of gas ejected by flares is concentrated in a cone of about 60° , but they offered no explanation for the observed east-west asymmetry in flare effectiveness although from their other discussions it would have been logical for them to suggest that this was an effect of guiding particles through interplanetary space by a radial magnetic field which was slightly spiraled by the sun's rotation. This problem has received much attention in the literature and it will be pursued further in section 2.5.

Several authors (Obayashi, 1962, Hauriwitz, 1962; Dvoryashin, et al., 1961) have commented on the relation showing travel time (i.e. time

elapsing between flare and storm onset) to be shorter for storms which are preceded a day or so earlier by another storm. This effect is generally believed to result when storm particles are injected into a channel formed by an approximately radial magnetic field which was carried into space from an active region by the previously ejected plasma.

Since almost all studies of solar effects on the earth's magnetic field have relied on the magnetic indices K or C for a measure of geomagnetic activity, some discussion of the definition and physical significance of these indices is warranted. As the K-index was originally defined by Bartels, Heck and Johnston (1939), it takes on integral values from 0 to 9 to indicate the difference between the highest and lowest deviation, within a 3 hour interval, from the smooth curve expected for a magnetically quiet day, according to the season, the sunspot cycle, and the phase of the moon. Thus, the K-index is designed to discriminate between effects of solar wave radiation and effects of particles, and is supposed to mirror only the influence of the latter. K-index is a quasi-logarithmic measure of activity which ranges over about 2 orders of magnitude on a linear amplitude scale. Actually, the linear variation of a magnetic disturbance corresponding to a given value of K varies greatly from one station to another since K is determined differently for all stations in order to normalize the data and remove the effect of each station's geographical location. Thus, the linear ranges are chosen so that an auroral zone station which experiences large linear fluctuations will have the same number of indices 0, 1, 2, ...9 for a specific year as an equatorial station with relatively small linear fluctuations.

In order to provide a magnetic index for the whole world, the "planetary index", K_p, was defined by Bartels and Veldkamp (1949) as the

average of the standardized K-indices from 11 observatories scattered over the globe but mostly in the polar regions. To avoid an unjustified impression of exactness, Kp is given in thirds (indicated by + or - following the index) instead of tenths. Kp is now available for about the past 25 years, but the oldest world wide measure of magnetic activity is the character figure, C, which was originally assigned the values 0, 1, or 2 according to whether a day was quiet, moderately disturbed, or very disturbed. Days were classified in this manner rather arbitrarily by the observer in charge at each station, with the result that there was very poor agreement among stations as to the number of days of C = 0, 1, or 2 in a given time interval. In spite of this subjective definition, the world wide character figure which is formed by averaging the C-indices from all observatories, and which is available since 1884, has been useful in many studies. Since 1937 a new index, Cp, based exclusively on Kp, has been used.

Magnetic disturbances are primarily ascribed to electric currents of variable intensity flowing in the vicinity of the earth. In general, the world wide pattern of magnetic variations produced by solar particle streams can be attributed to 3 current systems: the Chapman-Ferraro system flowing at the magnetospheric boundary; a simple ring current in equatorial regions; and a complex auroral zone and polar cap current system in both the northern and southern hemispheres. Currents in these latter systems (called S_p) flow across the polar cap toward the sun and then divide to flow east and west around the auroral zone to complete their circuits. Magnetic indices are a measure of the magnitude of these currents, and thus are a qualitative measure of the number of solar particles

reaching the earth, but a primary shortcoming for studying solar-terrestrial relations is that there has never been a quantitative interpretation of the physical significance of the magnetic indices.

In recent years there has been an increasing tendency toward a magnetohydrodynamic interpretation of geomagnetic disturbances. Carrying this development one step further, Dessler and Fejer (1963) have objected to the traditional interpretation of Kp as representing the flux of solar particles at the earth. They contend instead that Kp is a measure of the time rate of change of the sum of plasma plus magnetic pressure acting on the earth's magnetosphere. According to them, there is no geomagnetic effect so long as the solar plasma flow is laminar, regardless of the stream velocity or density; and they have proposed that storms are due to the presence of turbulence or irregularities in the streaming plasma. However, Snyder, Neugebauer, and Rao (1963) have discounted this theory with their findings that Kp is a measure of plasma velocity and is probably not a measure of the time rate of change of plasma velocity, at least not within the 3.7 min time resolution of the Mariner 2 instrument. Another magnetohydrodynamic interpretation has been suggested by Dessler and Walters (1964).

2.3 AURORA

Aurora, one of the most magnificent of all natural phenomena, is visible in the arctic sky on almost any clear night. The luminosity arises from the atmospheric constituents, mainly nitrogen and oxygen, which emit visible radiation when excited by collisions with energetic charged particles (including secondary particles) as they are precipitated into the earth's upper atmosphere. The incoming stream is made up of

both protons and electrons, and the former add their characteristic emission lines to the auroral spectrum as they are neutralized. The particles come initially from the sun and are guided into auroral latitudes, centered about 23° from each geomagnetic pole, by the earth's magnetic field. It is also possible that the auroral particles do not come from the sun but instead are magnetospheric particles which are accelerated and precipitated when the solar plasma reaches the earth. However, regardless of the origin of the actual auroral particles, solar plasma in the vicinity of the earth is a necessary prerequisite for auroral disturbance.

Modern theories of the aurora are concerned with plasma streams impinging on the magnetosphere and injecting particles into the Van Allen radiation belt to be either trapped or dumped according to the initial angle of travel with respect to the direction of the geomagnetic field. As a result of the complexity and variety of the phenomena involved, any theory of the aurora is subject to criticism both on the grounds of unexplained observations and neglected theoretical considerations. Owing to these difficulties, there is no generally accepted detailed auroral theory, but it is uniformly acknowledged that streams of solar particles are the ultimate source of all auroral disturbances.

Aurora is unique among the terrestrial effects of solar corpuscular bombardment in that it is the only one which can be observed without instruments. However, in spite of this advantage, it was not until the all-sky camera was developed and used in quantity during the IGY that it was possible to recognize a pattern in the temporal and spatial variations of auroral occurrence. The systematic behavior of the location, orientation, and movement of auroral forms was described by Davis (1960, 1962) and interpreted in terms of a pattern under which the

earth rotates. This pattern is centered on the geomagnetic pole and fixed with respect to the sun, and it was noted to be remarkably similar to the idealized S_D current system described briefly in section 2.2.

What is known about the response of aurora to the 11 year changes in solar activity has been reviewed by Chamberlain (1961). Like geomagnetic activity, the maximum of auroral activity is observed one to two years after sunspot maximum. There is also a suggestion that aurora occurs further south during sunspot maximum and retreats to the north during minimum years, a trend which reflects the known relation of aurora to magnetic activity, namely that the southern extent of auroral displays increases with increasing geomagnetic disturbance. Aurora and geomagnetic activity are such closely related phenomena that the previously discussed dependence of geomagnetism on solar processes can be considered as holding equally well for aurora. This correspondence is assumed because K_p , the most commonly employed index of solar corpuscular effects, is sensitive almost exclusively to disturbances in the auroral regions.

The occurrence of aurora is seldom used as an index of solar particle bombardment since observations are limited by cloud cover, sunshine, moonlight, and to some extent by geographic inaccessibility. There is also some difficulty in defining a measure of auroral activity which can be suitably interpreted in terms of the energy flux of incoming auroral particles. This problem has been discussed by Basler (1963). Hartz and McAlpine (1960) can be mentioned as an example of one study of solar-terrestrial relations which utilized an auroral index, in this case the southern extent of visible aurora. Akasofu and Chapman (1963) have shown that the equatorward shift of quiet auroral arcs is closely related to the growth of the ring current.

For a comprehensive up-to-date treatment of aurora and related phenomena see Akasofu, Chapman, and Meinel (1964).

2.4 COSMIC RAY EFFECTS

The earth is subject to a continual rain of energetic particles which because of their extraterrestrial origin are known as cosmic rays. These particles have energies ranging up to 10^{19} electron volts or more, and they are nuclei of the elements, mostly hydrogen but with heavier nuclei also present and in greater proportions than in the universal abundances. Although cosmic radiation is primarily of galactic origin, it is subject to a few small variations which are produced by the sun. These solar influences are accomplished in 2 ways: 1) by means of the interplanetary solar magnetic field's modulating the radiation in the vicinity of the earth; and 2) by the sun's occasionally emitting particles which are added to the background of galactic radiation. In the first group are included the 11-year and 27-day variations and the Forbush decreases; in the second are the ground level cosmic ray increases which follow certain large solar flares. Brief discussions of each of these phenomena will be given here; more complete treatments can be found in Simpson (1960) and Webber (1962).

The Forbush decrease is prominent among many lesser short time variations, and it can be considered as the basic example of the negative effect of the sun on cosmic rays. The decrease starts 1-6 hours after the onset of a geomagnetic storm and continues rapidly for up to 24 hours. The recovery is approximately exponential over a period which ranges from a few days to weeks or months, and the maximum decrease is usually around 5% although it is occasionally as much as 15-20%. There

is no general agreement on the mechanism causing Forbush decreases, but some suggest that they result when the earth is temporarily shielded by solar magnetic fields. In particular, it is assumed that the magnetic storm plasma ejected by a flare carries a frozen-in magnetic field which envelops the earth in a magnetic bottle whose neck is in the sun's active region which produced the flare. This model is generally attributed to Gold (1960, 1962). Forbush decreases sometimes recur when the active region rotates around with the sun and again encloses the earth in the magnetic bottle. Many long series of smaller scale decreases (1-4%) have also been found with recurrence intervals of 27 days.

On a longer time scale, the intensity of cosmic radiation has been found to vary inversely with solar activity in an 11-year cycle which was thought at one time to be controlled by meteorological or geomagnetic processes. However, it is now apparent that the variation is caused by a change in the flux density and energy spectrum of the primary particles. During the last sunspot cycle the number of low rigidity particles (8GV) varied by about 25% while high rigidity (50GV) variations were of the order of 3%. To interpret this anticorrelation with sunspot numbers it is assumed that the intensity observed at solar minimum represents the galactic intensity as it would appear outside the solar system, but at solar maximum the essentially radial magnetic field of the sun diverts part of the primary radiation away from the inner part of the solar system. This magnetic filter is especially effective in the low energy range of the spectrum. To some extent the long term cosmic ray variation represents the superposition during times of high solar activity of a large number of short term effects of the Forbush type, but not all of the 11-year cycle can be accounted for in this manner.

The understanding of primary cosmic rays has increased greatly in recent years since the perfection of balloon, rocket, and satellite techniques. Also important has been the world wide network of ground based neutron monitors, most of which were put into service during the IGY and replaced the previously used ion-chambers which were much less sensitive to solar (i.e. low rigidity) particles. Having examined the negative solar effects, attention is now turned to the sun's positive contribution to the primary beam of cosmic radiation. A recent review of this subject has been given by Carmichael (1962).

The intensity of cosmic radiation at the earth's surface has been observed to increase above the normal level on about a dozen different occasions during the last two sunspot cycles. These increases have been attributed to the sun both because of their close association with flares and because in several instances the particles were observed to arrive from the general direction of the sun. There has been great variety in the detailed characteristics of these events which suggests differences in acceleration conditions on the sun as well as in traveling conditions in the interplanetary medium. Nevertheless, it is possible to make a few important generalizations. Ground level events do not occur during years of maximum solar activity, but it is not known whether this is because the particles are not produced or just because they are prevented from reaching the earth. However, Fokker (1963b) has found that large microwave outbursts likewise exhibit a tendency to avoid the maximum phase of the sunspot cycle, which implies that high energy cosmic rays may not be emitted by the sun at these times. Cosmic ray flares show a preference for the western side of the solar disk, the highest frequency of occurrence being at the western limb, and this asymmetry

is interpreted as an effect of guiding by solar magnetic fields in space bent into a slight spiral by the sun's rotation. Confirmation of this interpretation is found in observations of the arrival of particles from directions west of the sun. Carmichael (1962) also points out that a transit time anomaly exists for all events for which the time interval between the generation of particles and their arrival at the earth is known precisely. The observed transit times average about 24 minutes while the calculated times (even taking into account the curved flight path) are about 12 minutes. This anomaly suggests that the particles must have been held in the vicinity of the sun by some storage mechanism after they were accelerated to their relativistic energies.

2.5 RADIO WAVE ABSORPTION

When radio waves pass through an ionized medium they are attenuated by an amount which is proportional to the electron density (among other factors). Charged particles impinging on the earth's atmosphere can thus be detected by measuring the absorption of radio waves which propagate through the region of resulting ionization. Particle induced absorption occurs in the terrestrial ionosphere in high magnetic latitudes and is of two basically different types called polar cap and auroral absorption. Brief discussions of previous studies of the relations of these two types of absorption events to solar phenomena will be given here in order to round out this chapter's treatment of terrestrial reactions to solar particles, and to serve as background for Chapters 4 and 5 where the problems of absorption and its relation to solar activity are investigated in detail.

It is now well established that polar cap absorption (PCA) is produced by protons with energies up to a few hundred Mev which are expelled from the sun at the time of some flares, especially those accompanied by Type IV (continuum) radio emission. It is also apparent that the number of PCA events varies in phase with the sunspot cycle and does not show a 27-day recurrence tendency (Collins, Jelly, and Mathews, 1961). However, beyond these generalizations, there is considerable lack of agreement among the various groups who have investigated the details of the relation of PCA to solar activity. Two particular areas of disagreement are concerned with the east-west asymmetry in flare location and with the time required for the particles to traverse the sun-earth distance.

In an extensive study of the relation of PCA to solar activity, Warwick and Haurwitz (1962) concluded that there is no significant dependence of occurrence or of delay time of PCA on position of the associated flare. However, they did report a relation between delay time and phase of the solar cycle, with delay times decreasing with declining sunspot numbers.

The conclusion of Warwick and Haurwitz (1962) on the lack of an east-west asymmetry in the position of PCA producing flares is in disagreement with that of earlier authors (Reid and Leinbach, 1959; Obayashi and Hakura, 1960; Thompson and Maxwell, 1960a; and Hartz and McAlpine, 1961) and also has not been substantiated by the results of subsequent investigations (Jenkins and Paghis, 1963). Thus, the question of whether or not western flares are more effective in producing PCA still seems to need further investigation.

The question of the propagation time of the flare-ejected particles likewise seems to be unresolved. McCracken and Palmeira (1960) presented evidence that propagation time increases with the angular distance of the flare from the western limb of the sun, but their result was not corroborated by Warwick and Haurwitz (1962). The problem of the transit time is complicated by many factors. It is first necessary to choose the appropriate flare from the several possibilities usually available and then to decide at what time during the flare the particles were ejected. The most common practice is to assume that particles leave the sun at the flare's onset, although the time of flare maximum is sometimes used (Kahle, 1962). Carmichael (1962) used the start of the cm-wave solar noise burst, but he still found a transit time anomaly, which suggests that the particles did not leave the sun until sometime after the cm-wave burst. After determining the time of particle emission, there still remains the problem, in the case of PCA, of detecting the beginning of the particle stream's arrival.

Although there are many inconsistencies to confuse a synoptic formulation of the problem of travel time and its relation to flare location, a currently popular explanation contends that transit times are shorter for protons from western flares because interplanetary magnetic fields favor trajectories which are in the form of an Archimedes spiral rather than those which are rectilinear (Dvoryashin, Levitskii, and Pankratov, 1961; Obayashi, 1962). These interplanetary fields are believed to be the local fields of active regions which were carried into space by flare ejected plasma but which remained attached to the active regions and so were bent into a spiral by the sun's rotation. This model is supported by observations of increased travel times for protons with parent regions

at greater distances from the western limb and shorter travel times for protons which were preceded into space by a plasma ejected a day or two earlier from the same active region.

Noyes (1962) studied the solar active regions which produced PCA flares and found them to be characterized by magnetically complex ($\beta\gamma$ or γ) sunspots, youthfulness (their age rarely exceeding 2 or 3 rotations), large sunspots, and many major flares. However, these qualities are not particularly distinctive, and the associations were generally too weak to be of much significance. For instance, although he found 68% of all PCA events to be caused by $\beta\gamma$ or γ sunspot groups, only 20% of all $\beta\gamma$ and γ regions produced PCA.

In spite of the lack of completely consistent results, the groundwork for understanding the relation of PCA to solar phenomena has been reasonably well laid, but heretofore there has been little attempt to perform a similar analysis for aurorally associated absorption. This type of absorption is produced by electrons with energies of only a few keV which are dumped from the earth's radiation belt, and it is the dominant type of absorption observed at stations in auroral latitudes. Collins, Jelly, and Mathews (1961) found that auroral absorption occurs mostly during the declining phase of the sunspot cycle, and they suggested that it is more closely associated with solar M-regions than with flares and sunspots. However, auroral absorption which follows after a PCA event, within a few days, is generally considered to be an effect of the low energy particles which were ejected by the PCA flare and should not be confused with auroral absorption from M-region sources.

2.6 WEATHER

The previous sections of this chapter have dealt with the well established effects of solar particle streams, but for reasons of personal interest the treatment will now expand slightly into the realm of conjecture to include a discussion of the influence of solar corpuscles on terrestrial weather. Many meteorologists regard this subject as heresy and challenge its relevance on the grounds that any effect must be insignificant since the overwhelming majority of the earth's atmosphere (and thus its weather) is far below the average level of penetration of solar particles and also since corpuscles contain only a minute fraction of the total energy radiated by the sun. However, the complexities of abnormal weather changes, that is those changes which are not part of the regular daily and seasonal variations, are without any ultimate explanation. It is not known why one meteorological pattern develops instead of another, why one year is warmer or wetter than another, or what causes global climate changes. Since the sun supplies the energy for all meteorological processes, it is possible to seek an explanation for the triggering of these processes in terms of variations in the solar energy supply, but so far as it has been possible to determine, there is never any significant change in the energy output of the sun, at least not in the visible spectrum where almost all of the energy is radiated. However, there are large fluctuations in the amount of corpuscular and ultraviolet energy received by the earth. These fluctuations, although infinitesimal when superimposed on the background of the total energy received, might conceivably be capable of precipitating chain reactions which result eventually in some of the observed anomalous weather patterns. Of course, many other explanations are also readily

available, and it is not intended here to establish more than the possibility of a solar-weather relationship.

Unfortunately, it is not possible to speak more specifically, except at a highly speculative level, about the mechanisms through which corpuscular perturbations influence the weather. Consequently, most solar-weather studies have sought statistical relationships between various meteorological and solar parameters in hopes that an empirical discovery would indicate the physical mechanisms involved. Because of the long series of data available, sunspot numbers have been used most frequently in these studies, but this has been unfortunate since, as was discussed in section 1.2, sunspots are not directly related to corpuscular emissions. Some studies have used geomagnetic indices, which are more directly related to particle flux than sunspots, but the results were by no means convincing although they were occasionally very suggestive. Thus, even the existence of a solar-weather relationship remains very much in doubt. Practically the only clear evidence lies in the discovery of an approximately 11-year cycle in the width of tree rings. The spacing of these rings represents changes in growing conditions and so provide a continuous climatic record stretching back in some cases for over a thousand years.

The most thorough treatise available on the many different aspects of the solar-weather problem was edited by Fairbridge (1961), and an excellent synoptic introduction to the subject was written by Craig and Willett (1951). In this latter work the authors describe the world's weather as oscillating between two extreme patterns which are present today and were present in the past in essentially the same intensity.

These oscillations display an almost continuous frequency spectrum, but strong components can be recognized and are presumably significant although they are not strictly periodic in nature. The fundamental period is exhibited by fluctuations which occur on a geological time scale, with glacial epochs appearing at approximately quarter-billion year intervals. These epochs last about 50 million years but are not continuous since they are always broken by several ice-free interglacial periods. On a historical time scale, changes occurring at intervals of a few thousand years have caused flourishing civilizations to crumble in one area and develop in another when the climate turned toward the glacial or interglacial type. Fluctuations lasting for centuries, decades, years, and even weeks have also been recorded, and the most plausible explanation for these world-wide changes is shown to lie in variations of the solar energy supply, although Craig and Willet (1951) do not refer specifically to corpuscular variations.

The most generally acclaimed results which indicate a solar-weather relationship on a day-to-day basis were given by Duell and Duell (1948). They found that the behavior of sea level pressure over Europe and the north-eastern Atlantic exhibited a clear relation to geomagnetic disturbances during the winter months of years with low solar activity. The pressure at a given station was noted to be lower than normal after magnetically disturbed days, with a minimum occurring 3 days after, and higher than normal after quiet days with a maximum occurring at 3-4 days. However, they were not able to find any consistent relationships during years with relative sunspot numbers greater than 40 or during any season except winter.

CHAPTER 3

METHODS OF ANALYSIS

3.1 INTRODUCTION

This chapter contains a discussion of how the absorption data used in this work were collected and analyzed, and a justification is given for their interpretation as an effect of the solar particles which impinge on the earth's atmosphere. Detailed treatments are given only for those aspects which are peculiar to the present work. Thus, ionization and loss processes, the magnetoionic theory of absorption, and the details of the equipment operation are largely ignored. However, the use of the daily average absorption as an index of solar particle bombardment in a superposed epoch analysis is discussed at some length. This application of riometer data has proved fruitful in the present study, and is not known to have been employed in any previous investigation.

3.2 RIOMETER DATA

The cosmic radio noise technique for measuring ionospheric radio wave absorption was introduced by Shain (1951). The riometer (Little and Leinbach, 1959) which is now the standard device used to measure cosmic noise absorption, was adapted from Ryle and Vonberg's radio astronomy receiver and was developed at the Geophysical Institute of the University of Alaska for the U. S. IGY program. Because of the pioneering work which was done here, and because of its location at the latitude of maximum absorption in the auroral zone, there is now a wealth of absorption data which has been collected continuously at College, Alaska over the past six years. There are also extensive periods for which data are on hand from stations in other parts of Alaska and from Thule, Greenland. In this

study riometer data were used from College, Ft. Yukon and Thule, and ionosonde data from Thule and Resolute Bay in the Arctic, and Byrd Station and South Pole Station in the Antarctic. The geographic and geomagnetic coordinates of these stations are given in Table 2.

TABLE 2
LOCATION OF RIOMETER AND IONOSONDE STATIONS

STATION	GEOGRAPHIC		GEOMAGNETIC	
	Latitude	Longitude	Latitude	Longitude
College	64°52' N	147°49' W	64.65° N	256.56° E
Ft. Yukon	66°34' N	145°18' W	66.69° N	257.05° E
Thule	76°33' N	68°50' W	88.0° N	1.0° E
Resolute Bay	74.7° N	94.9° W	83.2° N	289.3° E
Byrd	80.0° S	120.0° W	70°36' S	336°01' E
South Pole	90.0° S		78°30' S	0° E

The riometers were operated at 27.6 mc/s and were connected to vertically directed three-element Yagi antennas with half-power beamwidths of approximately 60° in the E plane and 120° in the H plane. The antennas were oriented so that the E plane was in the magnetic meridian.

For the most part the data were scaled at chart intervals of 15 minutes. The data from the least disturbed periods were used to define a "quiet-day curve" for each month. This curve showed the intensity of the radio noise received from the part of the galaxy monitored by the antenna at a given sidereal time. The charts are calibrated in terms of the current through a noise diode which is directly proportional to the received cosmic noise power. Absorption is calculated from the expression

$$\text{Abs(db)} = 10 \log_{10} I_q/I_d$$

where I_q and I_d are respectively the currents taken from the quiet-day curve and the (disturbed) riometer trace for the same sidereal time.

Assuming that equipment parameters do not change, it is theoretically possible to derive an "absolute" quiet-day curve from the data by noting the maximum cosmic noise intensity observed during each of the 24 sidereal hours. Data must be examined over a long period of time, at least a year, so that the incoming noise from all parts of the sky will be observed through the ionosphere during the quietest part of the day. The quiet day curve determined in this way comes as close as possible to representing the total incoming cosmic noise power.

Since the subject of this investigation was concerned with the disturbance absorption associated with solar particle streams, no effort was made to determine an absolute quiet-day curve and thus to measure the total absorption in the ionosphere over the various stations. Instead, a new quiet-day curve was made for each month corresponding to the quietest periods in that month. This technique effectively removed the "normal" (as opposed to disturbed) component of absorption from the data. Thus, the influences of seasonal changes in solar elevation angle, of changes in the intensity of the sun's ultraviolet radiation, and of changes in equipment parameters (such as the impedance match between the antenna and the receiver) were included in the quiet-day curve and do not appear in the absorption values.

3.3 IONOSONDE DATA

Because of the scarcity of high latitude riometer stations and because of the lack of continuous riometer data from Thule, it was necessary to use ionosonde f-min data to study the more recent PCA events. F-min

is the lowest frequency which is reflected from the ionosphere and received back on earth. Frequencies lower than f_{\min} are absorbed in the lower regions of the ionosphere before they return to earth, so f_{\min} is a qualitative index of ionospheric absorption. f_{\min} increases, indicating higher absorption, until the condition known as blackout occurs. In this case no reflected wave is received by the ionosonde because of the total absorption of all frequencies lower than the ionospheric critical frequency. The critical frequency for the F-layer (f_oF_2) is the theoretical upper limit for f_{\min} .

When studying disturbance absorption, it is common practice to work with Δf_{\min} , which is the difference between the f_{\min} observed at a particular time and the monthly median f_{\min} for that time. By this subtraction, the "normal" absorption component is removed from the data in much the same way as was done for riometer data by calculating monthly quiet day curves.

In this study, ionosonde f_{\min} data were used from Thule, Resolute Bay, Byrd Station, and South Pole Station, which were the only suitable high latitude stations from which data were available. The Resolute Bay data were made available by the Telecommunications Branch of the Canadian Department of Transport, and the other data were obtained from the IGY World Center A, Airglow and Ionosphere, Boulder, Colorado.

An excellent discussion of Δf_{\min} and its usefulness for studying polar cap absorption has been given by Jelly and Collins (1962). They compared the Δf_{\min} with the 30 mc/s riometer data at Churchill during a PCA event and found a very good correlation (about 0.9) with 1 mc/s of Δf_{\min} corresponding to about 0.6 db absorption on the riometer. Of course, equipment parameters vary greatly so these relations cannot be

expected to apply quantitatively at other stations, although in general close correspondence will be preserved.

3.4 DAILY AVERAGE ABSORPTION

3.4.1 Index of Solar Corpuscular Bombardment

It is assumed throughout this work that absorption is produced by the bombardment of the upper atmosphere by charged particles, so variations in absorption are interpreted as changes in the energy flux in the incoming particle stream. The range of particle energies to which the absorption technique is sensitive is determined by the height variation of such atmospheric parameters as density, collision frequency, and recombination coefficient. In particular, when the collision frequency ν is much less than the observing frequency ω , then absorption is proportional to ν , but when $\omega \ll \nu$, then absorption is proportional to $1/\nu$. For 27.6 mc/s $\omega = \nu$ at about 50 km, so the observed auroral absorption can be assumed to be caused by electrons with energies in the approximate range of 5-500 kev. Lower energy electrons are stopped too high in the atmosphere where ν is too low for significant absorption to occur, and higher energy electrons penetrate too deep, where $1/\nu$ is too low and also recombination and attachment remove the free electrons too quickly for them to contribute to absorption. Actually, the high energy electrons are relatively unimportant since the energy spectrums observed with rockets and balloons are so steep that very little of the total energy deposited is carried by electrons more energetic than 100-200 kev (Anderson and Enemark, 1960; McDiarmid et al., 1961). Expressed as a power law, dN/dE is proportional to E^{-5} or E^{-6} , or if an exponential behavior is assumed, dN/dE is proportional to $\exp(-E/22 \text{ kev})$. In practice, it is

probably safe to consider the daily average absorption as representing the energy flux in the 30-40 kev range since McDiarmid et al. (1961) were able to explain their observed absorption by assuming a monoenergetic 30 kev beam and O'Brien (1964) concluded that the absorption measured by Basler (1963) was caused by electrons with $E \geq 40$ kev.

Of course, only the effects of a small fraction of the world-wide total of the incoming particles can be detected from one station at a given time, but by averaging over 24 hours at a station near the latitude of maximum occurrence and intensity of absorption (such as College) a representative sample is taken of each day's total influx from the solar stream. This argument applies more to auroral than to polar cap absorption when observed at College, and it assumes that the particle precipitation which is responsible for the absorption is governed by a pattern which is fixed with respect to the sun and under which the earth rotates.

Indices of geomagnetic activity have long been used to indicate the influx of solar particles, but it is felt that daily absorption is a superior index since it is more directly related physically to particle bombardment and is thus a more quantitatively significant measure. The following discussion is intended to show some of the difficulty in interpreting geomagnetic activity directly in terms of the solar corpuscular energy flux. As was described in section 2.2, the planetary magnetic index, K_p , is largely controlled by the auroral electrojets. However, at least two separate factors contribute to the flow of these currents and thus to geomagnetic disturbances and K_p . First, an influx of energetic particles produces extra ionization which increases the electrical conductivity; and second, an electric field (electromotive force) is necessary to drive the current system. The precise origin of this electromotive

force is uncertain since it is affected both by charge separation and by the $\vec{V} \times \vec{B}$ field produced by the motion of charges with velocity \vec{V} in the earth's magnetic field \vec{B} . A discussion of this electromotive force and its generation by convective motions in the magnetosphere caused by the flow of the surrounding solar plasma has been given by Axford and Hines (1961). Since the current is proportional to the product of the electric field and the conductivity, there is no way of distinguishing between their relative contributions to the magnetic disturbance. Actually, because the earth's magnetic field makes the ionosphere a nonisotropic conductor, the current is related to the electric field by the tensor equation $J_i = \sigma_{ij} E_j$. Thus, the inability to resolve the complexities of the mechanism by which magnetic disturbances are generated is a severe limitation of the usefulness of indices of geomagnetic activity in studying solar-terrestrial relations. Section 3.4.3 shows that the physical interpretation of the absorption index is much more straightforward.

Since College is near the southern boundary of the northern polar cap (especially for weak events), it is not as well suited for studying PCA as for auroral absorption. A station with a much higher magnetic latitude would be more desirable, but unfortunately no such station has been in continuous operation for a long enough period to be of use in statistical studies of polar cap absorption data. Actually, because of the strong influence of sunlight on PCA, it would be necessary to combine data from a high latitude station in both the northern and southern hemisphere in order to derive a quantitatively significant index of polar cap proton bombardment throughout the year. However, even with the handicap of its quantitative inaccuracy, the College data are the best available for studying such problems as the recurrence phenomena in PCA.

3.4.2 Numerical Aspects

The daily average absorption is calculated by taking the average of the 15-min. absorption values expressed in decibels. A discussion of the errors introduced by this approximate numerical integration is given in an appendix. Since the sum of logarithms is the logarithm of a product, the average absorption in decibels is not a true average and so should be interpreted in the light of the following discussion.

Fractional absorption can be defined as the quantity $1 - I_d/I_q$, where I_d and I_q are the disturbed- and quiet-day currents. If the logarithmic function giving absorption in decibels is expanded in a power series, the first term is the fractional absorption as defined above. For small values of absorption the higher-order terms in the series expansion can be neglected, and so to a first approximation, absorption in decibels is directly proportional to fractional absorption. This approximation is reasonably good for absorption ranging up to 2 db, which accounts for most of the time, even during disturbed periods as can be seen from Fig. 1.

For absorption values increasingly greater than 2 db, the linear relationship becomes more and more inaccurate since absorption in decibels goes to infinity as fractional absorption approaches unity. Thus when the average of absorption expressed in decibels is taken, the higher values have been weighted more heavily than the lower ones, so that the apparent average absorption during disturbed periods is disproportionately exaggerated over the average calculated for a normal period. However, because of the low frequency of occurrence of larger absorption values, as is shown in Fig. 1, it is considered that averaging the decibel absorption values does not introduce a serious quantitative error. A greater limitation to accuracy is probably the error in determining each month's quiet-day curve.

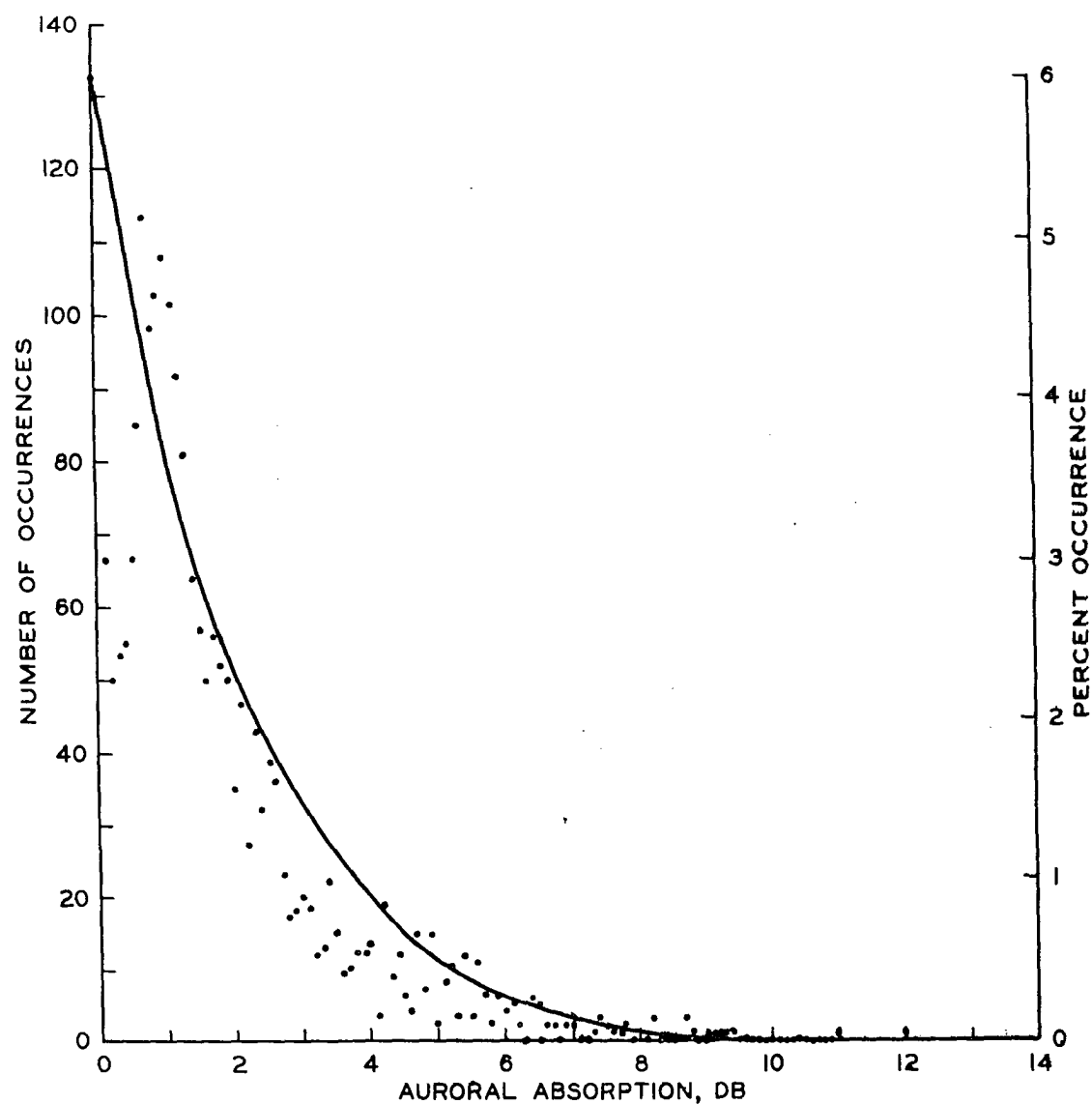


Fig. 1. Auroral absorption at College, Alaska, during February 1958. In all, 2213 points were scaled at 15-minute intervals. This figure is an example of the frequency of occurrence of auroral absorption during an extremely disturbed month. During this period the absorption was less than 2 db 63 per cent of the time.

Even more important, however, is the fact that the average of fractional absorption values has no simple physical interpretation, as is shown in the next section to be the case for the average of decibel values.

3.4.3 Physical Aspects

The physical implications of taking the average of decibel absorption values can be seen from the magnetoionic expression

$$\text{Abs(db)} \propto \int \frac{N\nu}{\nu^2 + \omega^2} dh$$

which gives the absorption of an angular observing frequency ω as an integral through the absorbing region having electron-density and collision-frequency profiles $N(h)$ and $\nu(h)$. If the absorption is assumed to be concentrated in an "effective" layer of thickness X at a particular height, this integral can be replaced by

$$\text{Abs(db)} \propto \frac{N_{\text{eff}} \nu_{\text{eff}}}{\nu_{\text{eff}}^2 + \omega^2} X$$

and

$$[A_1 + A_2 + \dots + A_n](\text{db}) \propto \frac{\nu_{\text{eff}} X}{\nu_{\text{eff}}^2 + \omega^2} [N_1 + N_2 + \dots + N_n]_{\text{eff}}$$

Thus, under this assumption, the average of decibel absorption values is directly proportional to the average effective electron density. Of course, absorption events may not all occur at the same height, so it is not strictly valid to assume that the effective collision frequency remains constant. Nevertheless, the above treatment suggests that average absorption in decibels has some physical significance in terms of average electron density, and thus also in terms of the corpuscular energy flux into the ionosphere.

3.4.4 Distribution Function

The daily absorption indices were calculated by averaging the 15-minute values over 24 hours. Because of the strong diurnal variation of absorption it was deemed necessary to sample over at least 16 of the 24 hours in order for the sample to be sufficient to give a meaningful average. Thus, because of the occasional periods during which the equipment was not functioning for more than eight hours in one day, a total of 118 out of 2,068 days (or 6%) are listed as "no data" for the period from Sept. 1, 1957 to April 30, 1963.

The distribution function of the average absorption for the remaining 1,950 days is shown in Fig. 2 for absorption values through 2.5 db, which includes 97% of the data. Almost all of the remaining 3% are PCA days with high average absorption reaching a maximum of 13 db. Quiet days, arbitrarily defined as days with $\text{abs.} \leq 0.4 \text{ db}$, occur 31% of the time, and disturbed days, with $\text{abs.} \geq 1.0 \text{ db}$, occur 27% of the time. Of course, any value greater than zero indicates some degree of disturbance, so the terms should more accurately be "relatively quiet" and "relatively disturbed".

3.5 SUPERPOSED EPOCH TECHNIQUE

The superposed epoch technique, one of the most powerful analytical tools in geophysics, has been in use for over half a century. The name "superposed epoch" was introduced by Chapman and Bartels (1940), but the technique was developed primarily by Chree (1912, 1913, 1927) and Chree and Stagg (1928) in studies of magnetic disturbances, their recurrence tendency and their relation to sunspots. Modern studies of solar-terrestrial relations still rely heavily on the method (Bell and Glazer

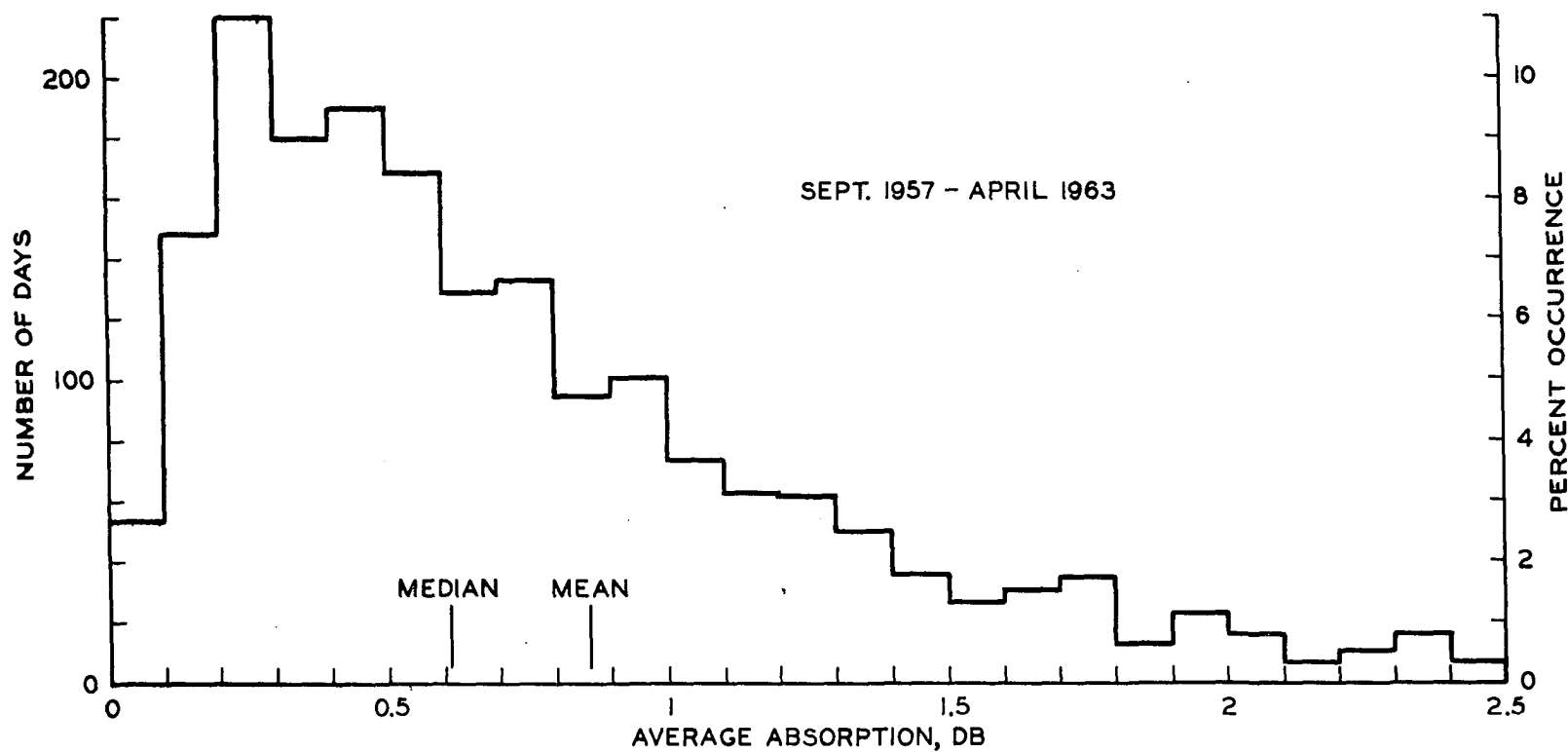


Fig. 2. The distribution of the daily average absorption as calculated for 1,950 days between September 1, 1957 and April 30, 1963.

1957, 1958; Bell, 1961; Mustel, 1961a, 1962a, 1963), and since it is employed so extensively in the present work the procedure used is outlined here.

The technique can be used in general to search for patterns in the time sequence of the variation of any quantity, and it is particularly useful for finding patterns which are obscured by larger but randomly occurring variations. Taking the basic unit of time as one day, the procedure is to first define the epoch or "zero-day" and then list the value of the variable in question for all zero-days in a vertical column with the values for the days preceding and following each zero-day in the successive columns to the left and right of the zero-day column. Thus, each row gives the time sequence of the variation during a particular event, and by taking the average of each column a new row is formed which gives the sequence for the average event. Deviations from the normal behavior which are random tend to cancel when data from a large number of events are superposed in this manner, whereas systematic departures accumulate and produce recognizable features in the graph of the average event.

This type of calculation is readily programed for a digital computer, so all of the superposed epoch computations reported in this work were performed with an IBM 1620. A separate card was punched for each day which contained the average absorption and the various solar indices for that day. These cards were then read into the machine in chronological order, and the appropriate sums were formed automatically with the averages being printed out after the last card was read in.

There has always been a problem in determining the statistical validity of the results from a superposed epoch analysis. The usual tests for significance employed in statistics are of no use since the data are

not selected from a population with a normal distribution (as shown in Fig. 2 for absorption data). Also the standard deviation in any selection is always much larger than the deviations revealed by the superposed epoch technique since the effects which are sought are swamped by randomly occurring variations of much greater magnitude. Different investigators have resolved this problem in various ways. Simon (1956) calculated the probability that his observed deviations in the average of ΣKp were a result of pure chance by transforming to a gaussian distribution, utilizing in place of ΣKp the logarithmic function $t = 9.260 (\log \Sigma Kp + 19) - 14.635$. Lincoln and Shapley (1948) judged that variations shown in a superposed epoch diagram were real if they were preserved for arbitrary divisions of the data and if they formed a more or less smooth curve. Warwick (1959) used the mean value of A_p and the frequency of values of $A_p \geq 30$ in a superposed epoch analysis and calculated the probability of chance occurrence for each of these quantities. According to her discussion, she computed these probabilities from Student's distribution, taking into account the autocorrelation of A_p for days 0,1,2,26,27,28. Bell and Glazer (1957, 1958) estimated the statistical significance of their results using the standard error of the mean Kp -sum corrected for the positive autocorrelation for 1,2,27, and 54 days. However, they point out that their criterion of significance is not exact when applied to results obtained by the superposed epoch method, and they mention that comparison of results from two or more independent samples of data provides an important test for the reality of the results of any superposed epoch analysis.

In the present work, the only evidence to be presented for the statistical significance of the results will be the regularity and similarity of patterns derived from different data samples. The weight of this sort

of evidence is readily appreciated intuitively and is generally acknowledged by other researchers.

CHAPTER 4

POLAR CAP ABSORPTION

4.1 INTRODUCTION

This chapter is concerned with PCA events and their relation to solar phenomena. As was indicated by the background discussion presented in section 2.5, various aspects of this subject have been treated by other authors, but the inconsistency of their conclusions suggests the need for further investigation of a few specific points. For example, it has not yet been possible to define the necessary and sufficient conditions for the ejection of low energy cosmic rays from the sun, nor have the problems of flare distribution on the disk and transit time of the particles been solved.

It was hoped that the greater amount of information now available on PCA events would by the sheer weight of the statistical evidence resolve some of the conflicts of earlier conclusions. However, this has not been the case. In general, the relationships brought to light by the new data have been as confusing and ill-defined as those which existed earlier. In as much as has been warranted, some of the concepts introduced by previous workers have been examined on the basis of the new body of data, but no clear understanding of any of the relations has emerged.

The only new contributions contained in this chapter are the compilation of a more extensive list of PCA events than has ever before been made available, and a treatment of the recurrence tendency in PCA events, a problem which is not known to have been dealt with elsewhere.

Since this chapter is concerned only with the solar and interplanetary control of polar cap protons, the terrestrial behavior of

PCA, including its temporal and spatial variations, are summarized here. The most striking temporal features of PCA are the seasonal and diurnal variations. The latter is controlled by the nighttime recovery of absorption which is well understood as a result of the attachment of electrons to the neutral atmospheric constituents, mainly molecular oxygen, in the absence of photodetaching sunlight. However, there is no generally accepted explanation for the fact that only half as many PCA events occur during the winter (November, December, and January) as occur during the summer or equinoxes. It was thought at one time that this seasonal effect was also produced by the effectiveness of the attachment process in the absence of sunlight, but its confirmation by events observed in the southern hemisphere ruled out this explanation. Another temporal feature, the midday recovery of absorption near the southern edge of the polar cap, was described by Leinbach (1962b) and interpreted in terms of changes in the effective cutoff energy for solar particles as a function of time and location. PCA has a relatively abrupt onset since it builds up to high absorption values within a few hours but then requires a period of days to decay in an approximately exponential fashion. The typical length of a PCA event is 3 to 4 days. The defining spatial characteristic of PCA is its uniformity over the entire sunlit polar cap at magnetic latitudes higher than about 60-65°. This region contracts during the initial phase of magnetic storms and expands during the main phase, a behavior which Leinbach (1962b) also attributes to changes in the effective cutoff energy.

4.2 DESCRIPTION OF RECENT EVENTS

The purpose of this section is to describe recent PCA events which previously have been either overlooked or mentioned only briefly in the literature. These events will not be dwelt on since it is not the purpose of this chapter to treat the terrestrial aspects of PCA. The main aim of presenting data on these events is to verify their existence and thus justify including them in the list of events in section 4.3. It was intended that the Antarctic f-min data be included for all of the events, but data after December 1961 were not available at the time of this writing. In Figs. 3 through 9 the arrows indicate the beginning (up) and end (down) of civil twilight (i.e. sunlight at 35 km).

September 1961 - Three events occurred in this month, commencing on the 7th, 10th, and 28th. The latter event, which was the largest, has been discussed by others and so will not be referred to here. Solar protons were observed directly by Krimigis and Van Allen (1963) starting at 0000 U.T. on the 7th and reaching a maximum around 1500 U.T. the same day, which agrees with the time of maximum absorption at Resolute Bay as can be seen in Fig. 3. It can also be seen from Fig. 3 that this event was very weak and of short duration, having nearly disappeared by the end of the 8th. This event was not detectable on the ground before about 0500 U.T., and the absorption was too weak to be clearly recognized as PCA until about 1000 U.T. PCA can be seen in Fig. 4 to commence at about 2000 U.T. on September 10, about 30 minutes earlier than the first protons were detected by Krimigis and Van Allen (1963). This was a moderate sized event as seen on the ground, and the maximum flux of protons measured by Krimigis and Van Allen was 86 particles/cm² sec for $E > 23$ Mev compared to 54 particles/cm² sec for the same

0000 SEPT. 7, 1961

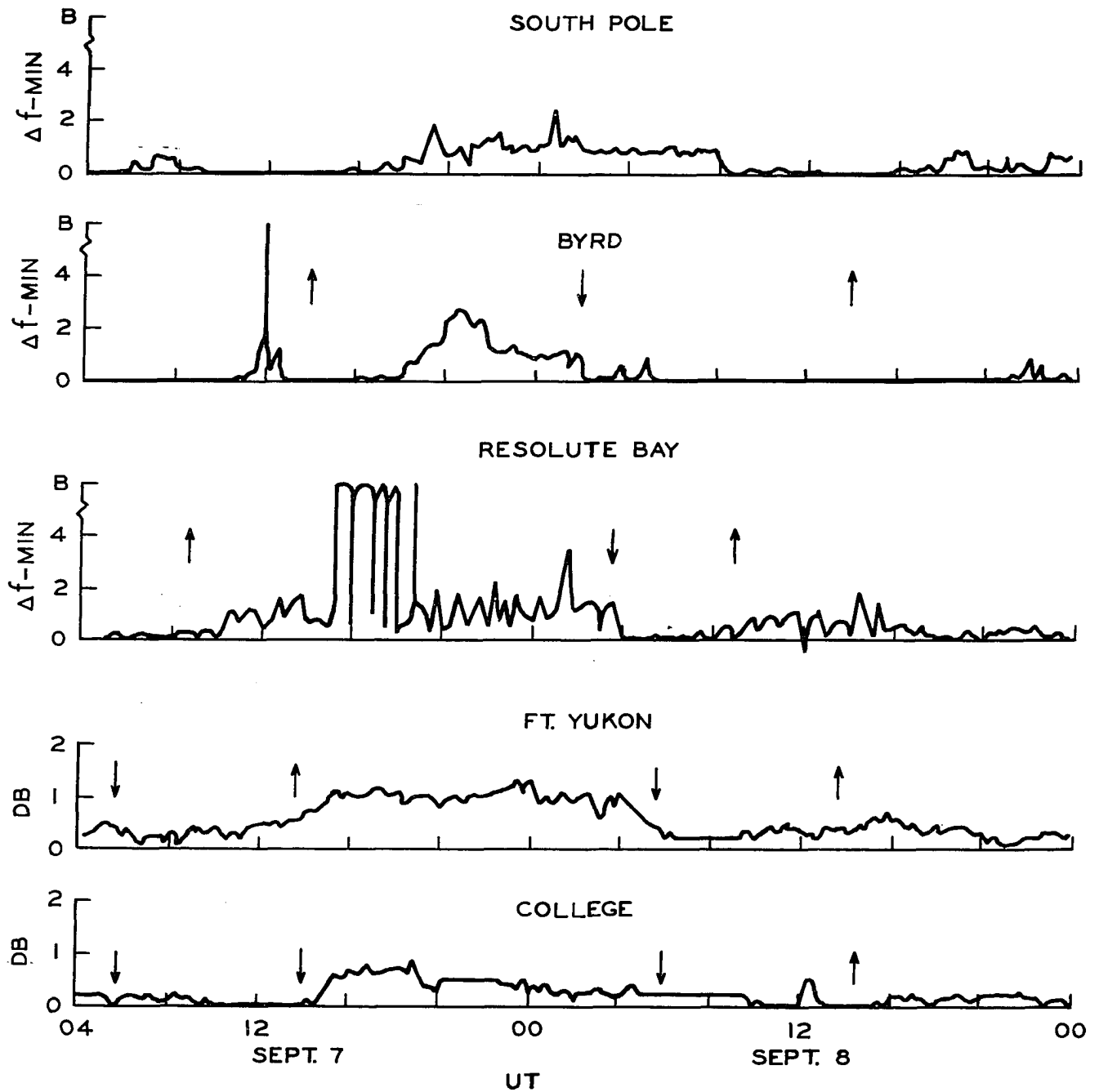


Fig. 3. The PCA event of September 7, 1961. The atmosphere above 35 km was continuously sunlit at the South Pole.

2000 SEPT. 10, 1961

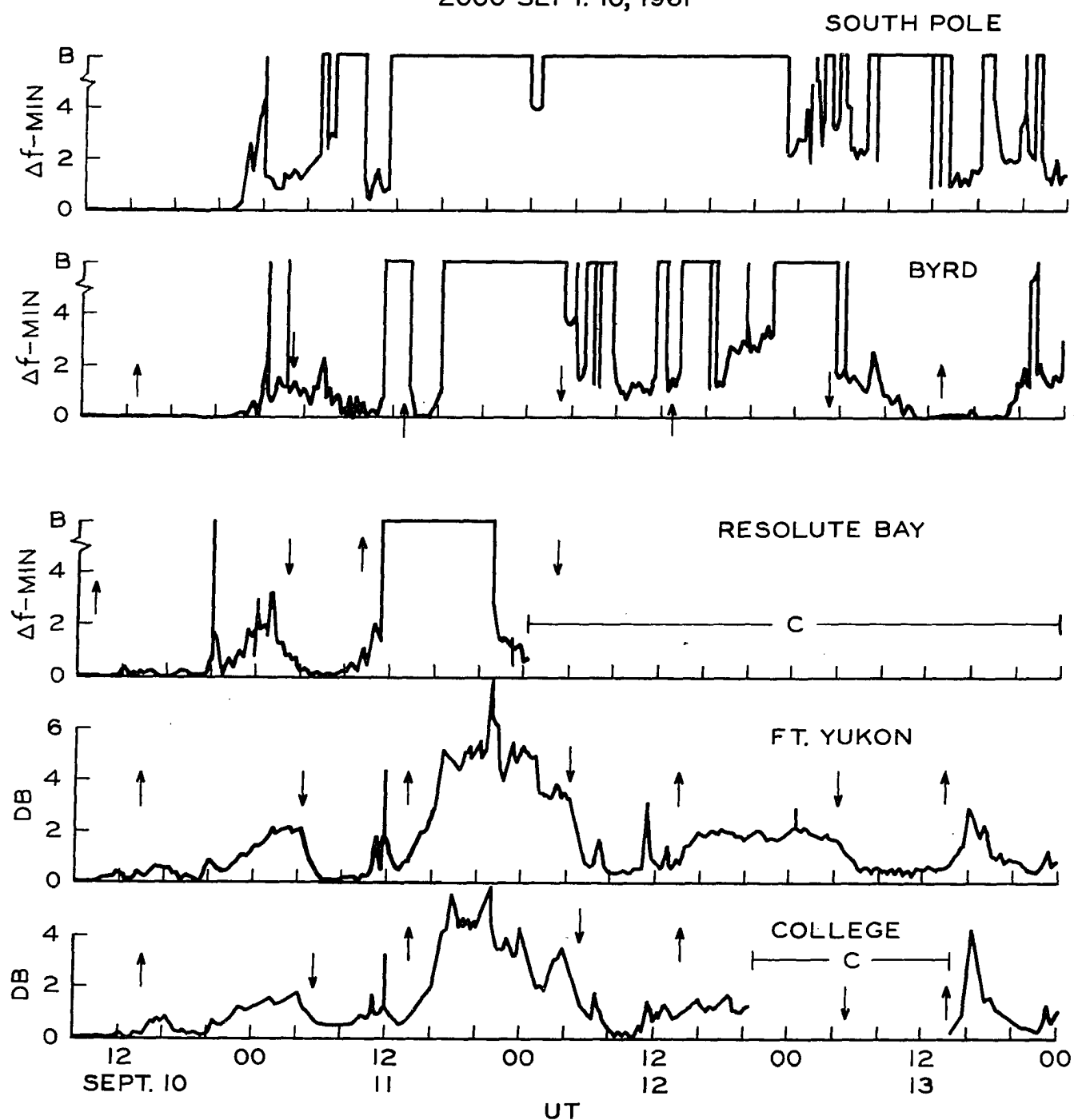


Fig. 4. The PCA event of September 10, 1961. The atmosphere above 35 km was continuously sunlit at the South Pole.

energies measured during the Sept. 7 event. Malitson (1963) lists 2300 U.T. on Sept. 10 as the onset time quoting a private communication from Harold Leinbach.

November 10, 1961 - The VLF propagation effects of this event were discussed by Bates (1962), and he listed the onset time as 1600 U.T. However, the high latitude stations in Fig. 5 show that PCA had begun by at least 1500 U.T. on Nov. 10.

February, 1962 - Two events occurred in this month commencing at about 2030 U.T. on Feb. 1 and at some time earlier than 1200 U.T. on Feb. 20. Zmuda, Pieper, and Bostrom (1963) reported that the satellite Injun 1 detected solar protons during Feb. 2-7, 12, and 20-23. They measured a maximum flux (in the energy range 1-15 Mev) of 2600 protons/cm² sec ster on Feb. 2, 20 protons/cm² sec ster on Feb. 12, and 70-100 protons/cm² sec ster on Feb. 20-23. Since there was no significant absorption detectable during Feb. 12, 20 protons/cm² sec ster is a lower limit for a flux which can produce a measurable amount of PCA. Goedeke and Masley (1963) reported the presence of weak absorption on Feb. 22 and 23 at McMurdo in the Antarctic. The Feb. 1 event can be seen from Fig. 6 to be a moderate but clear cut PCA event beginning at 2030 U.T. at Resolute Bay, but the Feb. 20 event was so weak it was barely detectable and the precise onset time could not be determined.

October 23, 1962 - Absorption beginning at 1730 U.T. on October 23 at McMurdo was reported by Goedeke and Masley (1963). This was a very weak event at Resolute Bay as can be seen in Fig. 7, and the maximum absorption at McMurdo was only 1 db. This event would have gone unnoticed except for the Antarctic riometer observations. Actually, there is some doubt as to whether this is truly a PCA event or is only a

1500 NOV. 10, 1961

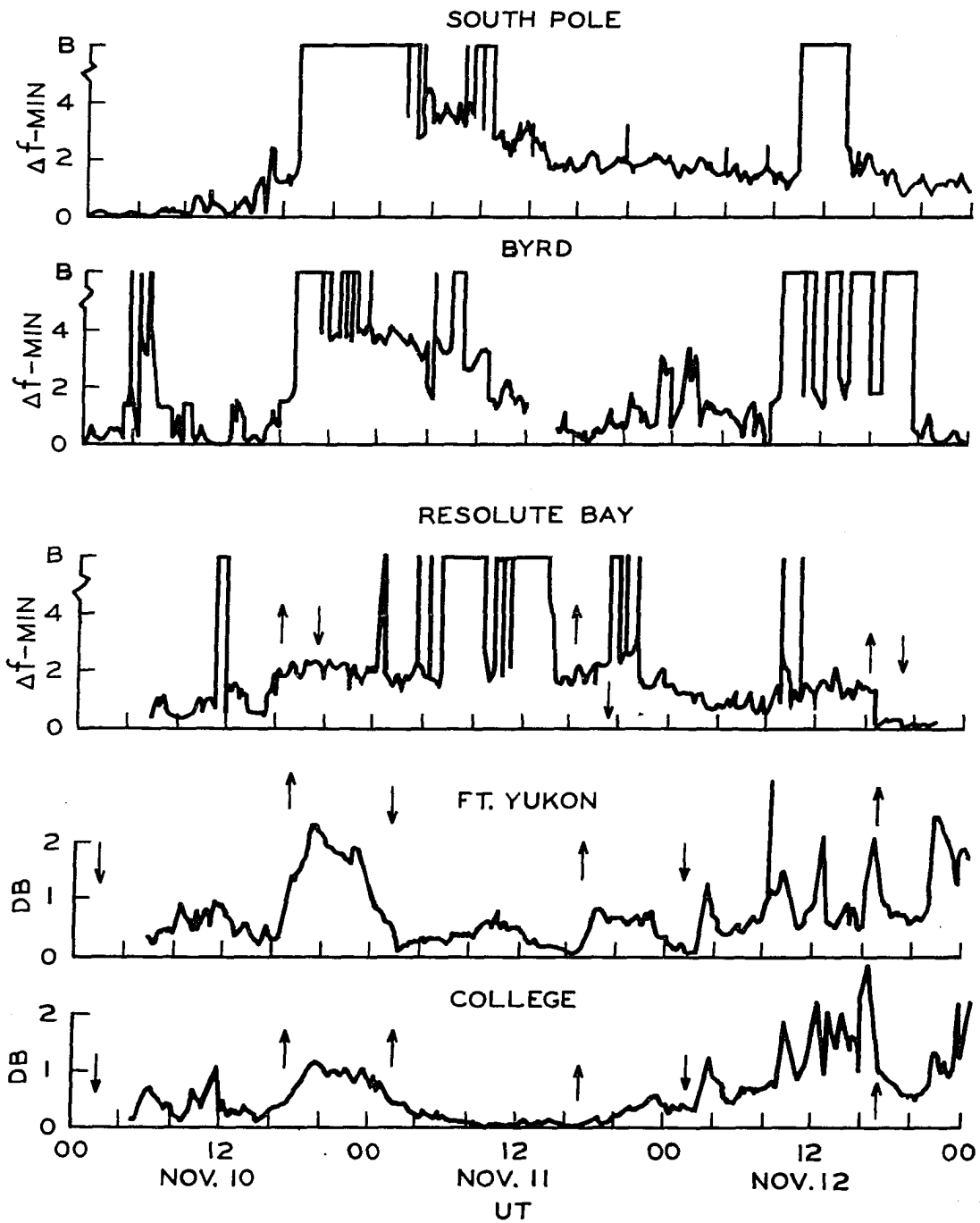


Fig. 5. The PCA event of November 10, 1961. The atmosphere above 35 km was continuously sunlit at the Byrd and South Pole stations.

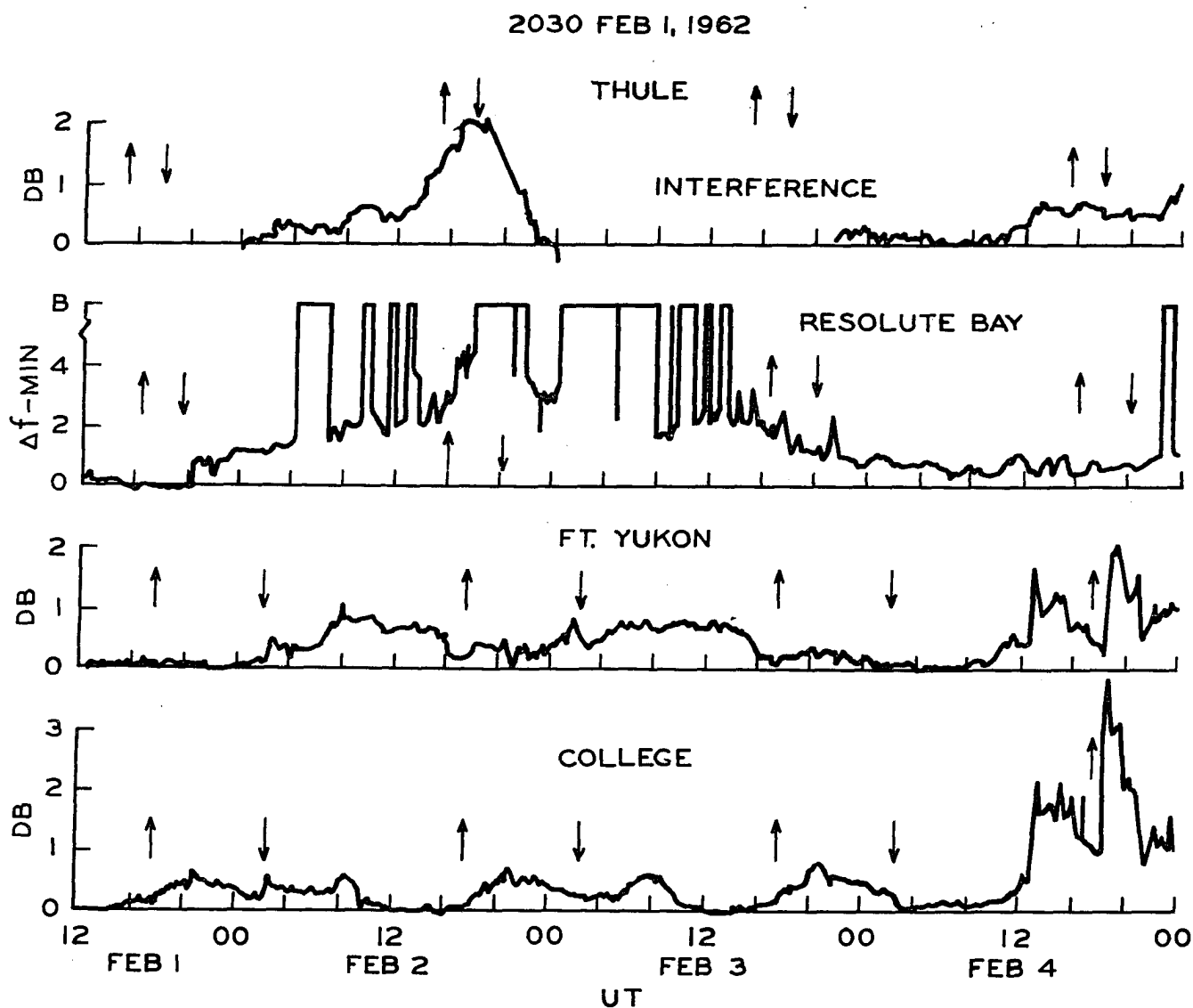
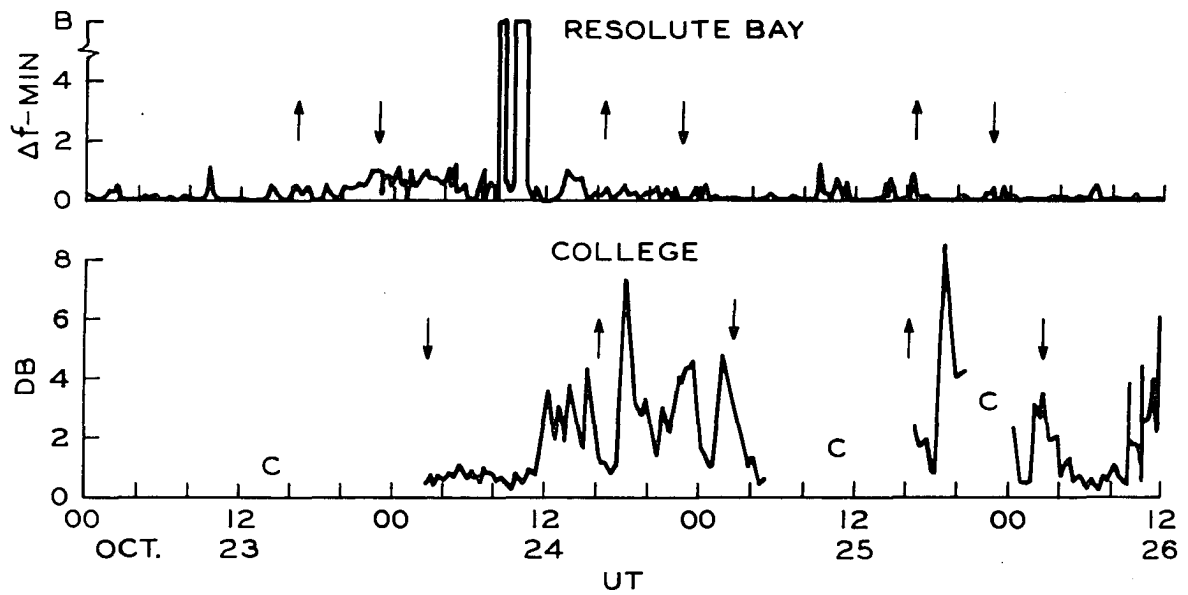


Fig. 6. The PCA event of February 1, 1962.

1730 OCT. 23, 1962



1842 FEB. 9, 1963

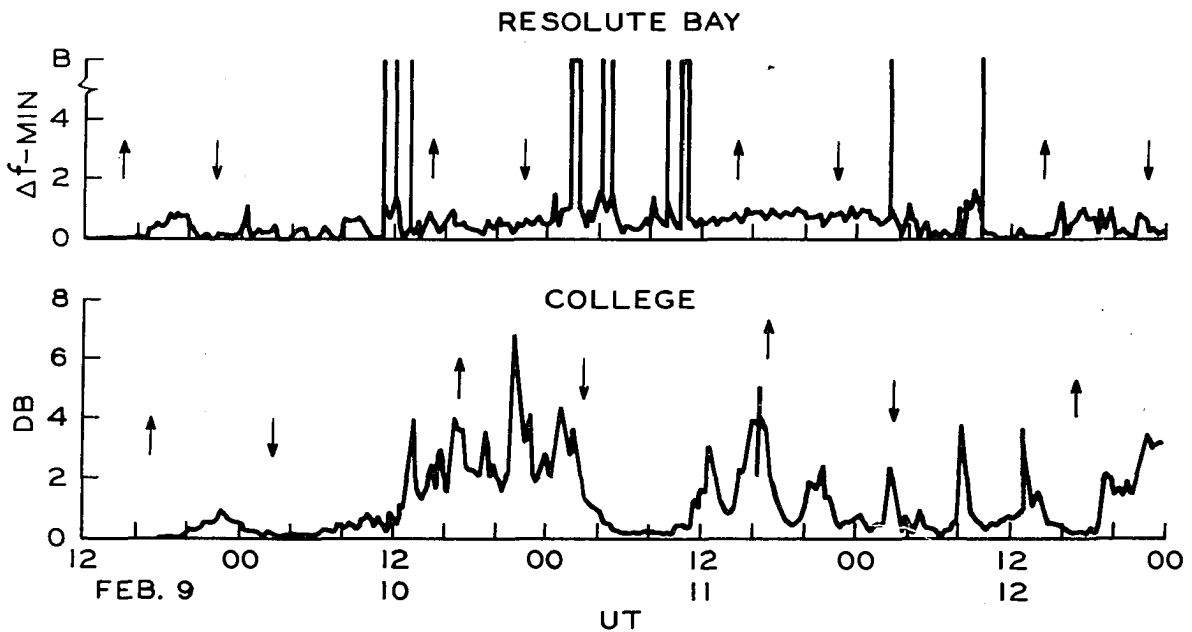


Fig. 7. The PCA events of October 23, 1962 and February 9, 1963. These were very weak events and possibly do not merit the name "PCA event" (see discussion in text).

strong auroral event which had some high latitude effects. The doubt is supported by the fact that this event falls in the middle of what is shown in Fig. 20 in the next chapter to be a well developed sequence of M-region disturbances. However, energetic solar protons were observed by Mariner 2 and Explorer 12 during this event which makes a stronger case for a flare-associated origin and classification as PCA. Probably both types of particle streams were present, and the confusion has resulted because the flux of energetic solar protons was too small to produce the amount of ionization uniformly over the polar caps that is the distinctive feature of most PCA events.

February 9, 1963 - Another very weak event was observed to begin at McMurdo at 1842 U.T. on Feb. 9 (Masley, private communication), but as can be seen in Fig. 7 this event, like that in October 1962, was at best barely detectable in the northern hemisphere. Again there is some doubt as to whether this is truly a PCA event or is only a strong auroral event which had some high latitude effects. This event can be seen in Fig. 20 in the next chapter to occur in the same sequence of M-region disturbances as the supposed October 1962 event.

April 15, 1963 - Fig. 8 shows a well defined moderate sized PCA event beginning at 1200 U.T. on April 15 at Resolute Bay. This same onset time was also recorded by the McMurdo riometer (Masley, private communication).

September, 1963 - Three events occurred during this month commencing on the 14th, 21st, and 26th. Fig. 9 shows the Resolute Bay f-min data in which all three events are apparent; but in order to determine accurate onset times it was necessary to refer to the McMurdo riometer data which were kindly supplied by Masley (private communication). The

1200 APRIL 15, 1963

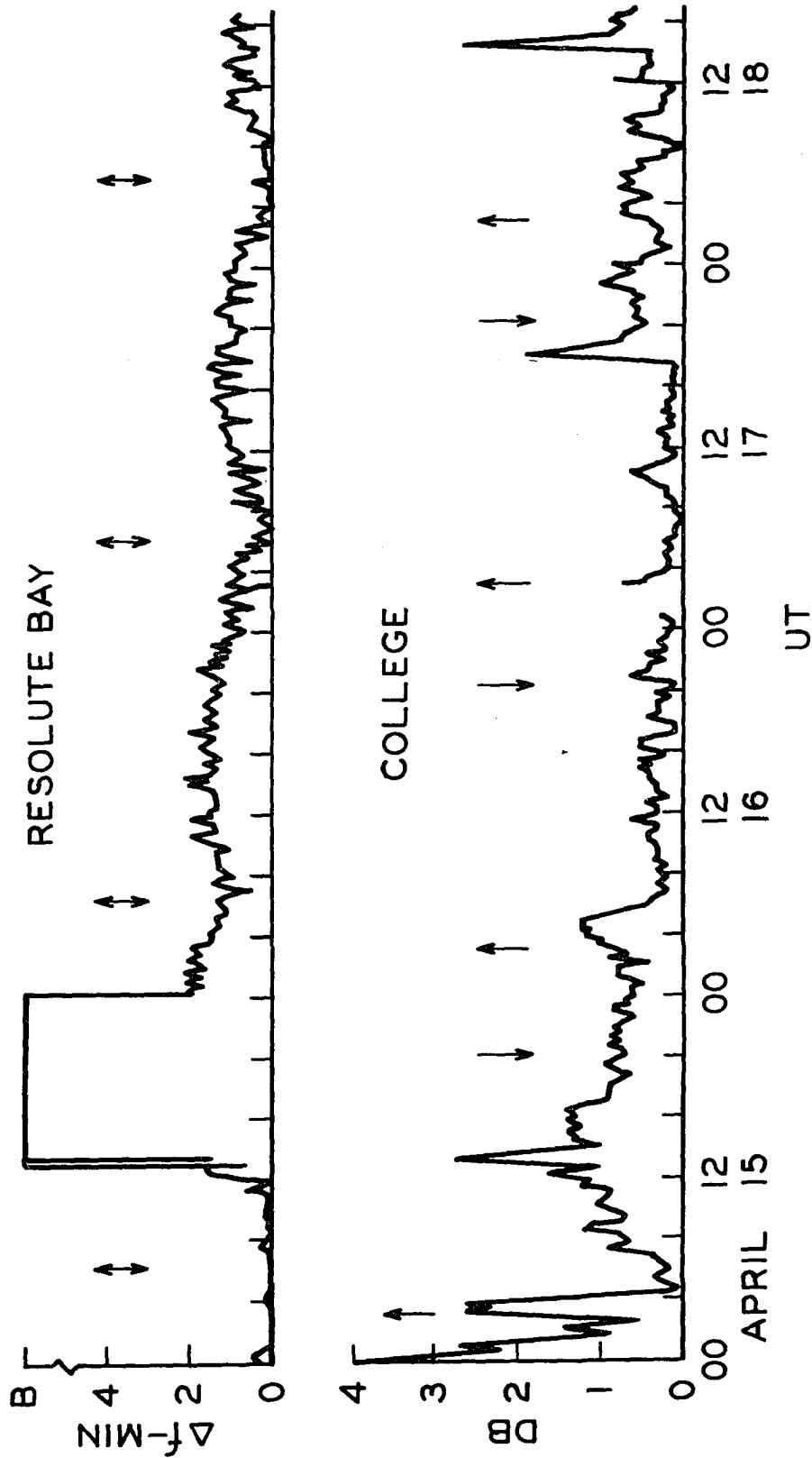


Fig. 8. The PCA event of April 15, 1963.

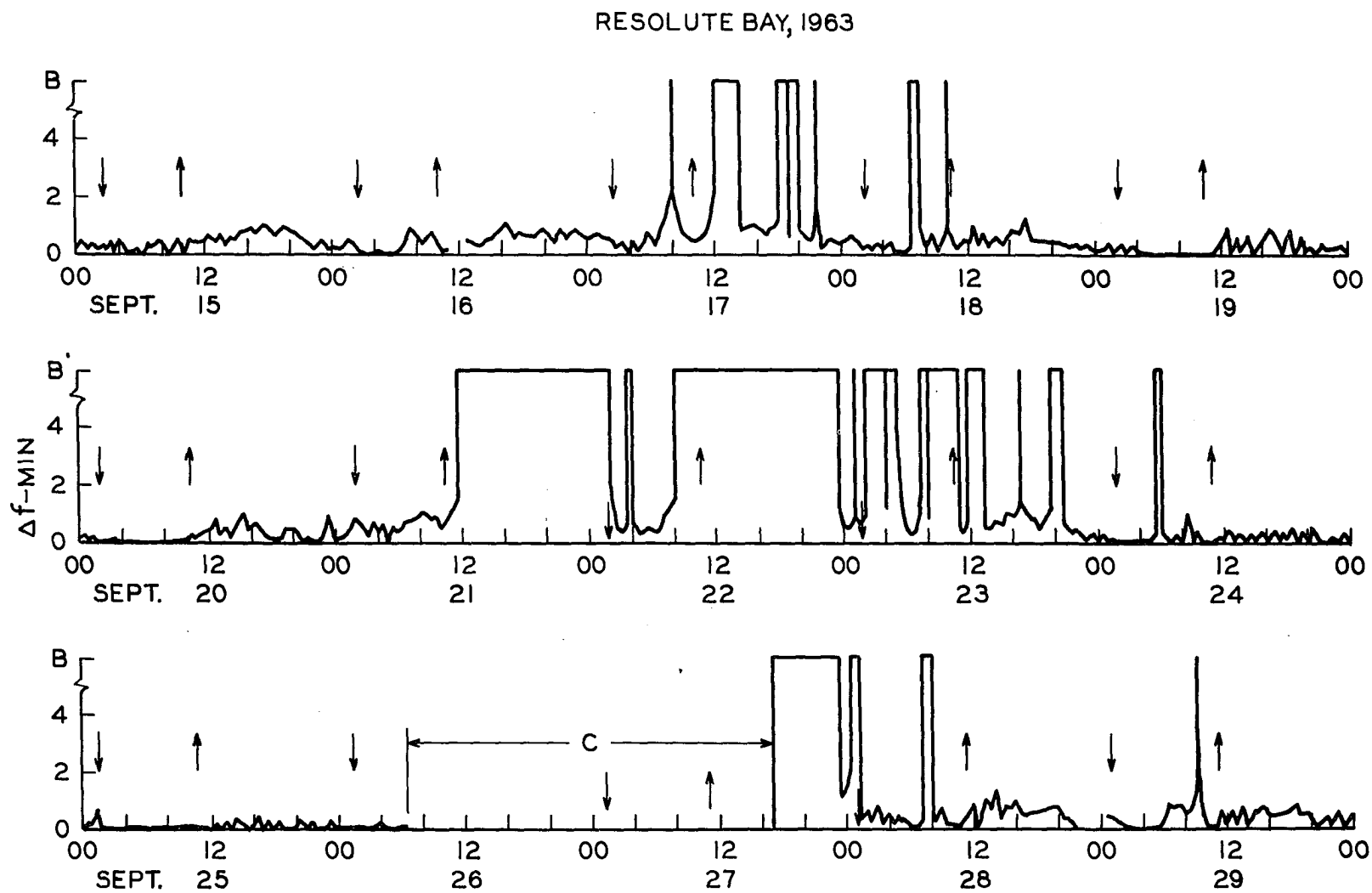


Fig. 9. The three PCA events of September 1963 commencing on the 14th, 21st, and 26th.

first event was weak, but the onset is believed with reasonable certainty to have taken place at about 0000 U.T. on the 14th. The second and third events were both quite strong and the onsets were observed to take place at 0020 U.T. on the 21st and 0745 U.T. on the 26th, respectively. The flare responsible for the PCA event on the 21st had some of the most dramatic features ever recorded. Occurring near the center of the disk (N10 W09) and starting at 2351 U.T. on the 20th, it was well recorded by the Lockheed flare patrol in 3 colors, centered on $H\alpha$ and displaced $1/2 A$ to each side of $H\alpha$ (Harry Ramsey, private communication). Some of the more unusual features included a bright spray-like ejection and a giant dark surge preceding the flare, and a high speed disturbance was observed during the flare with the appearance of a ripple traveling at high velocity across the disk outward from the flare.

4.3 LIST OF POLAR CAP ABSORPTION EVENTS

The following is a reasonably complete list of all PCA events which have been detected since January 1957. With the exception of the events which have occurred since the end of 1960, no effort has been made to check the original data, all results being taken from the sources indicated. Events with no referenced source are discussed in section 4.2 where they are described on the basis of the available high latitude riometer and ionosonde f-min data. Some of these events have not been reported previously.

A total of 135 separate events are listed below, but it is quite probable that in several instances different observers have recognized and reported the onset of a new event when in reality they were seeing an event which had already been in progress for several hours. It is also possible that in some instances auroral absorption has mistakenly

been identified as PCA. Thus, the actual number of distinct events may be closer to 100 or 110 than to 135.

When the onset times reported by the various investigators have differed by only a few hours, only one event is listed, and the earliest and latest reported times are given. However, when it is felt that there is a reasonable possibility that more than one event took place, all are listed although, of course, it is recognized that all might not be discrete events.

This inability to identify positively the commencement of separate PCA events is the result of a combination of several factors, only the most important of which are mentioned here. A principal source of confusion lies in the fact that a single active region on the sun's surface will frequently generate low energy cosmic rays in multiple bursts with varying time durations, particle densities, and energy spectra. These bursts flood interplanetary space with particles which arrive at the earth in waves or streams which are then diverted into the polar regions by the earth's magnetic field. The superposition of the effects of the bombardment of the polar ionosphere by these particle streams sometimes causes the onset of new PCA events to be obscured by the continuing effects of preceding events.

In addition to the difficulty of sorting out multiple events, there is also the problem that, because of differences in sensitivity, the starting times of an event may differ by several hours when observed by different techniques. In particular, ionosonde f-min is sensitive to ionization at greater heights, and thus is a better indicator of the influx of low energy protons, than the absorption which is recorded with riometers or the signal intensity received on forward scatter

circuits over the polar cap. Besides the differences in sensitivity, a difficulty in comparing observations made all over the world is introduced by the strong dependence of riometer and ionosonde data on the photodetachment of electrons from negative ions by sunlight. Thus, a station on the dark side of the earth will tend to miss the onset of an event and will not discern its presence until sunrise.

A further complication in reconciling the onset times as determined from different parts of the world is the apparent anisotropy in the flux of solar cosmic rays during the early stages of a PCA event. As an indication of the great variation in the onset times which have been reported, the earliest and latest times are listed in the table. No latest onset is listed if there is no disagreement about the earliest onset, and if more than two sources agree on a time, an asterisk is listed in place of the references. If two sources agree, both are referenced only if they seem to be independent.

Of the 135 events listed, the number reported by each of the major sources is as follows:

B:41	M:54
Ge:33	N:40
G:38	S:46
JP:37	WH:47
K:39	OH:22

As more people become interested in PCA events and as their observing techniques become more varied and sensitive, the number of events observed in any extended period of time is likely to be much greater than would previously have been expected. Since solar flares expel many clouds of protons with energies and densities which make them only

marginally detectable with present techniques, it is quite plausible that there are many more which are as yet undetectable.

Because much of the labor on this project was completed before the paper by Gregory (1963) was published, those PCA events which have been reported by him alone have not been included in the studies described elsewhere in this work. Using the backscatter sounding technique at 2.3 mc/s at a geomagnetic latitude of 79°S, he noted many weak events which have not been reported elsewhere. The omission of his events does not mean that they are less reliable than others, but that it was not practical to repeat the many analyses in which the list of PCA events was used. However, it has been determined that the inclusion of these events will not significantly alter any of the conclusions which are reached.

The publications which were used in compiling this list of PCA events are referenced by the following symbols:

A: Anderson (1964)
B: Bailey (1962)
Ba: Bates (1962)
Be: Besprozvannaya (1962)
Bo: Bookin (1962)
CJM: Collins, Jelly, and Matthews (1961)
DLP: Dvoryashin, Levitskii, and Pankrator (1961)
EHO: Egeland, Hultqvist, and Ortner (1962)
G: Gregory (1963)
H: Hill (1962)
HG: Hakura and Goh (1959)
JC: Jelly and Collins (1963)
JP: Jenkins and Paghis (1963)
K: Kahle (1962)
KVA: Krimigis and Van Allen (1963)
M: Malitson (1963)
N: Noyes (1962)
OH: Obayashi and Hakura (1960a, 1960b)
PS: Piggott and Shapley (1962)
R: Rourke (1961)
S: Sinno (1961)
WH: Warwick and Haurwitz (1963)

LIST OF PCA EVENTS
(January 1957-September 1963)

Year	Month	UT Day	UT Earliest Reported Onset	UT Latest Reported Onset	Sources
1957	Jan	20	1500B	1500(21)CJM	B, Be, CJM, DLP, M, S, WH
	Feb	21	1800JC	0205(22)DLP	DLP, JC
		22	0500S	1600Be	Be, JP, S
	Apr	2	2300Be		
		3	1100JP	1200(4)CJM	B, CJM, JP, M, WH
		11	1300Be		Be
		12	1700JC		JC, JP
	May	19	0200M	0300Be	Be, M
		9	0500Be		Be
		19	0200*		K, S, WH
	June	19	2215S	2300JP, Be	Be, JP, S
		20	1800CJM		CJM
		21	1300B		B
		22	0530B	1000K	B, CJM, K, M, WH
		28			Be
	July	1	000QH	1200CJM	CJM, H
		3	0815DLP	1100S	B, Be, Bo, DLP, H, HG, JP, K, M, N, OH, PS, S, WH
	Aug	24	1000PS	2100Bo, JP	B, Bo, JP, K, M, N, OH, PS, S, WH
		25	000H	0100PS	H, PS
		28	1500H	2100PS	H, JC, PS
		9	1500JC	0000(10)H	Be, H, JC, K, M, N, PS
		27	1400CJM		CJM
		28	0400PS	0500(29)OH	A, Be, Bo, DLP, H, OH, PS
		29	0030B	0500*	B, HG, M, OH, PS, S, WH.
		29	1100K	1330B	B, HG, K, M, N, WH
		31	1340A	1530B	A, B, H, K, M, N, S, WH
	Sept	1			OH
		2	1500K	2100HG	B, Bo, H, GH, K, M, N, OH, WH
		3	1500H		H
		10	0600H		H
		12	0200PS	2315HG	B, Be, Bo, DLP, H, HG, JP, K, M, N, OH, PS, S, WH
		18	2000Be	0300(19)H	Be, DLP, H, PS
		20	0300H		H
		21	1100K	1930*	B, H, HG, K, M, N, PS, S, WH
		22	1000PS	1200H	H, PS
		26	2100*	2315*	Be, Bo, H, K, M, N, OH, PS, S, WH
	Oct	5	0300H		H
		20	1300K	2200JC	Be, Bo, JC, K, PS
		21	0000H	0915DLP	B, DLP, H, HG, JP, K, M, N, OH, S, WH
	Nov	4	2300Be	0300(5)DLP, H	Be, DLP, H, JC, PS
		24	0200PS		PS
		26	1200H		H
	Dec	17	0300H	1600PS	H, JP, PS, R
		28	2300JC	0000(29)H	H, JC, PS

LIST OF PCA EVENTS (Cont'd.)

Year	Month	UT Day	UT Earliest Reported Onset	UT Latest Reported Onset	Sources
1958	Jan	25	1600JC		JC
	Feb	10	0500Bo	2400HG	B,Be,Bo,CJM,DLP,HG,K,M,N,OH,PS,S,WH
	Mar	11	0300PS	1000S	Be,JC,PS,S
		14	1500PS	2200CJM	Be,CJM,JP,PS,S
		17			Be
		21			JC
		23	1830B		B,Bo,M,WH
		25	0300HG	1545PS	B,Be,CJM,DLP,HG,JC,K,M,N,OH,PS,S,WH
		31	1600JP		JC,JP
	Apr	10	0800Be,JP	1400CJM	B,Be,CJM,HG,JP,K,M,N,OH,PS,S,WH
	June	4	2300Be	0815(5)PS	Be,DLP,JC,PS,S
		6	1345HG		Bo,HG,M,N,OH
	July	7	0100K	0600B,CJM	B,Be,Bo,CJM,DLP,HG,JP,K,M,N,OH,PS,S,WH
		29	0400Be	0500B	B,Be,Bo,DLP,JP,K,M,N,OH,S,WH
	Aug	16	0600*	1200JM	B,Be,Bo,CJM,DLP,HG,JP,K,M,N,OH,PS,S,WH
		21	1400Be	1615DLP	Be,DLP,K,M,N,S,WH
		22	1400Bo	1600	B,Bo,CJM,DLP,HG,K,M,N,OH,PS,S,WH
		26	0100*	0300PS	Bo,CJM,DLP,HG,JP,K,M,N,OH,PS,S,WH
	Sept	22	0530PS	1600Be	B,Be,Bo,HG,JP,K,M,N,OH,PS,S,WH
1959	Jan	26	1500JP		JC,JP
	Feb	13	0900Be	1400JC	Be,JC
	May	10	2300EHO,WH	0300(11)Be	B,Be,CJM,DLP,EHO,JP,K,M,N,OH,S,WH
	June	9			JC
		13	0800Be	1300M	Be,JC,K,M,N
	July	9	2000Be		Be
		10	0400EHO,WH	1000CJM	B,CJM,DLP,EHO,K,M,N,S,WH
		14	0445K	0800B	B,CJM,EHO,K,M,N,S,WH
		16	2200EHO	2250*	EHO,K,N,S,WH
		17	0200M	0600JP	B,CJM,JP,M
	Aug	18	1045K	1200DLP,JC	Be,DLP,JC,K,N
		19	0900JP	1000S	JP,S
	Sept	2	0400B		B,EHO,M,N,WH
	Oct	6			M

LIST OF PCA EVENTS (Cont'd.)

Year	Month	UT Day	UT Earliest Reported Onset	UT Latest Reported Onset	Sources	
1960	Jan	11	2200G	0700(12)B	B,G	
		13	1600S	2000JC	JC,S	
		16	0300G		G	
	Feb	7	0700G		G	
		15	1000G		G	
		29	1600G		G	
	Mar	10	1800G		G	
		17	1800G		G	
		29	0800B	1100G	B,G,	
	Apr	30	0930K	2000B	B,JP,K,S	
		31	0300WH	1400EHO	EHO,K,M,N,S,WH	
		1	0930B	1005EHO	B,EHO,G,JP,K,M,N,S,WH	
		5	0400G	1000JP	B,EHO,G,JP,K,M,N,S,WH	
		15	1000G		G	
		28	0200B	1000JP	B,EHO,G,JP,K,M,N,S,WH	
		29	0200G	0700JP	B,EHO,G,JP,K,M,N,S,WH	
		May	4	1030B	1100JP	B,EHO,G,JP,K,M,N,S,WH
			6	1400JP	0124(7)EHO	B,EHO,G,JP,K,M,N,S,WH
			9	0800G		G
	13		0615K	0800B,EHO	B,EHO,G,JP,K,M,N,S,WH	
	17		1500G		G	
	June	26	1000G		G	
		1	1400G	2000(3)JC	EHO,G,JC	
		15	1000G		G	
		25	1700G		G	
		27	2300G		G	
		28	1900G		G	
		Aug	12	0000G	1315(14)S	G,S
	26		1000G		G	
	Sept	3	0500B	2300EHO	B,EHO,G,JC,K,M,N,S,WH	
		25	2100G	1328(26)M	G,JC,JP,K,M	
	Oct	3	1600G		G	
		29	1200G		G	
	Nov	10	1800G		G	
		11	0400G		G	
		12	1400*	1500S	B,G,JP,K,N,S,WH	
		14	2200G		G	
		15	0500S,WH	1200JP	B,G,JP,K,M,N,S,WH	
		19	1200G		G	
		21	0000G	1300JP	B,G,JP,M,N,S,WH	
		Dec	6	0500G		G

LIST OF PCA EVENTS (Cont'd.)

Year	Month	UT Day	UT Earliest Reported Onset	UT Latest Reported Onset	Sources
1961	July	11	2200L	2400M	L,M
		12	1800JP	0700M	JP,L,M,WH
		15	1545WH		M,WH
		18	1135WH	1200JP,L	JP,L,M,WH
		20	2200L	0300(21)M	L,M,WH
	Sept	7	0000KVA		
		10	2000	2300M	
		28	2300JP,L	2335WH	JP,L,M,WH
	Nov	10	1500	1600Ba	
1962	Feb	1	2030		
		20	<1200		
	Oct	23	1730		
1963	Feb	9	1842		
	Apr	15	1200		
	Sept	14	0000		
		21	0020		
		26	0745		

*Indicates more than 2 sources agree on this time.

4.4 RECURRENCE TENDENCY

If a PCA event is recorded on any particular day, it can be seen from the list of events given in section 4.3 that there is about a 20-25% chance that another event will occur on the next day, and then a third on the next. This clustering of events might result from a mistaken identification of two or more occurrences when only one actually took place, but it undoubtedly also indicates that activity is maintained at a high level on the sun for a period of 3-4 days during which protons are ejected in pulses which are separated by about 10-30 hours.

In order to determine whether or not PCA events tend to recur periodically after longer time delays, the number of days between PCA onsets was calculated for all events separated by fewer than 100 days. This was done by considering each PCA onset in turn and calculating the time intervals which elapsed before successive new onsets were observed. The results are given in Fig. 10. It can be seen from these results that there is a tendency for PCA events to recur after 35 days, and then again after 70 days. There are numerous small peaks in this frequency of occurrence diagram, but it is difficult to tell which if any of them are significant.

If a PCA event is recorded on any particular day, Fig. 10 expresses only the relative probability of occurrence of another PCA event after a given number of days, but Fig. 11 shows the effect of both the magnitude of the absorption and the period of recurrence. It can be seen from Fig. 11 that a distinct peak occurs at 33 days and a much smaller secondary peak at 68 days.

In comparing Figs. 10 and 11 the most striking feature is that the broad peak at about 35 days and the more sharply defined peak at 70 days shown in Fig. 10 generally correspond to the 33 and 68 day peaks in Fig. 11.

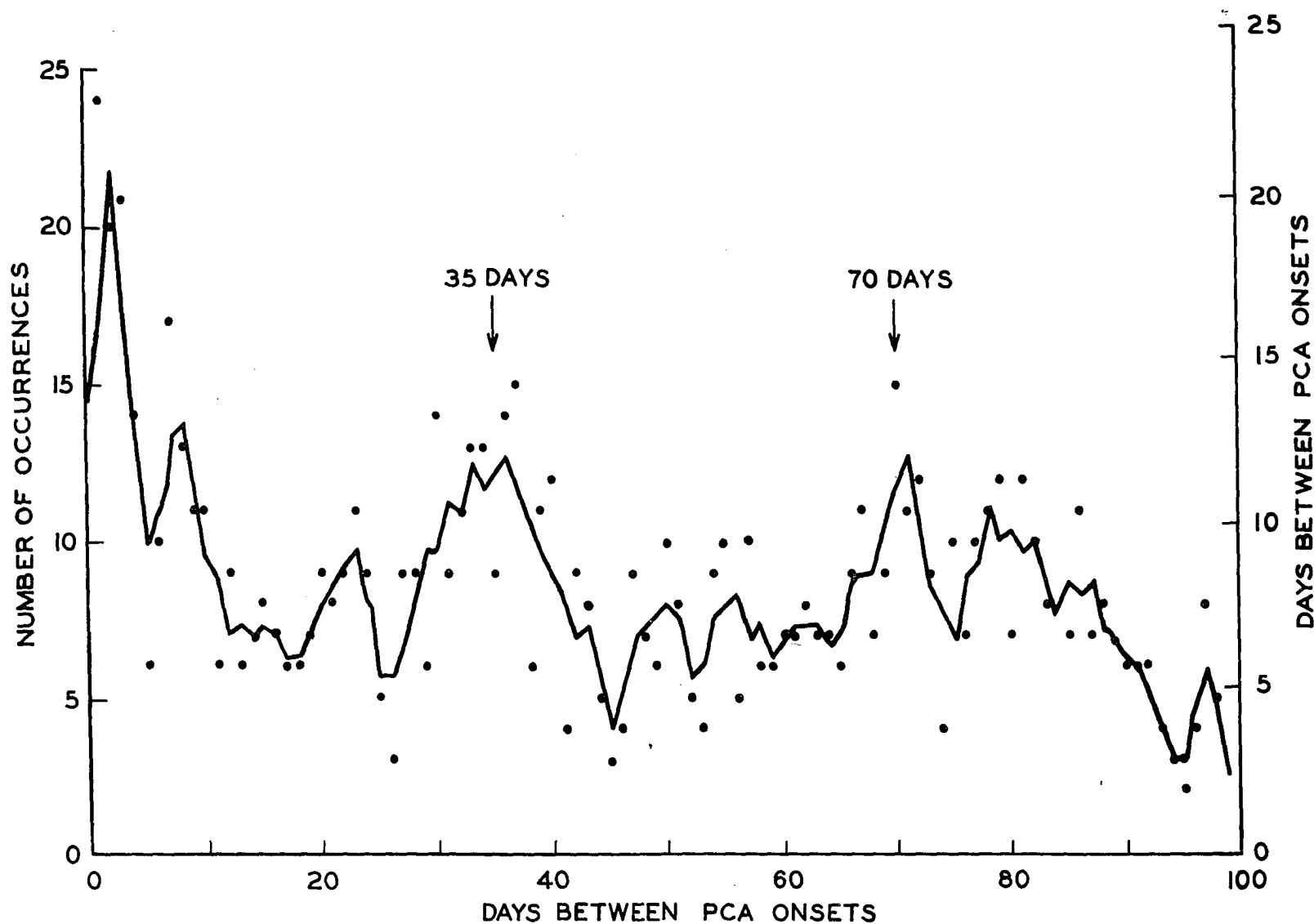


Fig. 10. The number of PCA onsets as a function of the time elapsed since a previous onset. The points plotted indicate the actual number of times a given separation interval was found using 105 events from Jan. 1957 to Feb. 1962. Some of the intervals listed as 1 day are actually < 24 hours, and likewise for all other days. Thus, the curve drawn through the points shows the three day running mean which compensates somewhat for the effect that, for example, intervals listed as 35 days may have actually been closer to 34 or 36.

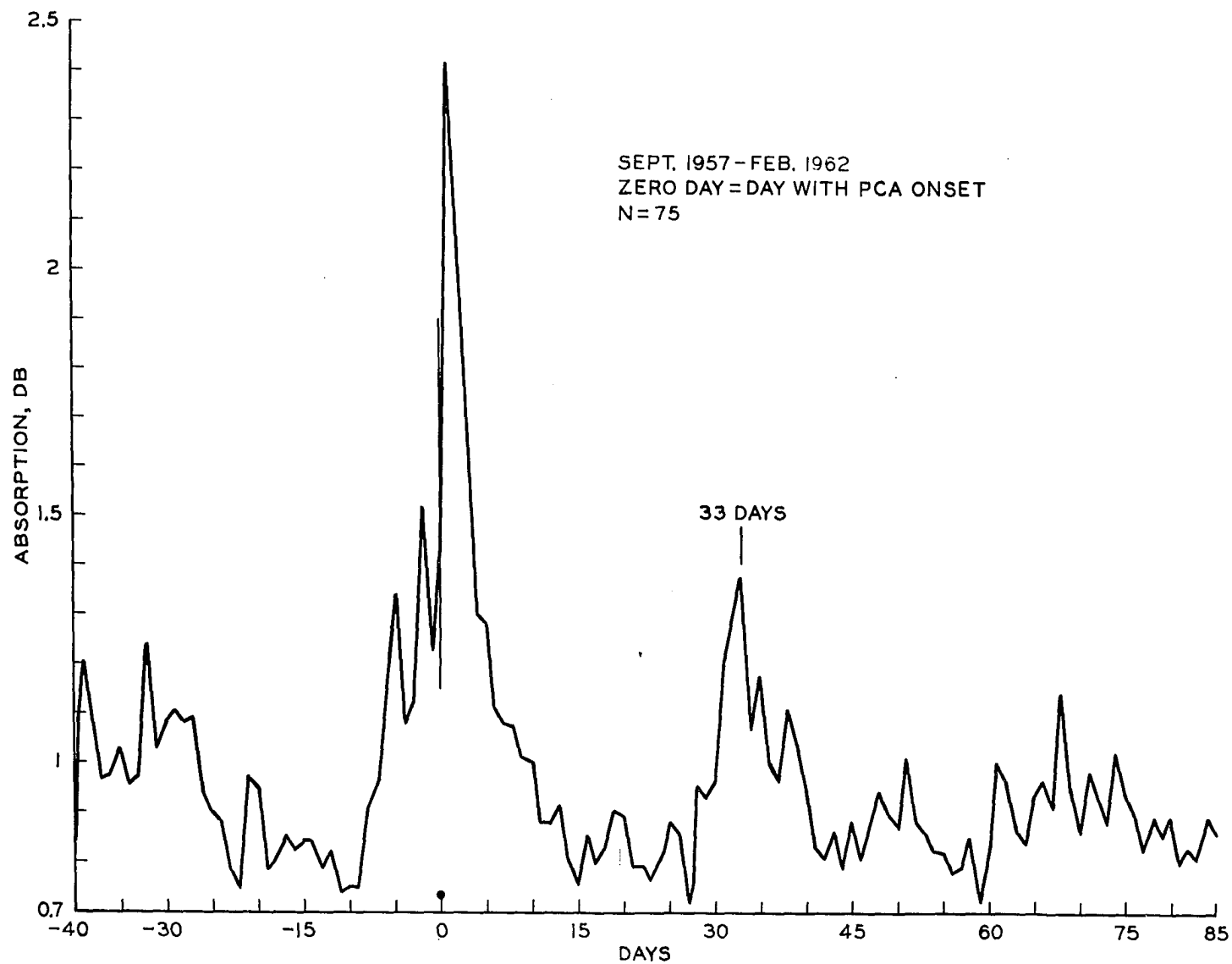


Fig. 11. The recurrence tendency of PCA as determined by the superposed epoch technique using the College riometer data.

Although these peaks do not coincide exactly, the agreement is certainly within reasonable limits considering the smaller number of events which could be used for the superposed epoch analysis in Fig. 11 and also the general unsuitability of College's magnetic latitude for recording PCA. It is also apparent from these figures that there is no significant tendency for recurrence at 27-day intervals, as has been reported by Gregory and Newdick (1964).

Assuming the results are not fortuitous, this evidence for a recurrence tendency in PCA which is definitely longer than the 27-day rotation period of active regions on the sun raises the question of whether the effect is caused by some intrinsic property of the sun or by the conditions in interplanetary space which control the propagation of low energy solar cosmic rays. It is not possible to answer this question at this time, and it is difficult to offer any acceptable theory for this 32-35 day cycle. One possibility would be an eastward migration of active regions on the sun, but no such thing has been observed. If solar rotation is to be considered, and this would seem to be a necessary part of any mechanism, there are two immediately obvious possibilities for the observed period: 1) rotation at high heliographic latitudes, near the poles; or 2) rotation at some depth below the photosphere which is deep enough to account for the longer period, assuming a decrease of angular velocity with depth, but not too deep to influence the escape of particles from the sun's surface.

The first suggestion is not acceptable because sunspots and their associated flares are not found at high enough solar latitudes to show a 32-35 day rotation period. However, the second suggestion had been made previously to explain the tendency of the greatest geomagnetic storms to

recur after integer multiples of 30 days. This 30-day recurrence in great storms has been discussed briefly by Chapman and Bartels (1940) in their section 12.10. The concept of deeper layers in the sun rotating more slowly than the surface was invoked by Angenheister (1922) to explain his evidence for a 30-day periodicity in the occurrence of great geomagnetic storms, but no details of the physical mechanism were worked out.

The differential rotation of the sun is probably ultimately responsible for all of the major aspects of solar activity, so any theory of the 32-35 day periodicity of PCA events is likely also to depend on this property. However, it is not clear at this point exactly how such a theory should be developed. As more PCA events are detected during the coming years and sunspot cycle, it will be important to see whether or not this apparent 32-35 day cycle persists.

4.5 RELATION TO SOLAR RADIO EMISSIONS

Descriptions of the various types of solar radio emissions, their interpretation in terms of the movement of electrons through the corona, and the observations of earlier investigators about their relation to magnetic storms and PCA events were reviewed in section 1.4. In this section the statistics of the relations of solar radio emissions (SRE) to PCA events will be brought up to date.

Using the SRE data published by Smith (1962), Maxwell, Hughes and Thompson (1963), and the IAU Quarterly Summary of Solar Activity, it is found that the percentage of PCA events which occur within 10 hours after the various types of solar radio bursts are: type I, 67%; type II, 26%; type III, 78%; type IV, 51%; type 5, 13%; and both types II and IV, 19%. Looking at the association from the other point of view, using the lists

of Maxwell, et al. (1963) it was found that 19% of type II bursts and 36% of type IV bursts occurred within ± 12 hours of a recognized PCA onset.

Figs. 12, 13 and 14 show the relation of the absorption observed at College to solar radio bursts of types IV, II, and V respectively as determined by the superposed epoch technique. As would have been expected, type IV bursts show a close association with high absorption during the days immediately following the burst, but a well defined absorption maximum which occurs 33 days later is also observed. A similar association is apparent for type II bursts except that in this case the later peaks in absorption at 32 and 68 days are even stronger than that occurring more immediately following the burst. The magnitude of the peak at 68 days is comparable to that observed at 33 days following type IV bursts. Thus, type II bursts are more indicative of events to occur 32 and 68 days in the future than they are of imminent events. Figs. 12 and 13 support the evidence presented in section 4.4 for a hitherto unknown cycle in solar activity with a period of around 32-35 days. However, it should be noted that no evidence was found in the dates listed by Maxwell, Hughes, and Thompson (1963) for any inherent recurrence tendency in either type II or type IV solar radio bursts.

Fig. 14 shows there to be no apparent relation of absorption to type V solar radio bursts.

4.6 INFLUENCES OF THE INTERPLANETARY SOLAR MAGNETIC FIELD

As has been discussed in sections 2.2, 2.4, and 2.5, the extension of magnetic fields into the interplanetary medium from active regions on the sun is felt to be responsible for some of the empirical observations which have been made regarding the temporal variations of cosmic ray

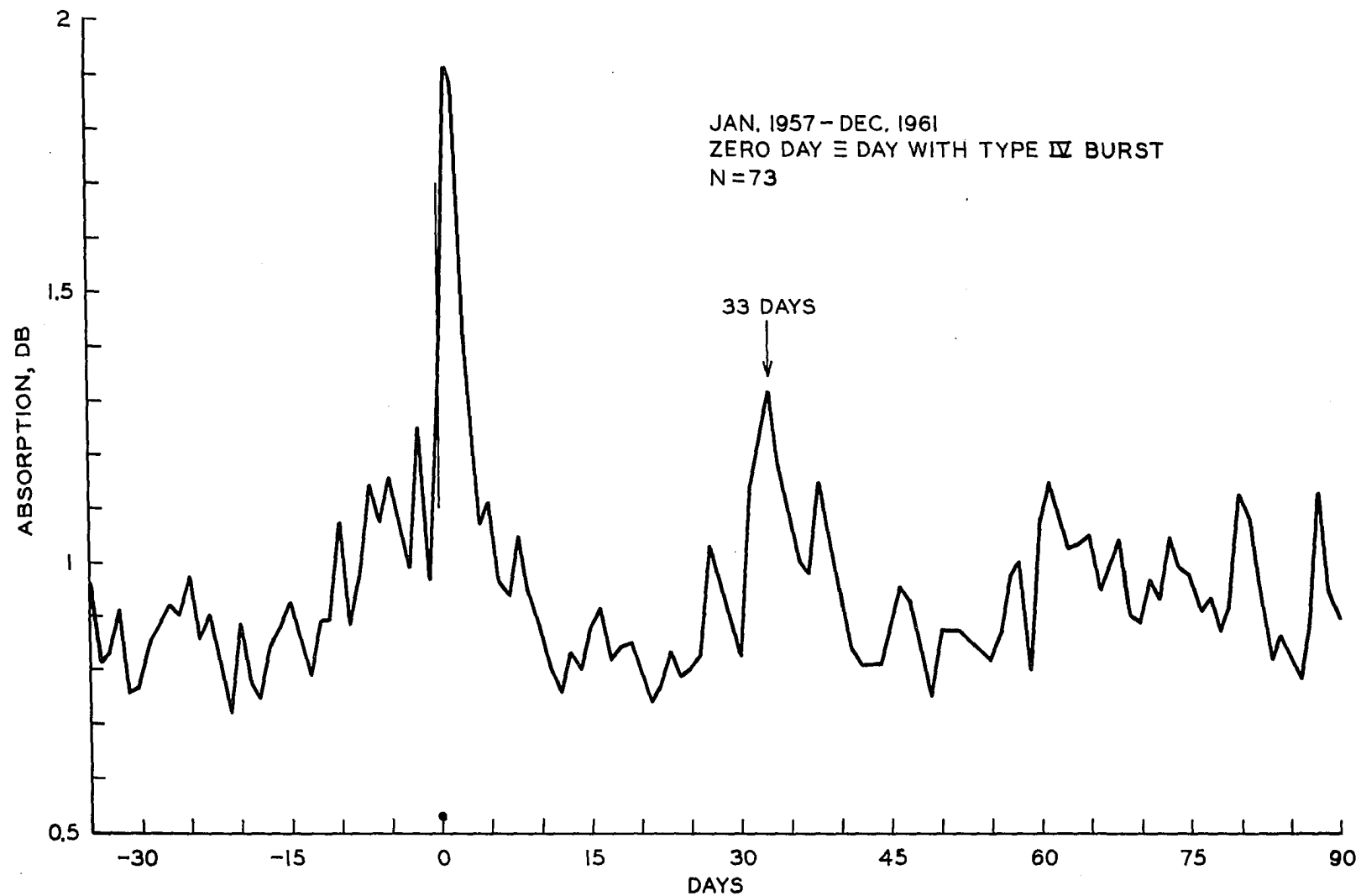


Fig. 12. The relation of absorption to type IV solar radio bursts. Zero days are those listed by Maxwell et al. (1963) as having a type IV burst.

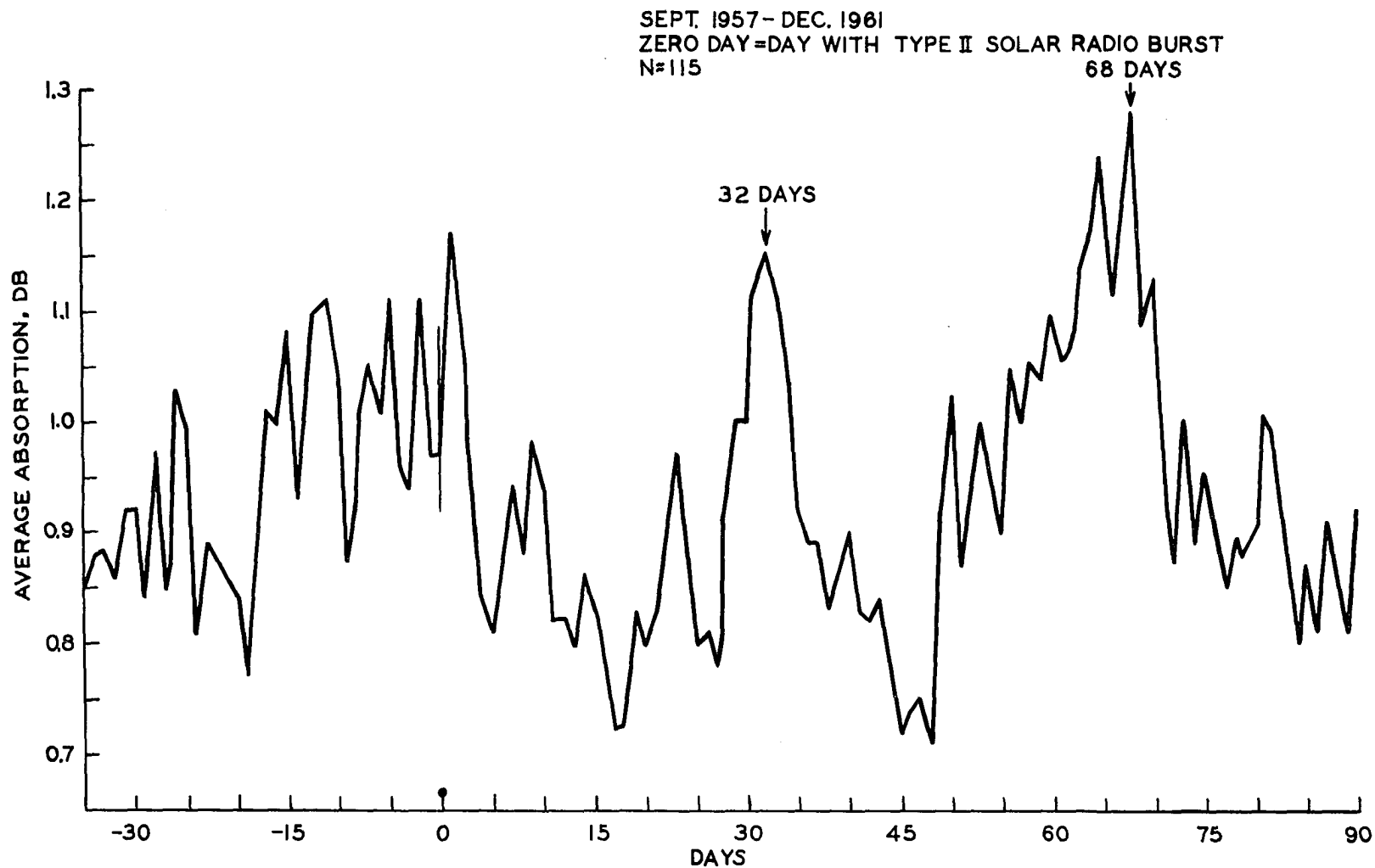


Fig. 13. The relation of absorption to type II solar radio bursts. Zero days are those listed by Maxwell et al. (1963) as having a type II burst.

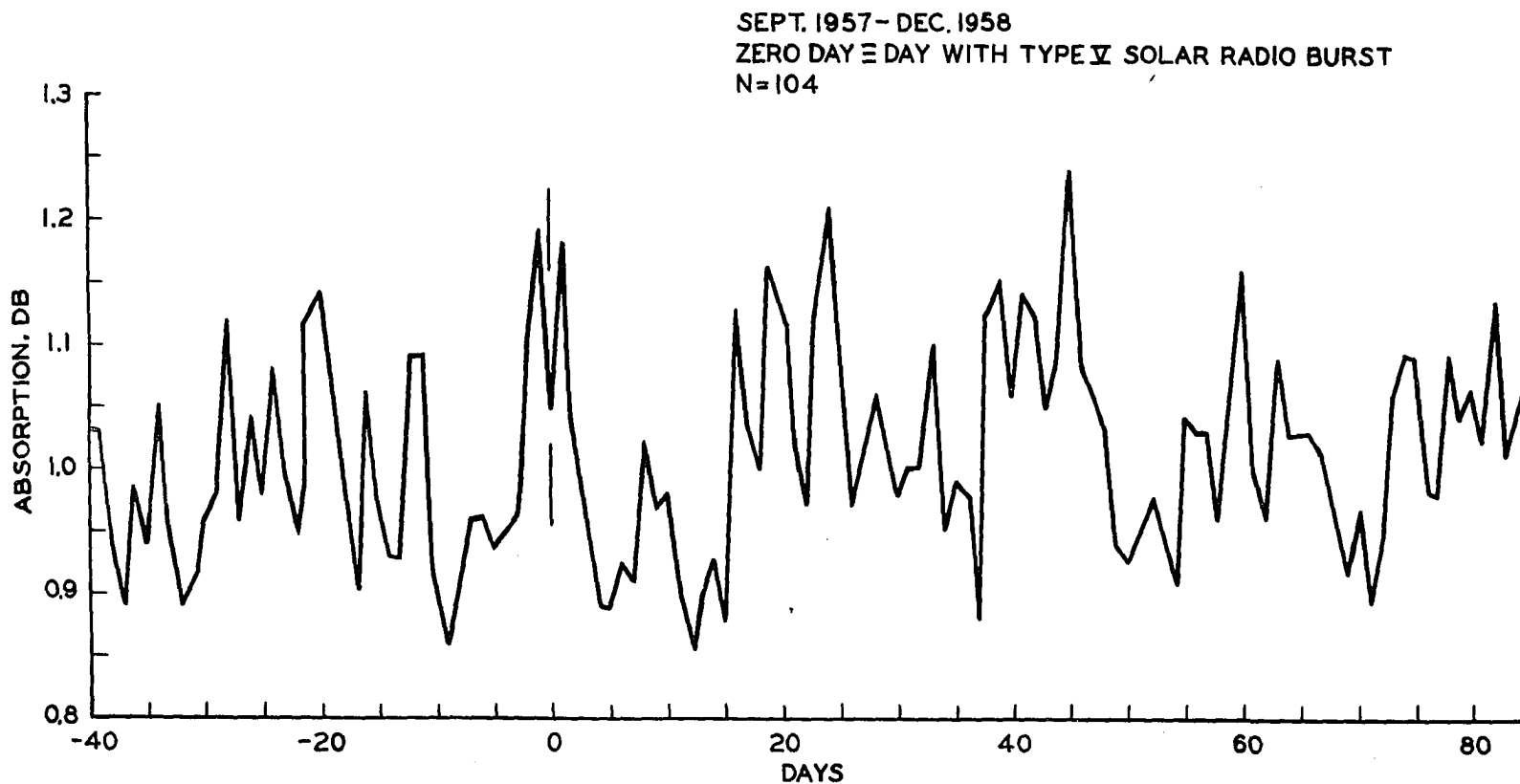


Fig. 14. The relation of absorption to type V solar radio bursts. Zero days are those days listed by Smith (1962) as having a type V burst. No apparent relation exists.

intensity, the distribution of cosmic ray and magnetic storm producing flares on the solar disk, and the travel time of the energetic protons from the sun to the earth. Having compiled the exhaustive list of PCA events given in section 4.3, it was hoped that the greater amount of data contained therein could help resolve some of the problems relating to the mode of propagation to the earth. However, this has not been the case. The discovery of new events and the new observations reported for the previously recognized events have not alleviated any of the confusion on this subject.

Assuming a cause and effect relationship and not violating the restriction placed by the observations of onset time by any of the sources listed in section 4.3, the flares which can be associated with specific PCA events are listed in Table 3. Even for these relatively few events the flare assignments are only reasonably and not completely certain. The usual policy has been to assign the largest and most spectacular flare to any PCA event which was observed during the next several hours, but there is no assurance, especially for the events with the long delay times, that some other seemingly insignificant flare which occurred in the mean time was not actually responsible for the ejection of the protons. Since it is difficult to imagine a storage mechanism which can account for delay times of the order of a day or more in the arrival of these energetic particles, events which seem to require a travel time longer than about 10 hours have not been included in Table 3.

TABLE 3

PCA EVENTS FOR WHICH THE FLARE ASSOCIATION IS REASONABLY CERTAIN

Date Yr-Mo-Day	UT PCA Onset	UT Flare Start	Flare Location	Date Yr-Mo-Day	UT PCA Onset	UT Flare Start	Flare Location
57-1-20	1500	1104	S27 W18	59-8-18	1045	1014	N12 W34
57-2-21	1800	1605	N20 W33	59-9-2	0400	1924	N12 E60
57-4-3	1100	0825	S15 W60	60-4-1	0930	0845	N12 W10
57-6-19	2215	1608	N20 E46	60-4-5	0800	0215	N12 W61
57-6-22	0530	0236	N23 E12	60-4-28	0200	0130	S05 E34
57-7-3	0815	0712	N14 W40	60-4-29	0400	0138	N12 W20
57-8-29	0030	2010(28)	S28 E30	60-5-4	1030	1000	N14 W90
57-8-29	1100	1031	S24 E20	60-5-13	0615	0519	N29 W67
57-8-31	1400	1257	N25 W02	60-9-3	0500	0038	N18 E88
57-9-18	2000	1818	N21 E03	60-9-26	0800	0525	S21 W64
57-9-26	2100	1907	N22 E15	60-11-12	1400	1320	N26 W04
57-10-21	0000	1637(20)	S26 W45	60-11-15	0500	0207	N26 W33
58-2-10	0500	2108(9)	S12 W14	60-11-21	0200	2023	N28 W90
58-3-23	1830	0947	S14 E78	61-7-11	2200	1654	S06 E32
58-7-7	0100	0020	N25 W08	61-7-12	1800	1000	S07 E22
58-7-29	0400	0259	S14 W44	61-7-18	1135	0938	S06 W58
58-8-16	0600	0433	S14 W50	61-7-20	2200	1552	S05 W90
58-8-26	0100	0005	N20 W54	61-9-28	2300	2202	N13 E30
59-5-10	2300	2101	N18 E48	61-11-10	1500	1433	N08 W90
59-7-10	0400	0210	N20 E66	63-4-15	1200	1118	S12 W08
59-7-14	0445	0319	N16 E05	63-9-21	0020	2351(20)	N10 W09
59-7-16	2200	2114	N15 W30	63-9-26	0745	0701	N15 W75

No simple solution for this difficulty of recognizing the time and place of emission of PCA protons seems to exist, at least not using current observational techniques. An obvious step toward such a solution however, would be for an experienced flare observer to make a systematic examination of the PCA flares recorded by the various flare patrols all over the world testing the relative merits of the criteria proposed by Dodson and Hedeman (1959, 1960), Athay and Moreton (1961), and Krivsky (1963 a,b,c).

For what it is worth, the data in Table 2, which are believed to be "reasonably" reliable, have been used to examine the problems of travel time and flare location. Some of the results are shown in Figs. 15 and 16.

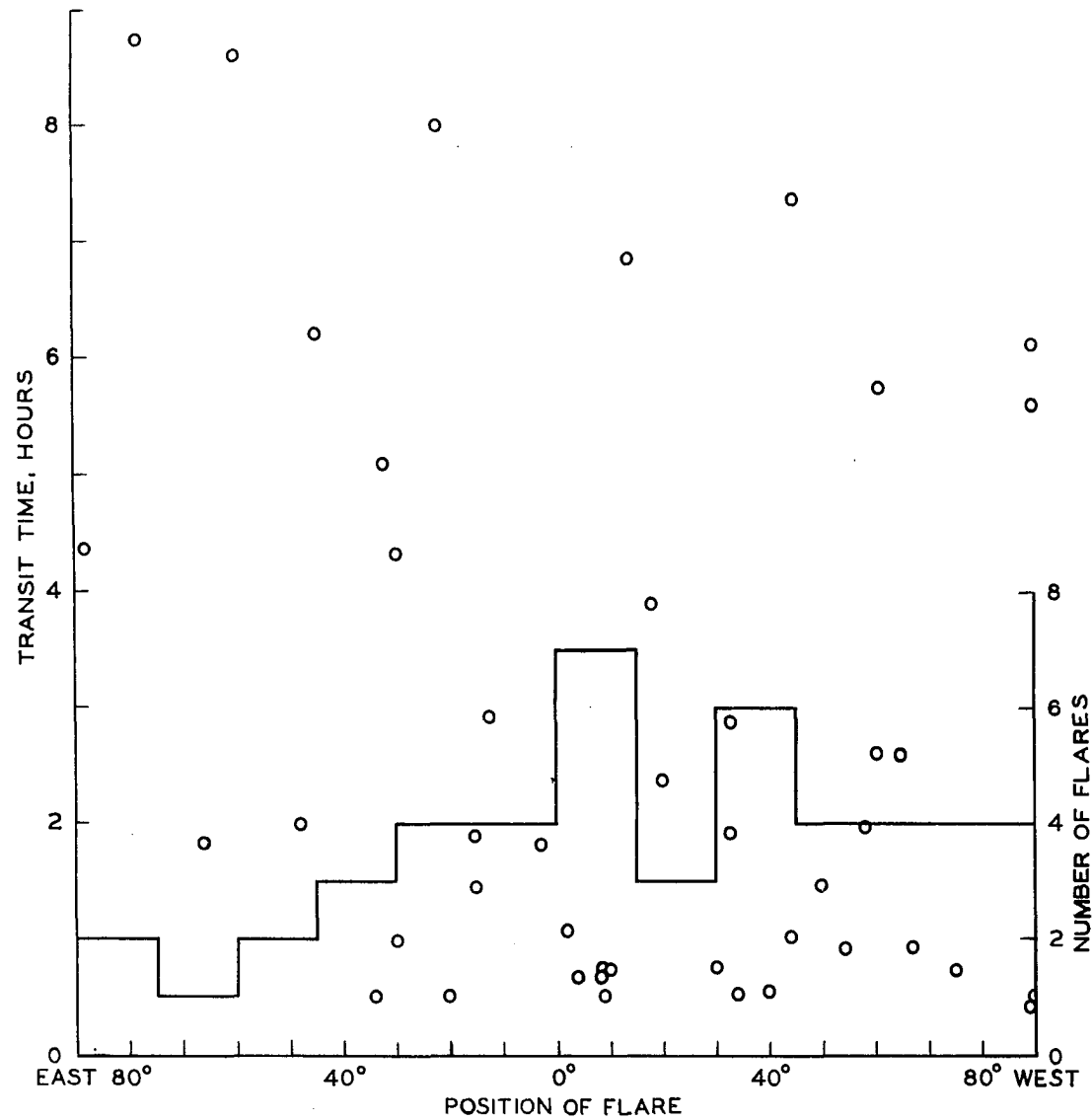


Fig. 15. The transit time of protons from sun to earth and the frequency of occurrence of PCA flares as a function of the distance of the flare from the sun's central meridian.

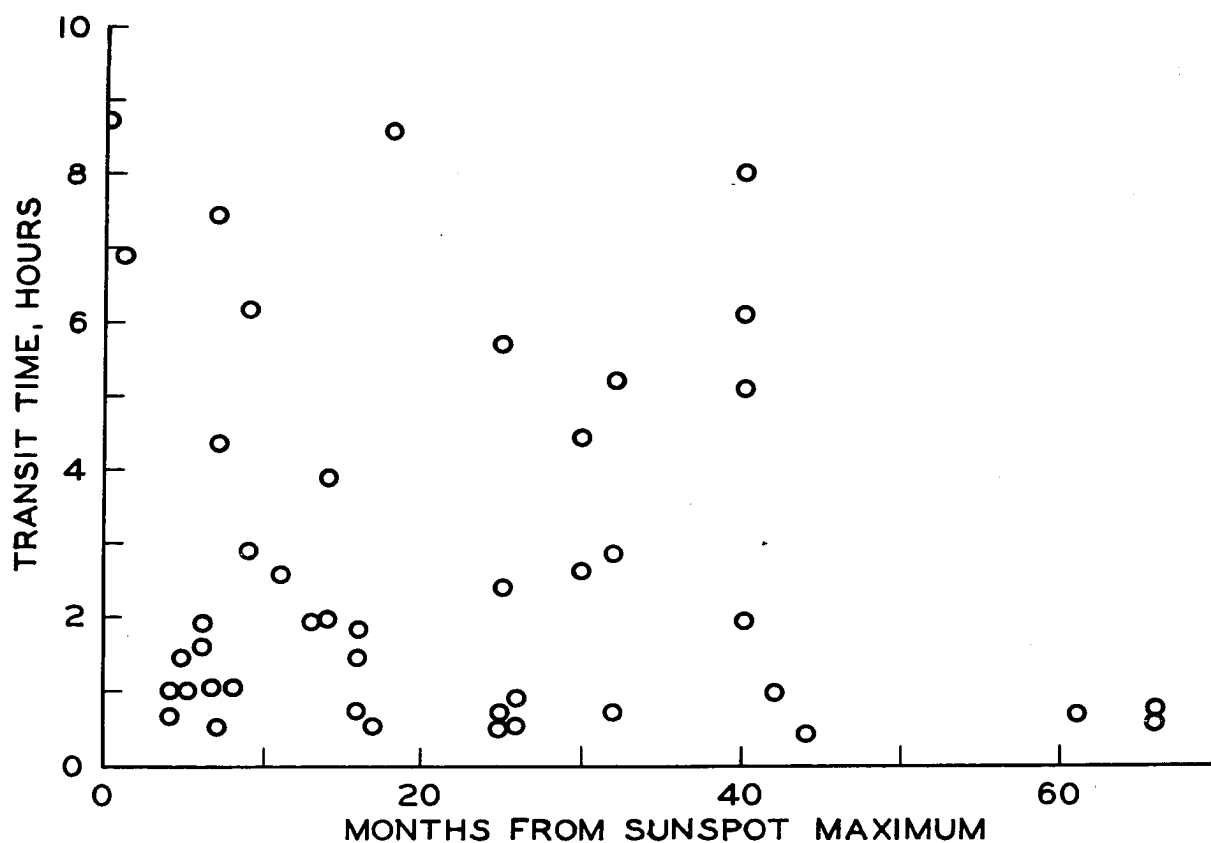


Fig. 16. The transit time of protons from sun to earth following PCA flares as a function of time of occurrence relative to the sunspot maximum.

Of the flares listed in Table 2, 64% occurred on the northern and 64% on the western side of the disk. The western excess is also apparent in Figure 15, which shows in addition the rough tendency for the delay time between flare and PCA onset to increase with distance of the flare from the west limb. Figure 16 does not seem to support the finding of Warwick and Haurwitz (1962) that travel time increases with the time since the maximum of the solar cycle. However, the results in Figures 15 and 16 are not claimed to be necessarily any more significant than those reported by earlier workers.

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CHAPTER 5

AURORAL ABSORPTION

5.1 INTRODUCTION

It is proposed in this chapter to seek an understanding of auroral absorption in terms of its dependence on streams of particles emanating from the sun. As was mentioned in section 2.5, this problem has been left relatively untouched by previous investigators, perhaps because the majority of them have focused their attention on polar cap absorption and its association with low-energy solar cosmic ray events. Although in its initial formulation this investigation was intended to find the cause of the absorption phenomena, the results have gone beyond this goal to provide in addition an insight into the older and more debated question of the nature of solar M-regions.

The temporal and spatial morphology of auroral absorption has been described in detail in an earlier paper (Basler, 1963), but for the sake of a self-contained presentation, a few of the pertinent findings will be summarized here. Auroral absorption is localized in those regions of the northern and southern hemispheres that correspond roughly to the zones of occurrence of the aurora. It never extends over the whole polar cap, as is usual with PCA events, but is restricted to occurrence within a fairly narrow range of geomagnetic latitude (roughly 60° - 70°). The longitudinal extend of an absorbing region is much greater than its range in latitude, a pattern suggestive of an analogy to the east-west elongation of auroral forms. Auroral absorption shows a strong seasonal variation, with a summer (May, June, July) minimum which is exactly opposite in phase to the winter minimum evident in the occurrence frequency of PCA events. Auroral

absorption generally occurs during periods of magnetic activity and is associated with the incidence of visible aurora, especially with the post-breakup phase of auroral displays. A detailed discussion of the relation of absorption to the luminous aurora has been given by Ansari (1963). The observed daily and seasonal variations of absorption, as well as the existence of an auroral absorption zone, are interpreted as effects of the temporal and spatial variations of the energy flux of the incoming stream of auroral particles. This interpretation of absorption in terms of particles precipitated into the upper atmosphere from the earth's radiation belt has been confirmed by satellite observations of the behavior of these particles made by O'Brien (1964) and Frank, Van Allen, and Craven (1964).

This chapter will not consider the problem of the nature of the interaction of the solar plasma with the earth's magnetic field. Some discussion of this problem is given in section 6.3, but the complexities of how the particles are injected into the magnetosphere, how they are accelerated to auroral energies, and how their precipitation is regulated, are mostly outside the scope of this study. In what way is auroral absorption related to physical processes occurring on the sun? That has been the motivating question for the research described here.

5.2 RECURRENCE TENDENCY

The 27-day recurrence tendency of auroral absorption was established by Collins, Jelly, and Matthews (1961) on the basis of a Bartels time pattern diagram of ionosonde f-min data. They pointed out that auroral absorption was present mostly in the years of declining sunspot numbers and, unlike magnetic activity, did not reappear during the ascending years of the next sunspot cycle. However, they used the ionosonde f-min data

from Churchill which is north of the latitude of maximum frequency and intensity of auroral absorption in Canada, so some of the details of the recurrence phenomena may well have been missed.

Using the College riometer data, the recurrence tendency was examined by means of both the superposed epoch technique and the Bartels time pattern diagram and the results are shown in Figs. 17, 18, 19, and 20. The superposed epoch analysis reveals a well-defined 27-day recurrence pattern which is more pronounced during the latter half of the declining phase of the sunspot cycle than it is during the years including the sunspot maximum. In addition, there is no evidence for any clearly defined periodicity significantly different from 27-days except for the 28-day peak in Fig. 18 which is discussed below. This analysis was performed before the list of PCA events given in section 4.3 was completed, so the upper limit of 5 db on the definition of the daily average absorption for disturbed days was set in order to eliminate the days with obviously strong PCA. Since many of the weak PCA events can be seen in Fig. 20 to have little effect on the daily average absorption at College, this lack of a rigorous method for eliminating PCA is not believed to have caused much contamination in the results.

Taking Fig. 17 for example, one difference which is noted from those figures of a similar nature derived from magnetic data (for instance, Chree and Stagg (1928) figure 5, page 57) is that the quiet and disturbed day curves do not intersect here as they do for the magnetic curves. This failure to intersect is probably largely controlled by the pronounced seasonal variation of absorption and also by the technique of selecting zero days from the magnetic data. This selection process maintains an even sampling throughout the year by taking the 5 magnetically quiet and

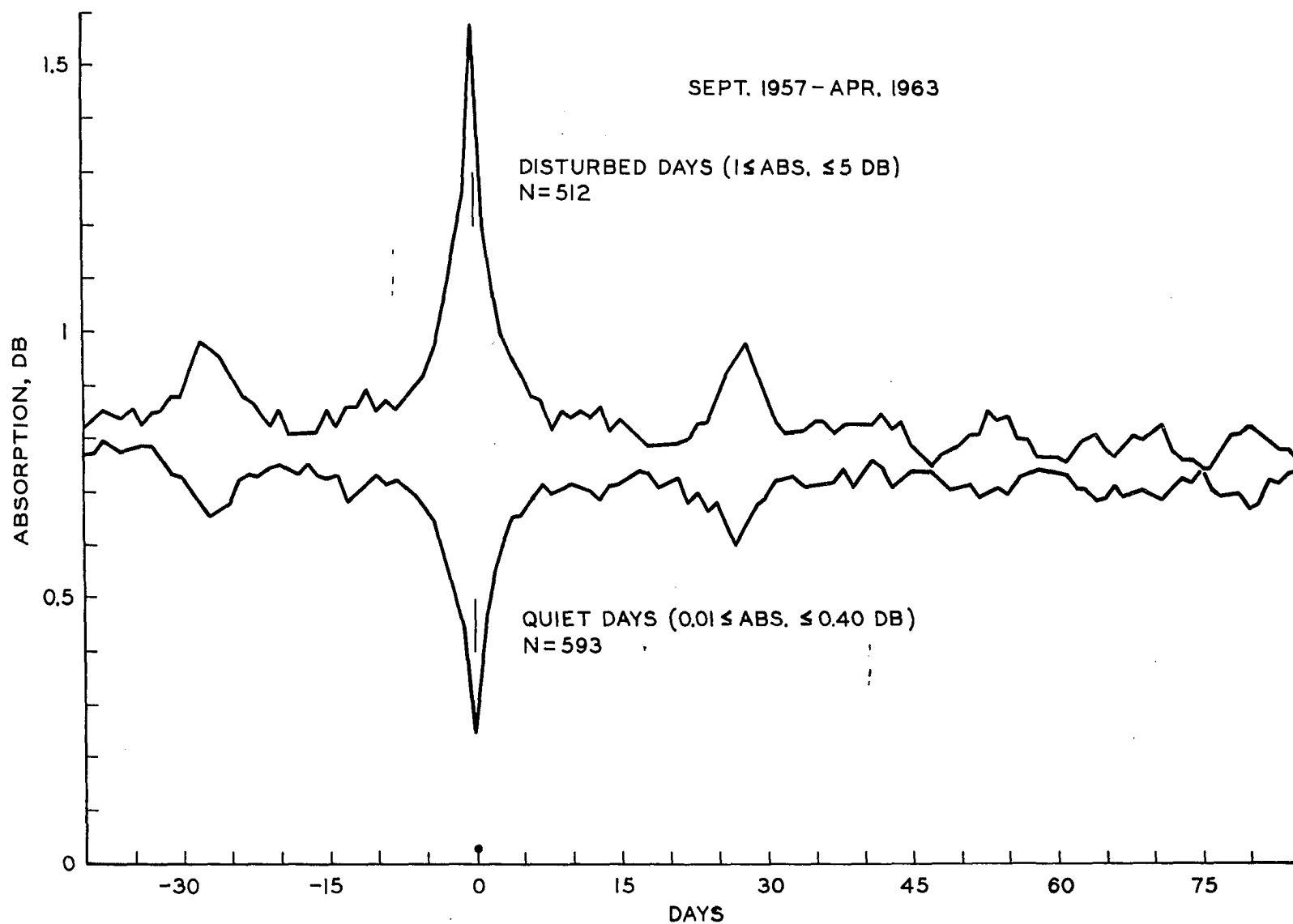


Fig. 17. The recurrence tendency of auroral absorption as demonstrated by the superposed epoch technique using about 5 1/2 years of data.

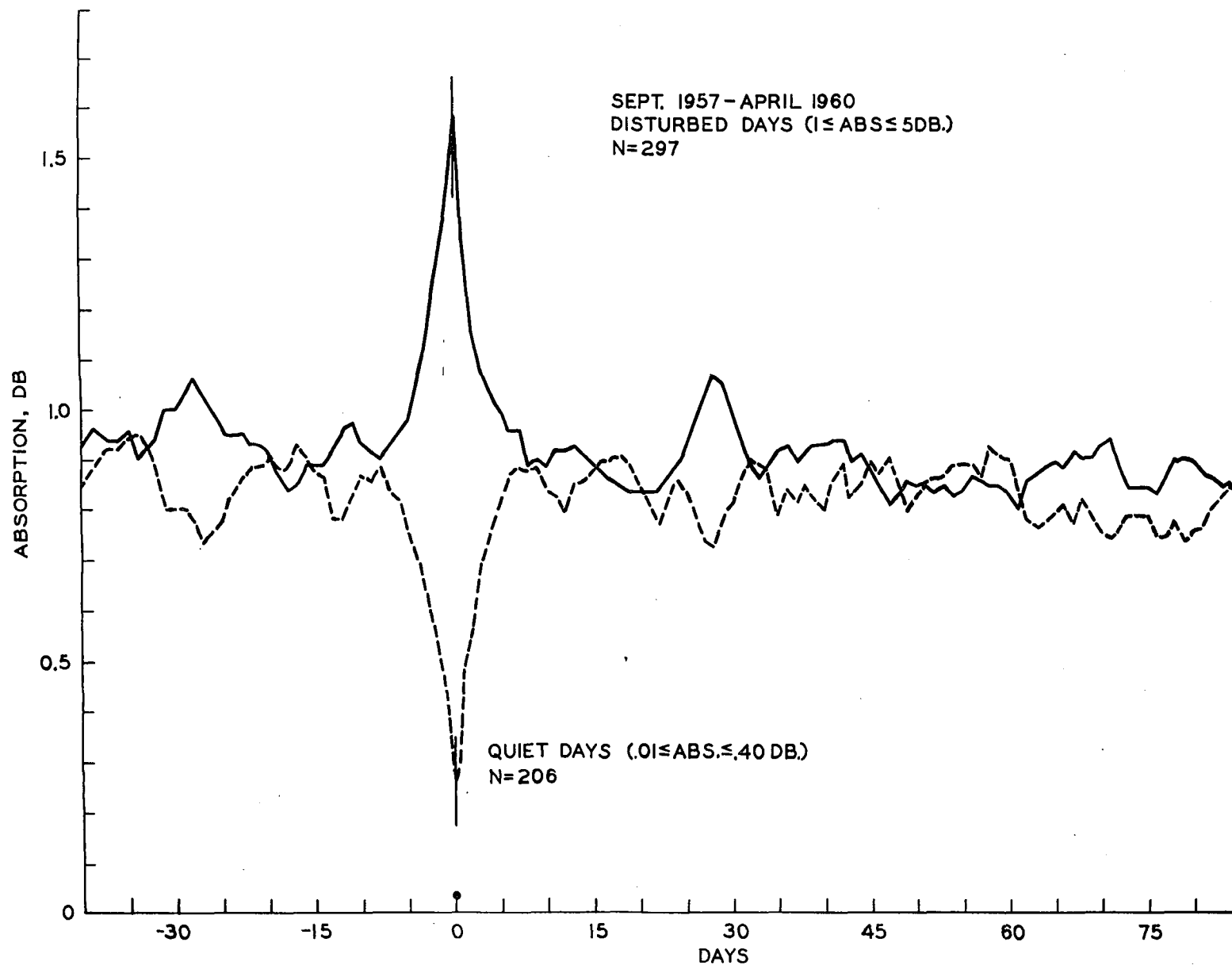


Fig. 18. The 27-day recurrence tendency of auroral absorption for years near the maximum of the sunspot cycle. The peak actually occurs at 28-days.

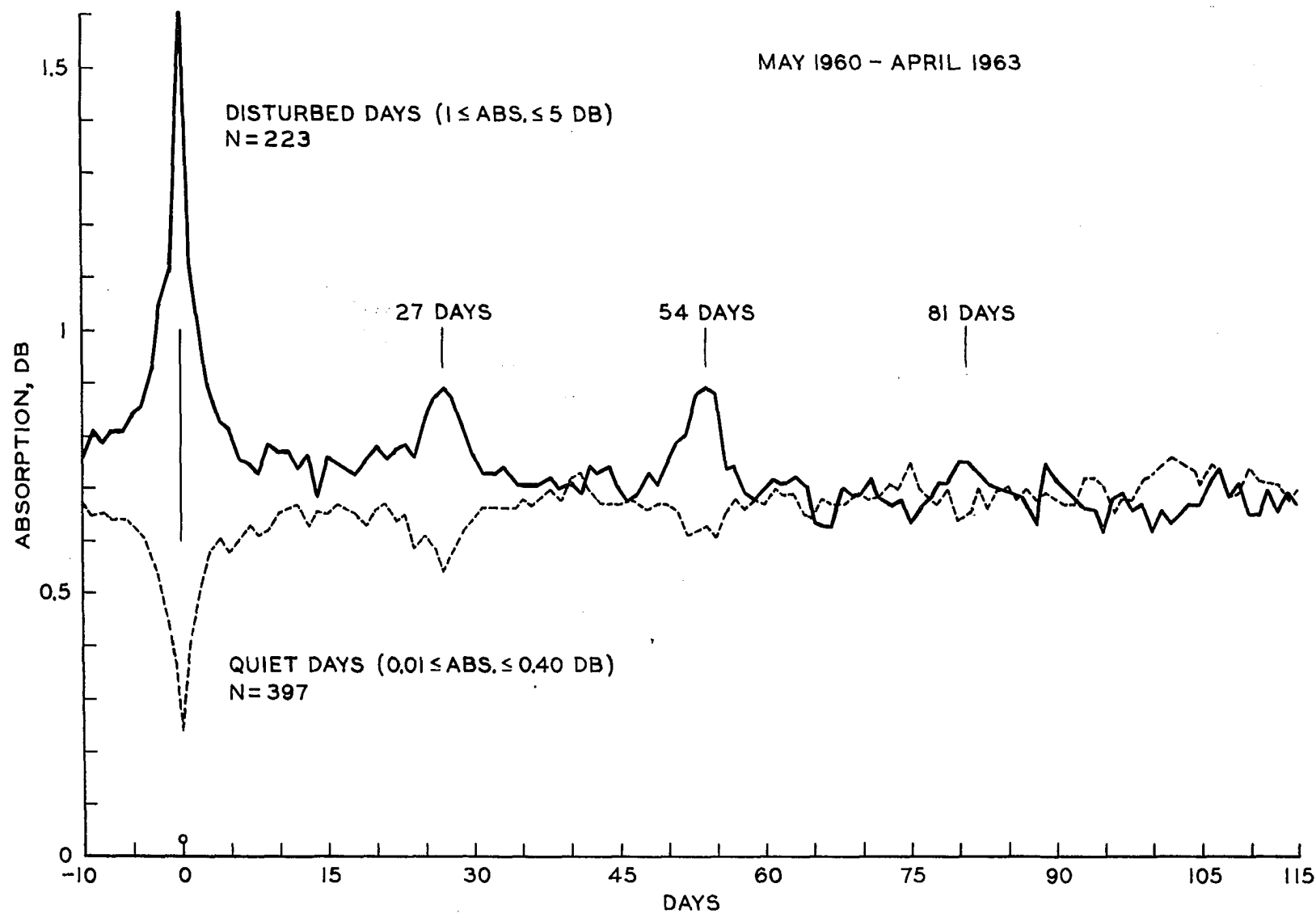


Fig. 19. The 27-day recurrence tendency of auroral absorption during the latter half of the declining phase of the sunspot cycle.

5 disturbed days each month regardless of how disturbed or quiet they are relative to other months, but for the superposed epoch analysis of absorption data, more disturbed days are taken in winter than summer, and vice versa for quiet days.

A close examination of Fig. 18 shows a recurrence tendency which maximizes at 28 instead of 27 days. Since Fig. 18 refers to years near sunspot maximum when solar activity was concentrated in the higher and more slowly rotating heliographic latitudes, the 28-day period exhibited by auroral absorption during these years suggests a similar distribution on the sun of the sources of these recurrent auroral disturbances. Because of their recurrence tendency these sources are called M-regions. Since Fig. 19 shows a well-defined 27-day period, it can be concluded that M-regions display the same migration toward the solar equator which is characteristic of active regions. However, it will be shown later that although they occur in the spot zone, they avoid any immediate association with the spots themselves.

In addition to showing the recurrence tendency, the superposed epoch results provide information on the dimensions of the solar particle streams which are responsible for the absorption. From Figs. 17, 18, and 19 it can be seen that disturbances persist on the average for about 5 days. This duration is determined by the time required for the curve to return from its peak back to the average level. Assuming that this duration corresponds to the time that the earth is enveloped by the stream, it is possible to calculate the angle subtended by the stream to be $5/27.3 \times 360^\circ$ or about 66° . The cross sectional dimension along the earth's orbit is thus about 1.7×10^8 km, or approximately 10^3 times the size of the earth's magnetosphere in this direction. Of course, this

argument assumes that the ecliptic plane contains the axis of a stream which has its effective source in the sun's equatorial regions, and it applies equally as well to a void stream (or void channel) as to a particle stream, the former being responsible for the quiet days which recur at 27-day intervals.

In order to be able to examine more carefully the individual sequences of recurring absorption events, the data were divided into 10 ranges according to magnitude of disturbance and were assigned integral representations from zero to nine as shown in Table 4. These integral values were then arranged in rows of 27 days, with 6 extra days included at the end of each row to provide continuity, a presentation identical to the classical Bartels time pattern diagram for magnetic data. The results are shown in Fig. 20. Several discrete sequences of auroral absorption events with durations ranging from 4 to 10 solar rotations are shown in the cross-hatched areas. During the years 1957 and 1958, the time of sunspot maximum, PCA events occurred with such frequency and the general level of absorption activity was so high, it was not possible to separate out any isolated recurrent sequences which might have been present.

TABLE 4
SYMBOLS USED IN BARTELS DIAGRAM

Symbol	Range db	Number of Days	Symbol	Range db	Number of Days
0	.01-.20	203	6	.83-.99	168
1	.21-.30	220	7	1.00-1.50	295
2	.31-.40	180	8	1.51-2.50	186
3	.41-.50	191	9	2.51-15.0	58
4	.51-.63	215	A	No data	118
5	.64-.82	234			

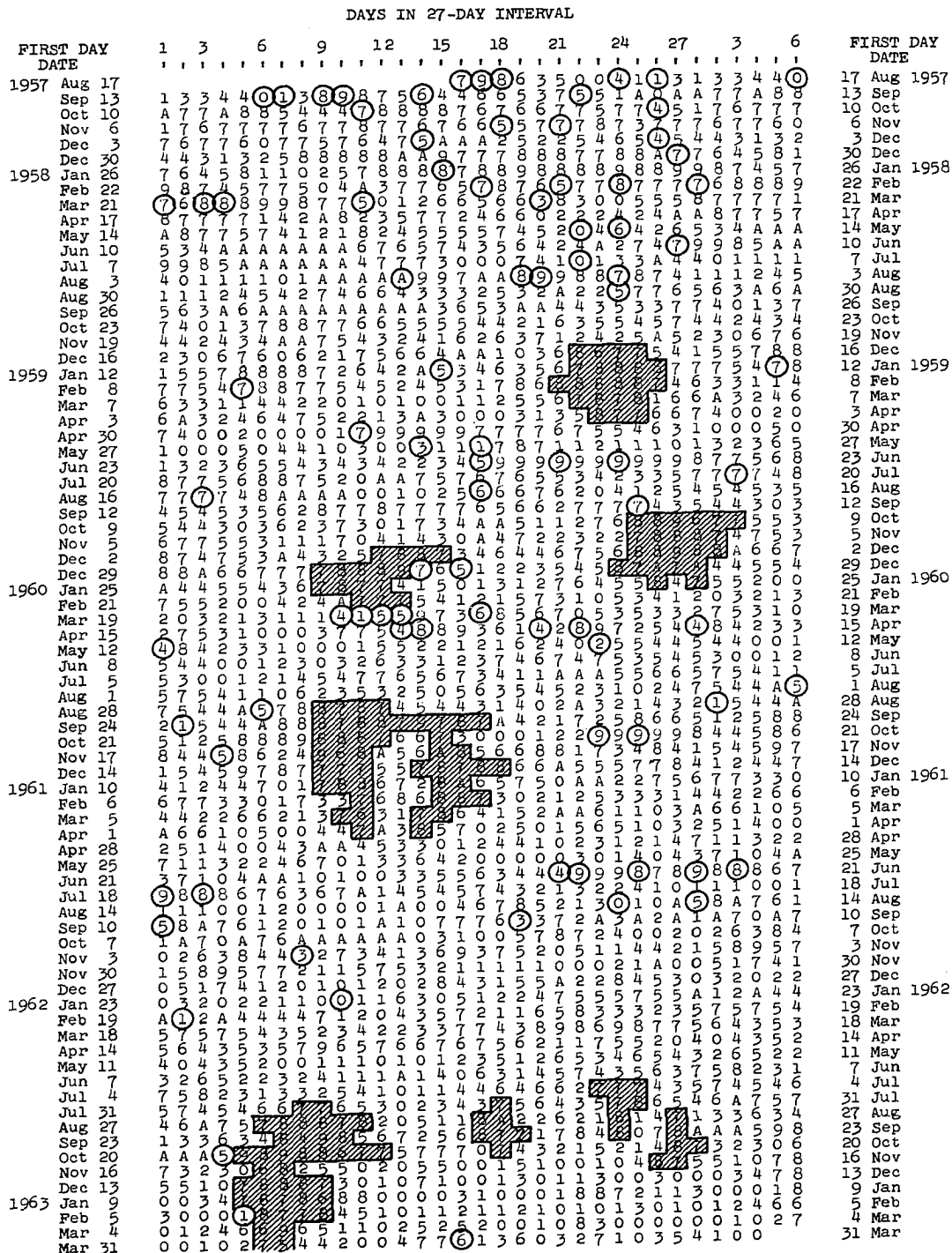


Fig. 20. The daily average absorption at College, Alaska, arranged in a Bartels time pattern diagram. Days with PCA onset are circled. Recurrent sequences of the M-region type are cross-hatched. Note that the days are determined by 150° WMT and not UT.

The ranges for the symbols listed in Table 4 were chosen so that 0, 1, and 2 correspond to the quiet days and 7, 8, and 9 (except for >5 db) to the disturbed days as they were defined for the superposed epoch analysis. Of course, these assignments are arbitrary since there is no obvious discontinuity in the transition from very quiet (which actually means very little disturbance) to very disturbed.

The 27-day recurrence patterns of auroral absorption which have been displayed in the diagrams of this section are most logically interpreted as effects produced by solar M-regions (see section 1.7). The remainder of this chapter will be devoted to a discussion of how the absorption is related to particular solar features, or in other words, to what is the nature of these M-regions.

5.3 RELATION TO DAILY SOLAR INDICES

Having demonstrated that the sun is directly responsible for the auroral absorption phenomena by virtue of having established its 27-day recurrence tendency, it is now important to see what conditions characterize the sun at the times when high absorption is observed on the earth. For this purpose the standard published indices of solar activity have been subjected to a superposed epoch analysis using the same disturbed (absorption) days as in Fig. 17 for the zero days. The results of this analysis of the daily solar flux at 2800 mc/s are shown in Fig. 21. Three features of this figure deserve comment: 1) high absorption occurs 3 days after a well-defined minimum of solar activity; 2) this minimum recurs regularly at approximately 27-day intervals; 3) solar activity shows an overall decrease from left to right which, as would be expected, corresponds very closely to the average decline of activity during the 5 1/2 year period examined.

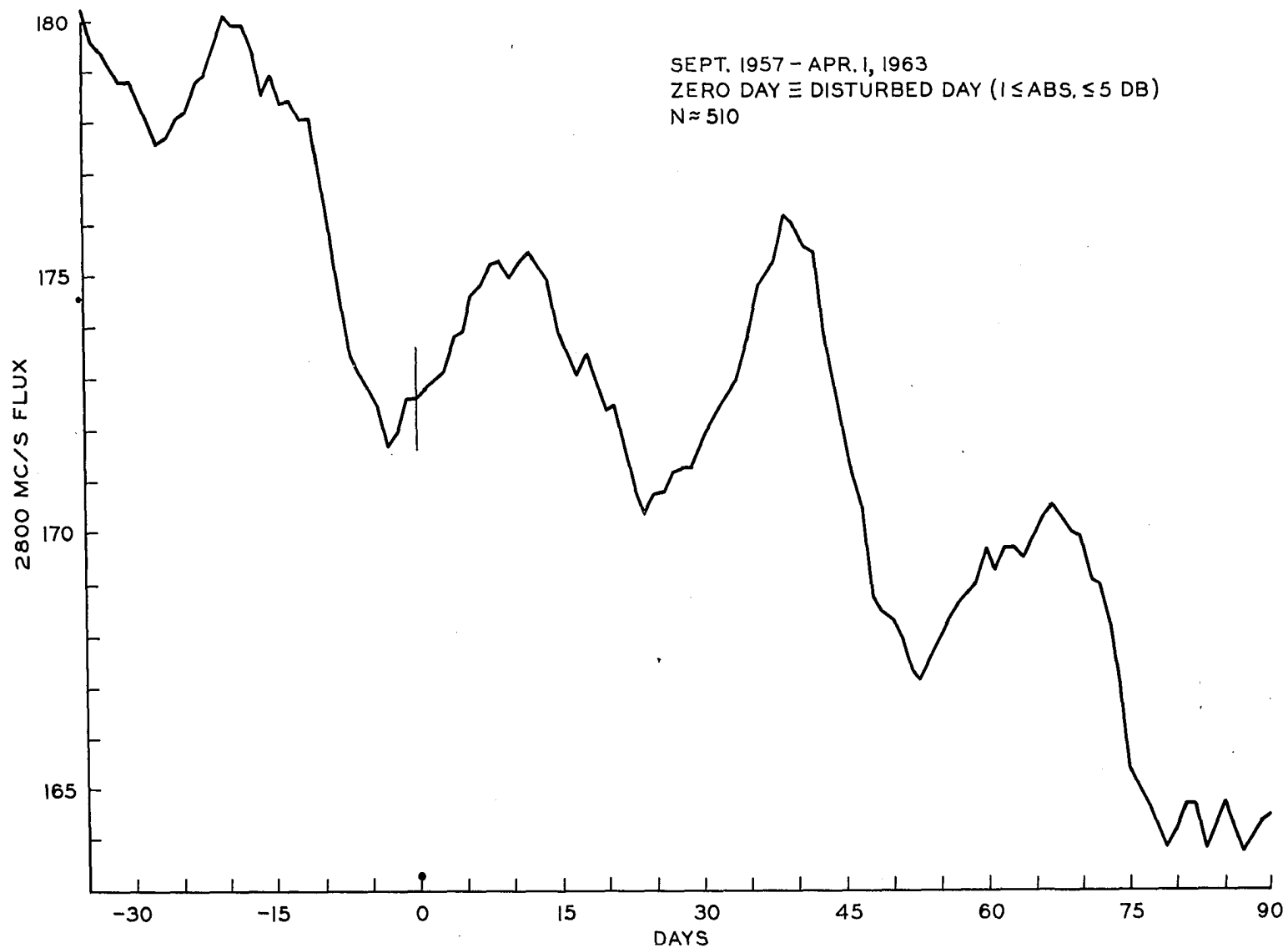


Fig. 21. A superposed epoch diagram showing solar activity to be near a minimum at times of high auroral absorption on earth. The units for the 2800 mc/s flux are watts/sq. meter/cycle/sec ($\times 10^{-22}$).

This same analysis was also performed for all other available daily solar indices including the American relative sunspot number, the 5303 Å coronal index integrated over the whole visible disk, an index of flare area, a flare activity index, and the flux at 200 mc/s. The same gross features apparent in Fig. 21 are exhibited by each of these indices when arranged according to the same days of high absorption, but the regularity of the results and thus the clarity of the picture which emerges degenerates with the order in which they are listed above. The 2800 mc/s results have been chosen for a sample presentation since they show the clearest relationship. However, the results were in general borne out by the other indices, which is not surprising in view of the known close correlation of all of these symptoms of solar activity.

Another way of approaching this same problem is to find the conditions which characterize the sun during quiet periods on earth when little absorption is recorded, so the aforementioned daily solar indices were again run through a superposed epoch analysis except this time with quiet days (defined as in Fig. 17) as zero days. The results for the 2800 mc/s flux are shown as an example, but all of the general features exhibited here are evident in the other results.

Fig. 22 shows that quiet days on earth occur during periods of enhanced solar activity which recur roughly every 27 days. A curious aspect of these results, however, is their failure to show the expected general decrease of activity with time which was apparent in Fig. 21. The fact that the average curve in Fig. 22 is approximately flat means that by arranging solar data according to when quiet periods are observed on earth, a component of solar activity is selected which does not show the usual

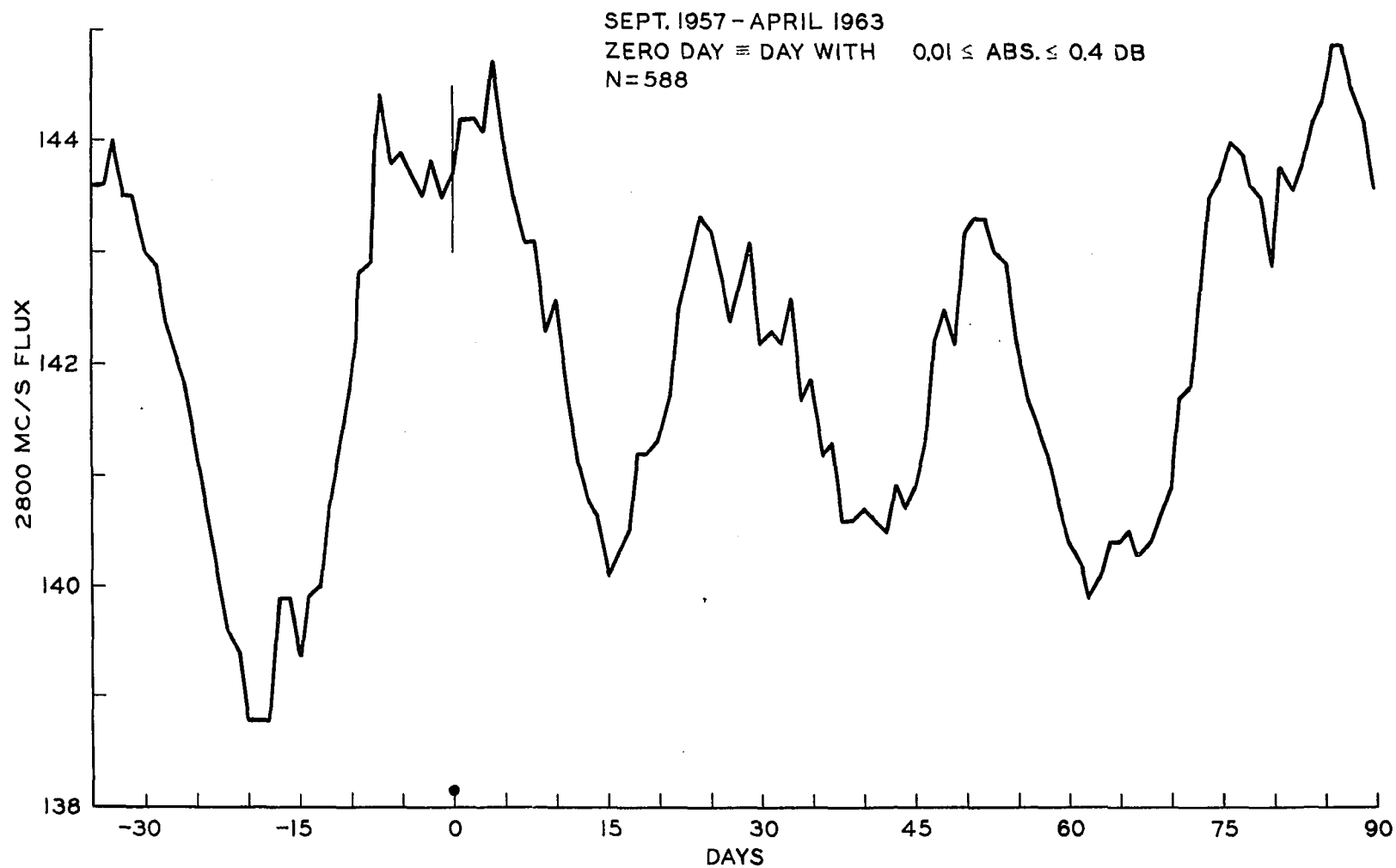


Fig. 22. A superposed epoch diagram showing solar activity to be a maximum during quiet periods with little auroral absorption on earth. The units for the 2800 mc/s flux are watts/sq. meter/cycle/sec ($\times 10^{-22}$).

tendency to follow the 11-year cycle. This is a puzzling observation for which no explanation can be offered at this time.

The results presented in this section are in clear and total disagreement with the theory that active regions are the source of the streams of solar plasma which cause recurrent geomagnetic and auroral disturbances (see discussion in section 1.7). Thus, from the point of view of auroral absorption, M-regions are identified with quiet and undisturbed areas on the sun since an inverse relation between solar and terrestrial disturbances has been demonstrated here.

The 2800 mc/s flux data used in Figs. 21 and 22 were recorded by Covington of the NRC at Ottawa, Canada and were published in Solar Geophysical Data (NBS Report CRPL-F Part B).

5.4 EFFECT OF THE CMP OF PARTICULAR SOLAR FEATURES

This section examines the behavior of absorption to find how it is influenced by some of the solar features whose effectiveness on geomagnetic activity was discussed in Chapter 1. To some extent, the results cannot be considered conclusive because the data were not sufficient to separate the systematic effects from those of a seemingly random nature. However, the difference between the relation of PCA and auroral absorption to sunspots is made apparent, and a strong case is made against activity centers and in favor of unipolar magnetic regions as the source of M-type disturbances.

An objection which is frequently voiced against statistical studies of the type presented here is that they obscure the role of the individual physical processes which must ultimately be responsible for all observed effects, but it is not possible with current observational methods to

recognize any solar feature which maintains a consistent relationship to geomagnetic or auroral phenomena. For every event which shows one relationship, several others can usually be found to show the opposite. Thus, the best that can be done at present is to search for relations which are true in a statistical sense in hopes that they will serve as guides for future detailed investigations.

5.4.1 Magnetically Complex Sunspots

The Mt. Wilson magnetic classification of sunspots was described in Chapter 1 along with a review of the role of the various magnetic classes in controlling geomagnetic disturbances. Fig. 23 shows the effect of the CMP of γ and $\beta\gamma$ sunspots on the College absorption, both including and excluding days with PCA. It is apparent from this figure that magnetically complex sunspots have a direct effect on PCA but not on auroral absorption. Much of the variation which remains in the lower curve is probably caused by an incomplete removal of the auroral-type absorption which accompanied the PCA events. The practice used here, as well as elsewhere in this work, is to exclude from the analysis those days following within 3 days of a PCA onset. This procedure effectively eliminates the absorption due to polar cap proton bombardment which sometimes causes a daily average absorption of around 10 db, but in some cases there are extended periods of auroral-type absorption following PCA events, and it is not always clear whether these are produced by the flare-ejected plasma or by an M-region stream.

The Mt. Wilson magnetic sunspot classifications since January 1959 have not been published, but they were made available for this study by Dr. Robert Howard.

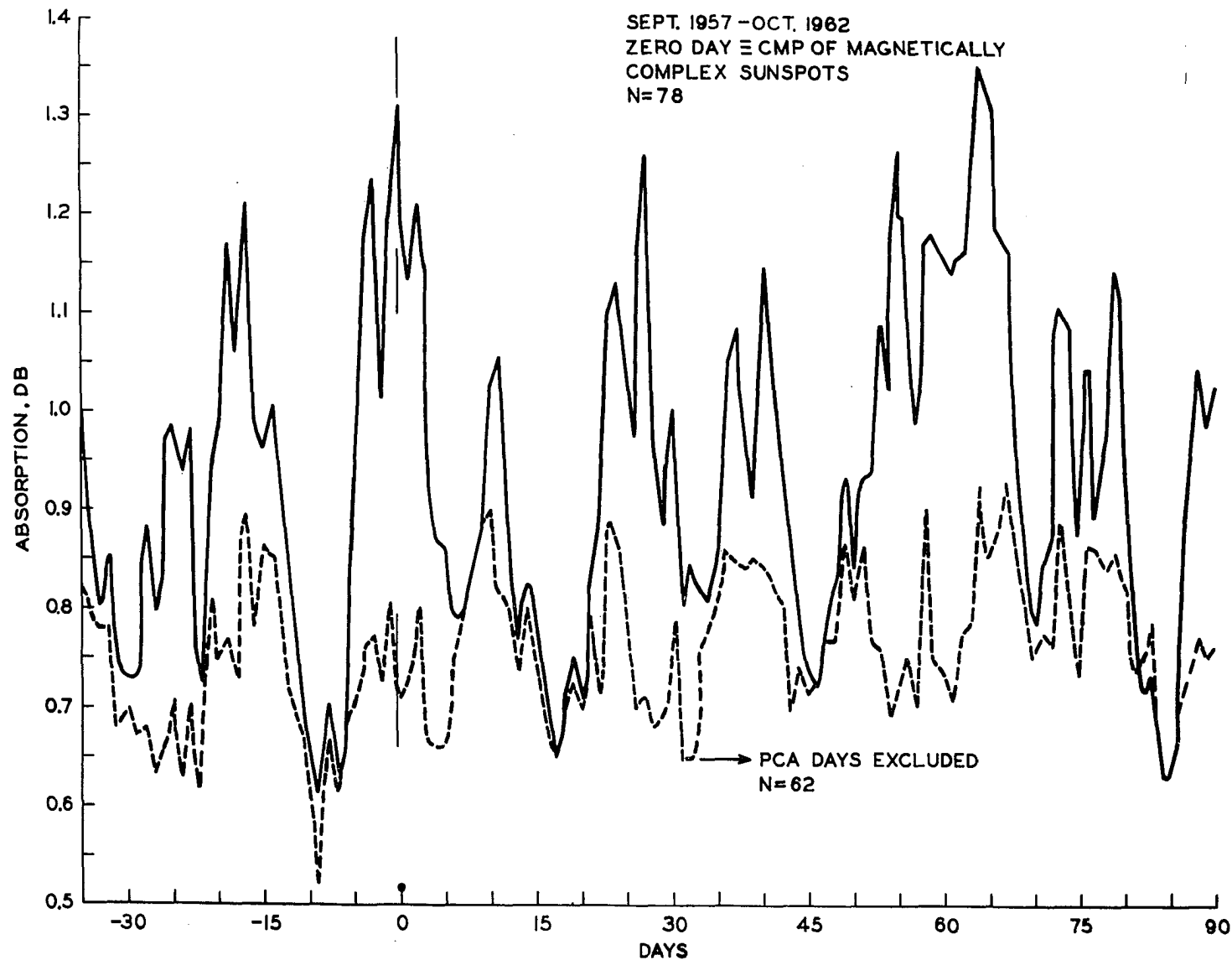


Fig. 23. The effect of magnetically complex (γ and $\beta\gamma$) sunspots on absorption at College as determined by the superposed epoch technique.

5.4.2 Large Sunspots

It was mentioned in Chapter 1 that there is some association of large magnetic storms with large sunspots, and it can be seen in Fig. 24 that this association also holds for PCA events. Again, much of the variation which remains in the lower curve is probably caused by an incomplete removal of the auroral-type absorption which accompanied the PCA events. Actually many of the large sunspots either were identical with or were closely associated with the magnetically complex sunspots used for Fig. 23, so it is not surprising they show a similar relation to PCA.

Since the maximum absorption in Fig. 24 occurs at minus three days, it seems that large sunspots send energetic protons to the earth most effectively from the eastern side of the disk. If this result is truly significant it will require some new concept in its explanation since the configuration of interplanetary magnetic fields is only capable of explaining an increased effectiveness on the western side.

Of course since it is well known that it is the spot-associated flares and not the sunspots themselves which are responsible for the ejection of particles producing PCA, the patterns shown in Figs. 23 and 24 should not be taken to mean that the CMP of sunspots have any direct effects. The results should rather be interpreted generally as showing that PCA is likely to occur when large or magnetically complex sunspots are on the visible side of the disk, especially near the central meridian.

One interesting aspect of Figs. 23 and 24 is that they show that the PCA which is related to these sunspots has some tendency to recur at approximately 27-day intervals. The recurrence patterns are poorly defined, and there are also many apparently random variations of a magnitude comparable to that with a 27-day periodicity. This evidence of a 27-day

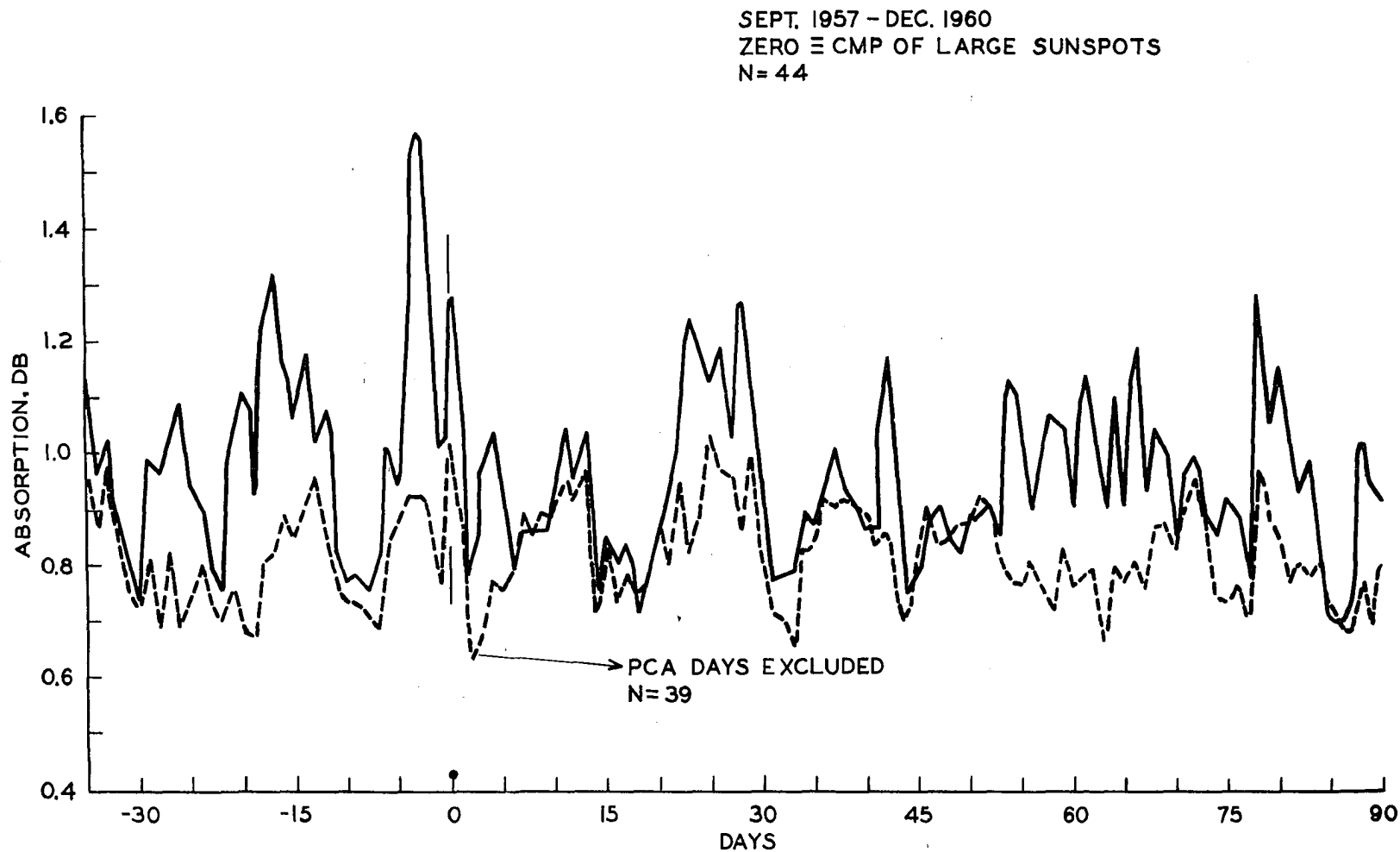


Fig. 24. The effect of large sunspots (area > 1000 millionths of the solar hemisphere) on absorption at College as determined by the superposed epoch technique.

recurrence for PCA does not contradict the previously presented evidence for recurrence at 32-35 days since it has considerably less statistical weight. Only about 10% of the large spots and 20% of the magnetically complex spots produce PCA, so the results in Figs. 23 and 24 are influenced by a very few events. The simplest interpretation of these results is that a specific, enduring photospheric feature which is conducive to PCA flare production, can, by means of its rotation period, introduce a 27-day square wave component in the probability of PCA occurrence. This square wave has a value of zero when the spot is on the invisible side of the disk and has a value greater than zero (though considerably less than unity) when the spot is on the side toward the earth. Since the results presented in Chapter 4 showed no evidence of a significant 27-day recurrence tendency for PCA in general, it is concluded that most PCA events are not associated with specific, enduring photospheric features.

The data on large sunspots were taken from Cragg (1958, 1959, 1960, 1961).

5.4.3 Centers of Activity

The controversy over the nature of M-regions was presented in section 1.7. It was there pointed out that there are basically two schools of thought, maintaining, respectively, that M-regions are and are not identical with centers of activity. Evidence against the activity center interpretation was set forth in section 5.3 where the average conditions on the sun were found corresponding to quiet and disturbed periods on earth. In this section the point of view is reversed and the average conditions on earth are examined preceding and following the passage of an active region across the sun's central meridian.

Data on centers of activity were taken from the IAU Quarterly Bulletin on Solar Activity. The CMP dates of active centers were used as zero days in several different superposed epoch analyses which took into account the influence of such variable parameters as the latitude, longevity, and importance of the active centers. There was some slight suggestion that centers with durations of less than two solar rotations had a positive effect on auroral absorption, but otherwise active regions were found to be either unrelated to auroral absorption or to have a negative relation, i.e., to cause a decrease in absorption.

Fig. 25 shows the results of all regions which crossed the central meridian in a nearly 5-year period. It is clear that no systematic relation existed over that period of time, and that the peak at +6 days and the trough at +3 days, which correspond to the important features in results of similar analyses by Mustel (1961a, 1961b), are insignificant when seen in the perspective of other variations which also occur in the interval from -35 to +90 days.

However, Fig. 26 shows that if only the active regions occurring in the later part of this period are considered, there is an obvious negative relation between absorption and active regions. This negative relation recurs at regular 27-day intervals. These data can be seen in Fig. 20 to have been taken from a period of generally less disturbance when M-region effects were more apparent than they were near the maximum of the sunspot cycle. This decrease in solar activity, which is reflected in the different values of N in Figs. 25 and 26, perhaps made it possible to separate the effects of individual active regions and thus to see a consistent, although negative, effect in Fig. 26. The division of the data into two parts was done rather arbitrarily but with the idea of dividing the total

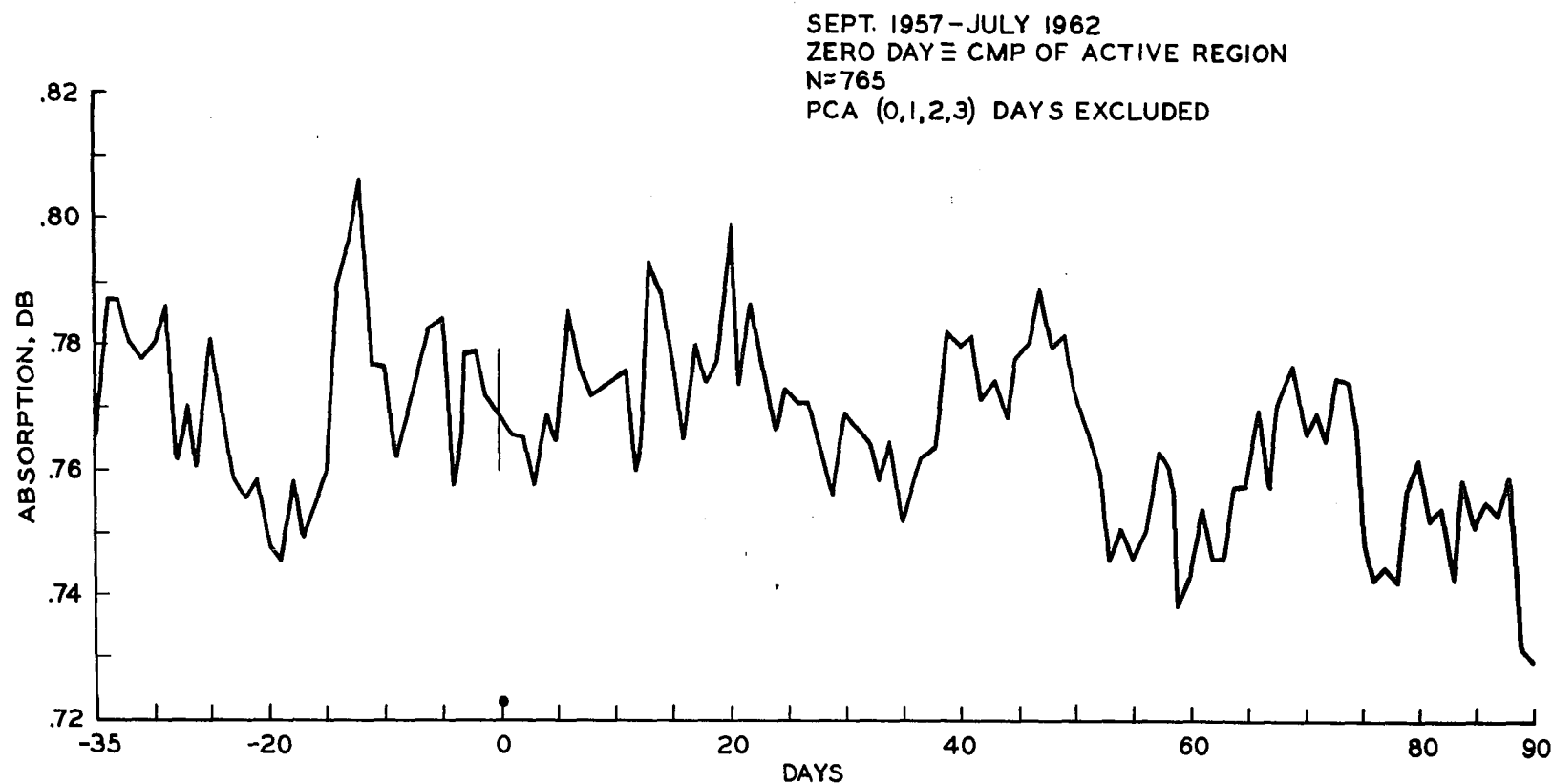


Fig. 25. The relation of auroral absorption to active solar regions over a nearly 5 year period as determined by the superposed epoch technique. No significant pattern is apparent.

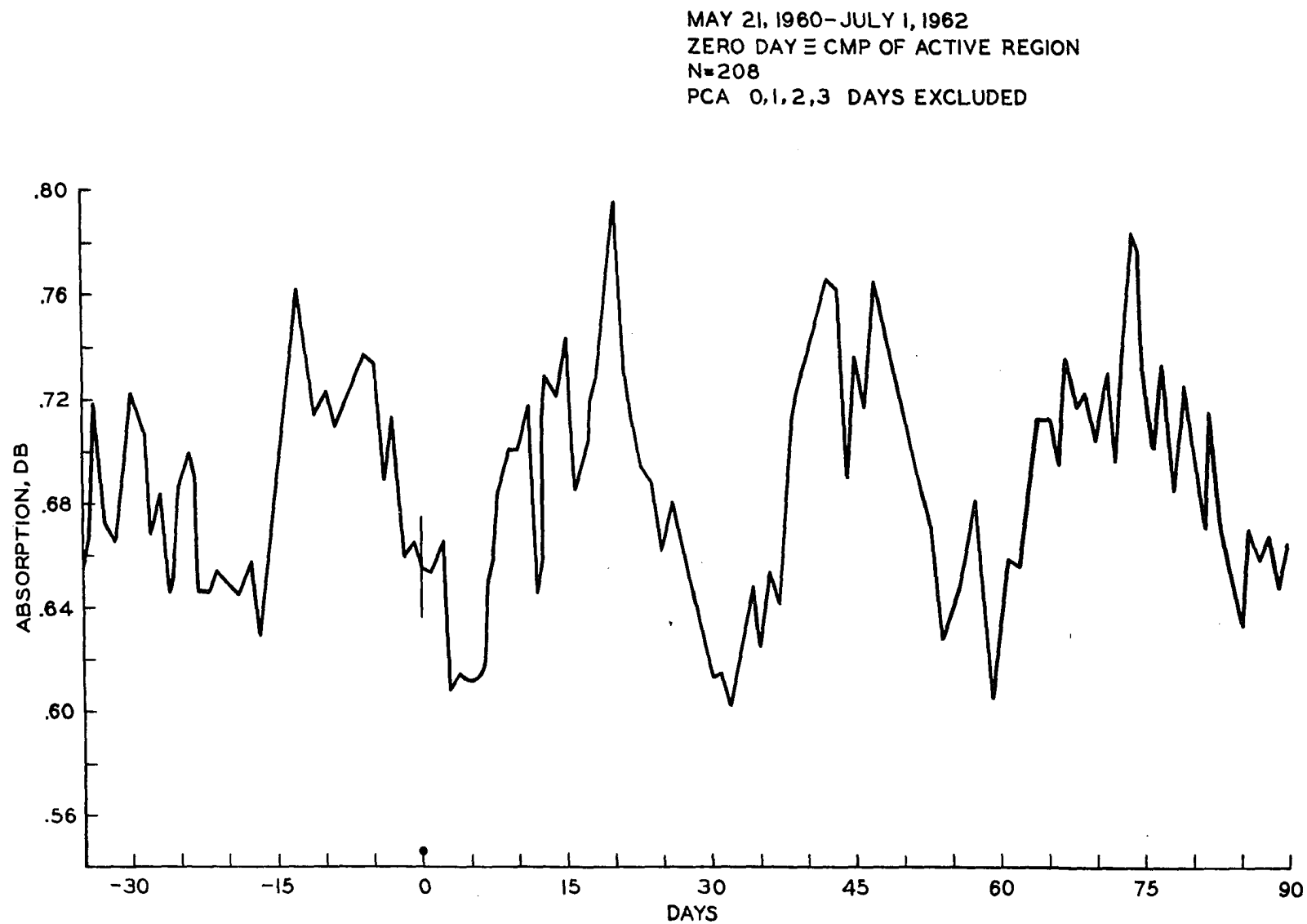


Fig. 26. The negative relation of auroral absorption to active solar regions during the later part of the declining phase of the sunspot cycle as determined by the superposed epoch technique.

period examined roughly in half. From the dates listed it can be seen that the data in Fig. 26 are included in Fig. 25, but the essentially random variations during the first part of the total period examined, which contained nearly $3/4$ of the active regions, more than offset the regular variations during the second part (shown in Fig. 26).

When the data used for Fig. 26 were divided according to whether or not the active region was on the same side of the solar equator as the earth, it can be seen in Fig. 27 that the pattern of the results did not differ significantly from that shown in Fig. 26. The fact that location on the sun, whether favorable or unfavorable in the sense of Bell's (1957) definition, does not influence the (inverse) effectiveness of an active region suggests that M-region streams (or void channels in this case) possibly have a dimension transverse to the ecliptic comparable to their extent in the ecliptic plane which was discussed in section 5.2.

In order to be certain of the lack of an effect due to the location of active regions on the sun, the 65 centers of activity which had their CMP within $\pm 6^\circ$ of the solar equator from January 1960 to July 1962 were used as zero days in a superposed epoch analysis. Except for not being quite late enough in the solar cycle, this definition corresponds to that used by Mustel, and the results were generally consistent with his results in as much as they showed a minimum at +3 days and a maximum at +6 days. However, these features were not both significant since the overall pattern from -35 to +90 days was found to agree in general with that shown in Fig. 26 in which the minimum at +3 days is repeated roughly every 27 days. Mustel's interpretation of the peak at +6 days as evidence for the positive effect of active regions is therefore rejected, and it concluded that centers of activity are "anti-M-regions."

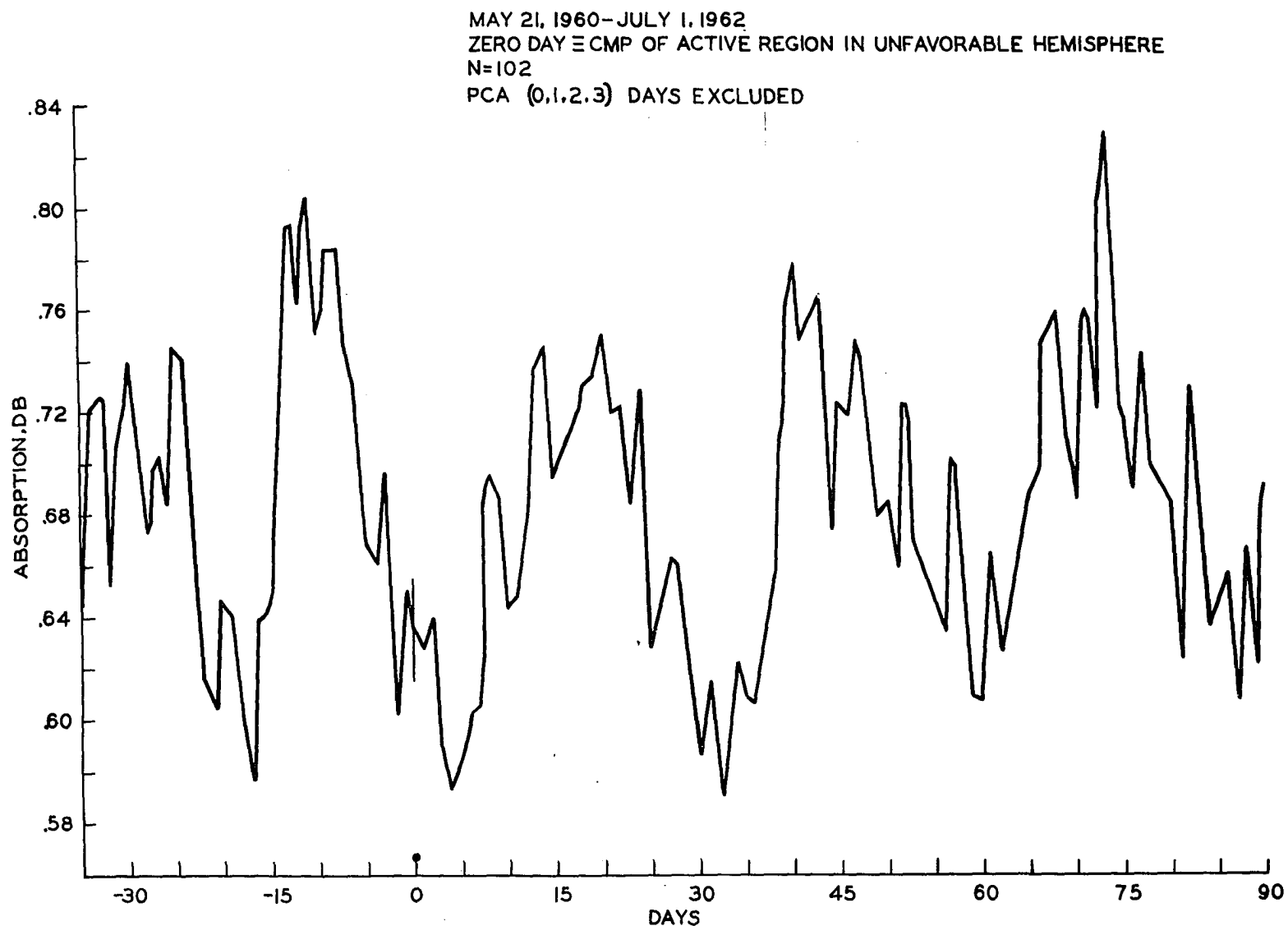


Fig. 27. The negative relation of auroral absorption to active regions in the unfavorable solar hemisphere during the later part of the declining phase of the sunspot cycle as determined by the superposed epoch technique. The unfavorable hemisphere is defined as that which does not contain the earth's heliographic latitude

5.4.4 Unipolar Magnetic Regions

Of all the suggestions for the nature of M-regions discussed in section 1.7, the only one which has not been challenged is that of Babcock and Babcock (1955) which proposes a unipolar magnetic (UM) field as the essential element differentiating between those portions of the sun's surface from which M-region streams can and cannot escape. One reason for the immunity of this suggestion has probably been the fact that Mt. Wilson has been the only observatory in the world which has been able to overcome the technical difficulties of routinely recording photospheric magnetic fields. In the nearly 10 years since the Babcocks' suggestion of an association between UM and M-regions, no one has published any detailed study which either verified or modified the original concept. However, Dr. Robert Howard and Sara Smith are currently making a comprehensive investigation of the Mt. Wilson solar magnetic field data and they kindly made these data available in reduced form for the present study of auroral absorption.

For this study attention was limited to the larger UM regions, the lower limit being established by the requirement that the product of their extents in latitude and longitude be at least 20 (in relative units approximately equivalent to 25 square degrees). The CMP dates of these larger UM regions were used as zero days in a superposed epoch analysis of absorption data, and the results are shown in Fig. 28. A positive relation is apparent in this figure since absorption increases to a maximum which is roughly symmetrical about +2 or +3 days and which recurs about 27 days later. However, if this systematic variation is truly present, there is no doubt that it is heavily obscured by large random variations. When the CMP dates of UM regions are plotted on a Bartels time

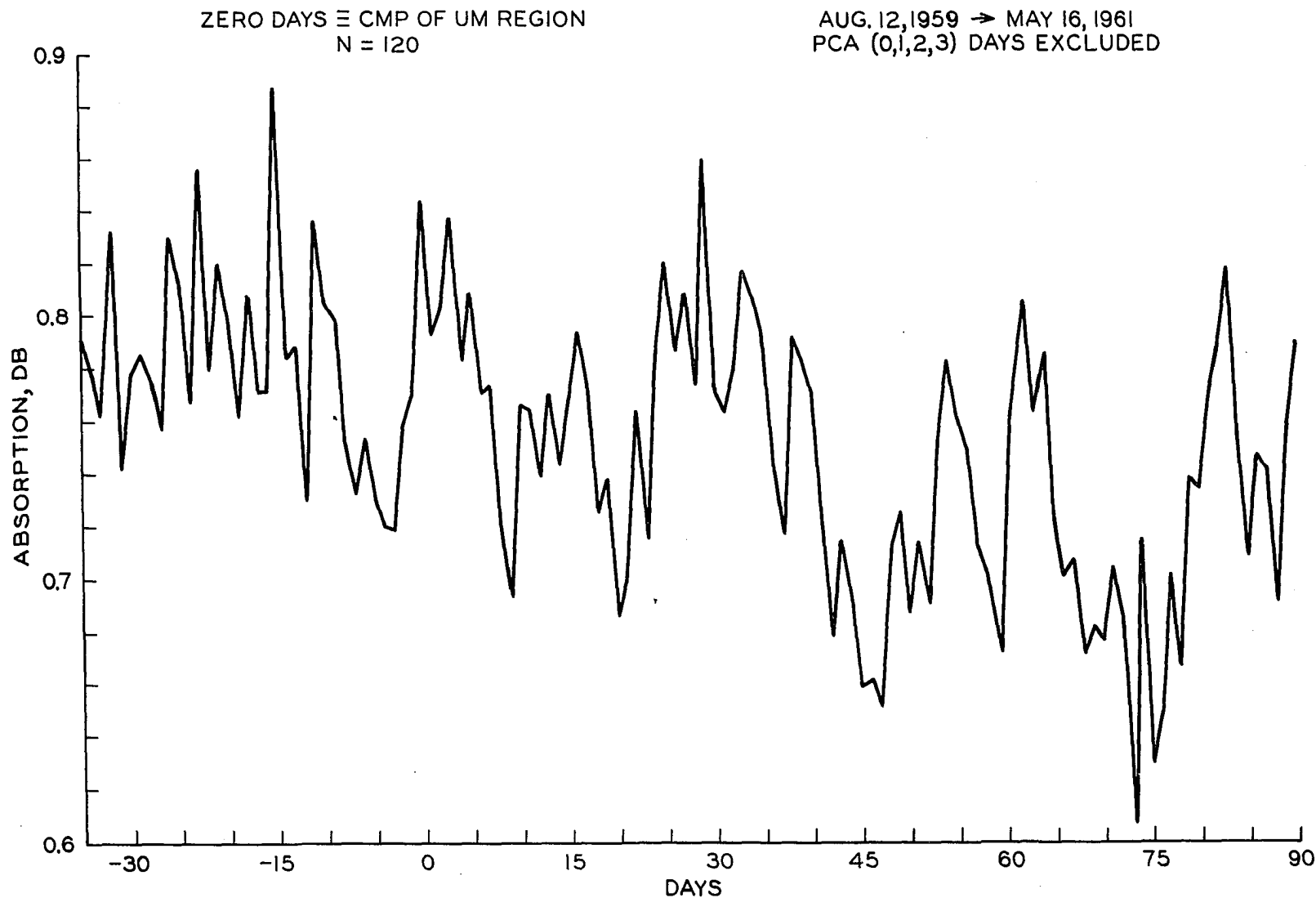


Fig. 28. The relation of auroral absorption to unipolar magnetic regions on the sun as determined by the superposed epoch technique.

pattern diagram of absorption it is found that almost as many occur before quiet periods as before disturbed periods, so there is definitely not a one to one relation between UM regions on the sun and M-type disturbances on earth. Thus, the existence of a UM region is not a sufficient condition for the emission of a long-lived particle stream, but there is a statistical indication that more often than not a direct relation does exist between these two phenomena.

The effectiveness of each of the individual UM regions was determined by examining the absorption data from one to five days following their CMP. Those UM regions which were followed by at least one disturbed day (abs. ≥ 1.0 db) and no quiet days (abs. ≤ 0.4 db) were classed as "positive." Those followed by at least one quiet day and no disturbed days were classed as "negative." All others, followed by both quiet and disturbed days, or neither, were classed as ambiguous. Calcium spectroheliograms were then examined and it was found that the positive UM regions were characterized by an absence of calcium plages, whereas the negative regions generally were associated with plages. This finding, of course, confirmed the previous result that M-regions are not associated with centers of activity, and also it gave a criterion for differentiating between those UM regions which are M-regions and those which are not.

However, this picture is not complete. So far as is known, all UM regions evolve from BM regions, which are known to correspond to centers of activity. At some late stage in its development, after a BM region has become large, weak, and diffuse, the identity is lost between its two halves of opposite polarity. At least the stronger half is then classified as a UM region. Thus, a new concept emerges for the life history of a center of solar activity. In its youth it produces flare associated

plasma clouds and PCA protons; in middle age its violent activity has disappeared and it is a BM region which inhibits the escape of matter from the sun; and finally, in very old age, as a mature UM region, it permits an enhanced outflow of solar plasma. This theory that M-regions are to be identified with old UM regions, which are a minimum of two or three solar rotations beyond the final BM stage, cannot yet be thoroughly substantiated. It is founded, for one thing, on the tendency for a 27-day recurrence pattern to be more readily discernible as time progresses from left to right in Fig. 26 (through more than four solar rotations). This behavior was also noticed for other superposed epoch results (not shown) using the CMP of UM regions as zero day. It also seems reasonable that "young" UM regions are not M-regions since they have only just evolved from active regions, which are known to be "anti-M-regions."

Assuming that M-regions are very old activity centers that have undergone a metamorphosis, the reason for the relatively abrupt disappearance of M-type storms at the beginning of a solar cycle can now be understood. It is not because activity suddenly shifts to latitudes too high for narrow angle streams of radially emitted particles to hit the earth, as has been suggested previously. It is rather because of the complete lack of any very old activity centers at the beginning of a new solar cycle.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

6.1 ABSORPTION AND THE PLANETARY MAGNETIC K-INDEX

Since almost all previous studies of solar-terrestrial relations have relied on geomagnetic disturbance to indicate the presence of solar particle streams, and the Kp index was specifically designed to function as such an indicator, it is appropriate to ask to what extent does the absorption index show the same effects as Kp, and how is it different. Also it should be asked whether absorption is a more sensitive index of the solar plasma influx, and whether it provides a better insight into the problem of the source of solar plasma than does Kp.

First of all it should be understood that PCA, which is caused by solar proton bombardment, occurs during times of magnetic quiet and is unrelated to magnetic activity except that it is generally followed after about a day by a large non-recurrent magnetic storm. Thus, Kp is not sensitive to solar cosmic rays, and when comparing absorption and Kp it is essential that PCA be excluded so that only the respective responses to the low-energy plasma streams can be examined.

Results of earlier studies, for instance Little and Leinbach (1958), have shown that absorption is closely related to magnetic activity in spite of the fact that the two phenomena show distinctly different diurnal variation patterns. However, these studies were made over limited periods and used the 3-hour values of the variables. In order to determine the gross aspects of the correspondence over longer periods of time the daily average absorption was compared to the daily sum of Kp. The results are given in Table 5.

TABLE 5
COMPARISON OF DAILY AVERAGE ABSORPTION AND ΣK_p

All Days Except PCA (0,1,2,3)	Average Absorption (db)	Average ΣK_p	Number of Days	Correlation Coefficient
Summer (M,J,J,)	0.56	20.0	371	.54
Winter (N,D,J)	0.82	18.3	484	.64
Equinox	0.76	20.1	859	.63
1957	0.94	21.2	68	.36
1958	0.84	21.2	256	.35
1959	0.79	22.3	312	.59
1960	0.79	21.9	296	.58
1961	0.59	17.6	310	.65
1962	0.72	17.4	352	.73
1963	0.53	13.5	120	.69
TOTAL	0.73	19.6	1714	.60
PCA Onset Day	1.43	25.5	74	.46
1 Day after Onset	2.41	28.8	74	.38
2 Days after Onset	2.00	33.5	72	.39
3 Days after Onset	1.72	30.8	73	.27
All PCA (0,1,2,3) Days	1.80	27.6	236	.40
TOTAL FOR ALL DAYS	0.86	20.5	1950	.47

The daily average absorption values used in this work were calculated on the basis of Alaska Standard Time (150° WMT) in order to take advantage of data which was reduced to decibel values in the early years of riometer operation before the inception of the present work. This choice of definition for the day was inconsequential to the rest of the analysis, but it precluded the possibility of direct comparison with K_p . It was therefore necessary to make the data as nearly simultaneous as possible by summing K_p over the eight 3-hour intervals beginning and ending at 2300 AST (0900-0900 UT) which was different by one hour from the 0000-2400 AST interval used for absorption. The magnitudes of the correlation coefficients calculated are slightly smaller because of this unfortunate limitation, but the significance of their relative values should be unimpaired. As an indication of the magnitude of the effect of this lack of simultaneity, a correlation coefficient of 0.79 became 0.81 when 104 days of absorption data were averaged over exactly the same 24 hours used to form ΣK_p .

Several important conclusions can be drawn from the results given in Table 5. First of all the minimum of absorption in the summer causes a marked drop in the correlation coefficient with K_p for this season. In the light of the fact that Fig. 20 in section 5.2 shows no M-region sequences which extend through the summer months, this result strongly suggests that the daily average absorption loses some of its sensitivity for detecting plasma streams during the summer months. The maximum of magnetic activity occurred in 1959, one year after sunspot maximum, followed by a continuous decline of activity in subsequent years, a typical solar cycle behavior of magnetic activity (see section 2.2). However, absorption has generally decreased since 1957 except for an increase in 1962, and the correlation coefficient has generally increased throughout the period

examined. In Fig. 20 in section 5.2 M-type absorption sequences can be recognized after the end of 1958 which show a considerable lack of similarity to those which are seen in a Bartels time pattern diagram of ΣKp . However, after 1962 there is quite close agreement in the patterns which emerge from the Bartels diagrams of the two kinds of data. The question of whether absorption or Kp is a better indicator of the solar plasma streams during the early years of declining sunspot number cannot be answered with certainty on the basis of present data, but it is probably significant that M-type sequences are better defined, especially from October 1959 to April 1961, by a Bartels diagram of absorption than of Kp .

It is also apparent from the results in Table 5 that there is poor correlation between absorption and Kp during PCA events in spite of the fact that the average of both these quantities is high during the events. This poor correlation suggests the inability of one or both of the indices employed to reflect adequately the total range of corpuscular effects during a PCA event, and thus supports one of the fundamental hypotheses of this work that no meaningful investigation of the terrestrial responses to solar corpuscular bombardment can be performed without separating, at least as much as possible, the flare induced events from those of other types.

One of the basic properties of absorption, the distribution of its daily average values, was defined in Fig. 2 in section 3.4, and the distribution of the Kp sums for the same period is given in Fig. 29. These figures show ΣKp to have a nearly normal distribution which is quite different from that of absorption which is heavily weighted on the lower (quieter) side. This striking difference in the distribution functions is

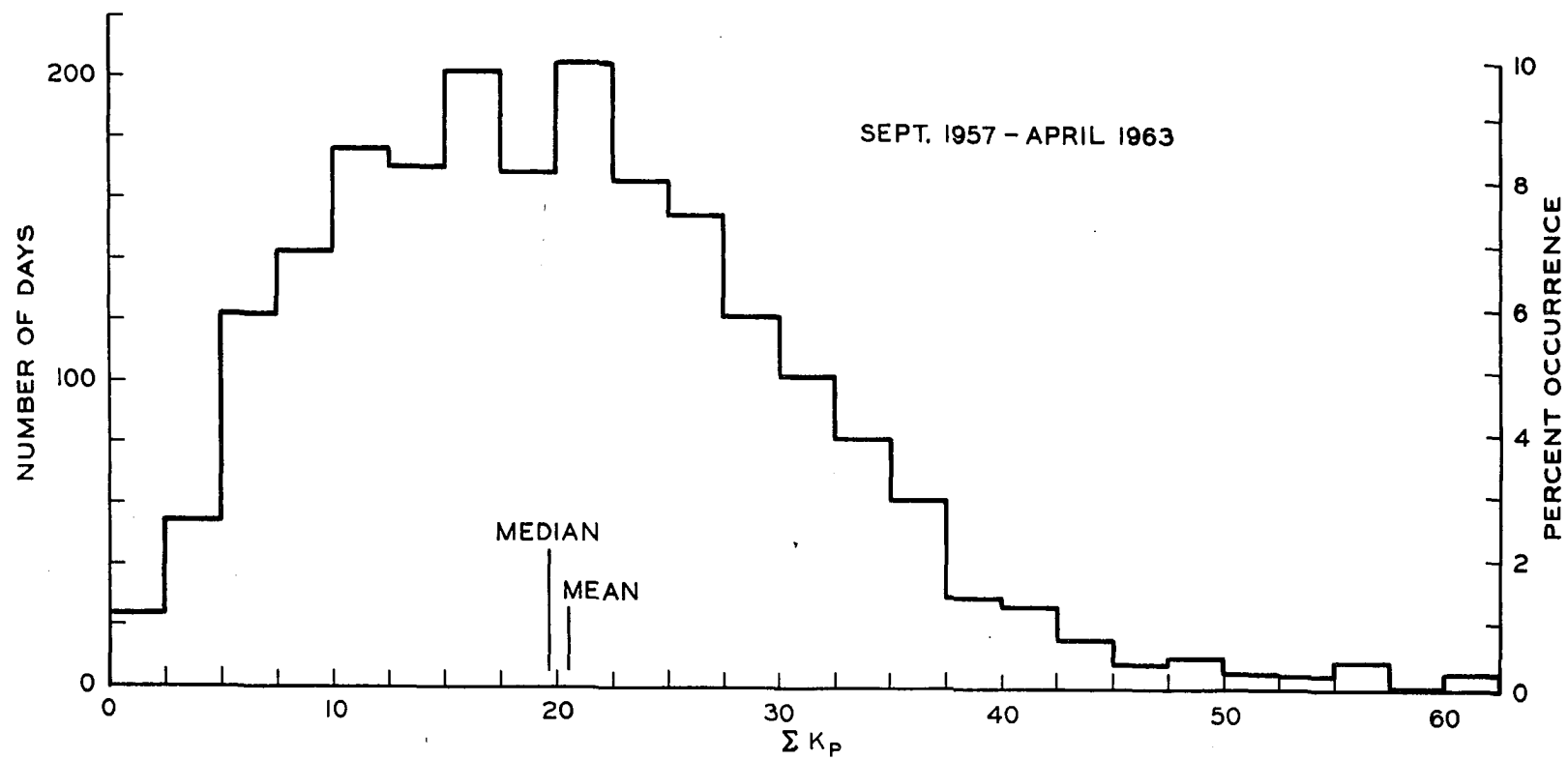


Fig. 29. The distribution of the daily sums of K_p as calculated for 2,068 days between September 1, 1957 and April 30, 1963.

surely not caused by the logarithmic nature of the absorption index since K_p is also defined in a roughly logarithmic manner, but it is probably a result of the artificial weighting of the various ingredients used to form the K_p index, making it generally conform to a normal distribution. This weighting possibly makes the larger disturbances seem less distinctive, when viewed in terms of K_p , than they actually are.

Having demonstrated that K_p is quite similar to absorption for the most part, although with a few important differences, it must now be determined whether or not these differences are sufficient to cause a change in the conclusions which were made in the last chapter on the basis of absorption data regarding the nature of solar M-regions. For this purpose the effects of the CMP of active regions and unipolar magnetic regions on geomagnetic activity were calculated for the same time intervals covered by Figs. 26 and 28 in the last chapter. The results are shown in Figs. 30 and 31 where it can be seen that although there are some small differences, the gross features are the same as were found using absorption, namely that solar active regions cause a decrease in terrestrial disturbance which is repeated regularly at 27-day intervals whereas UM regions are followed by a poorly defined but evident enhancement of terrestrial disturbance which shows a definite 27-day recurrence tendency. Thus, it is concluded that, given the means of identifying and excluding flare associated events, the K_p index is essentially equivalent to absorption (at least during the last years of a sunspot cycle) in its ability to delineate the large-scale average effects of solar particle streams.

However, a means of making a more detailed comparison of the relative effectiveness of absorption and K_p in detecting streams of solar plasma is

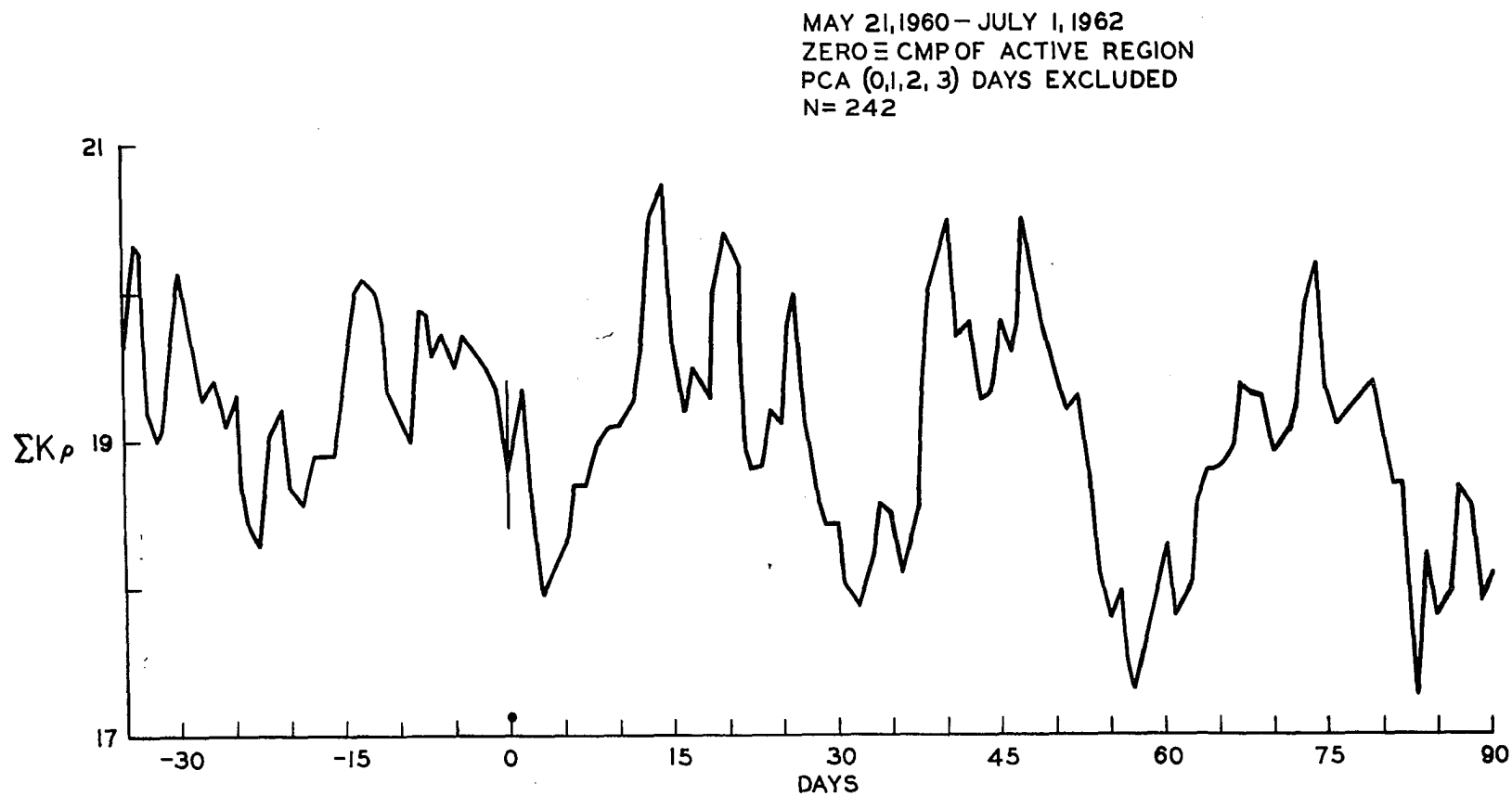


Fig. 30. The negative relation of ΣK_p to active solar regions during the later part of the declining phase of the sunspot cycle as determined by the superposed epoch technique. To be compared with Fig. 26.

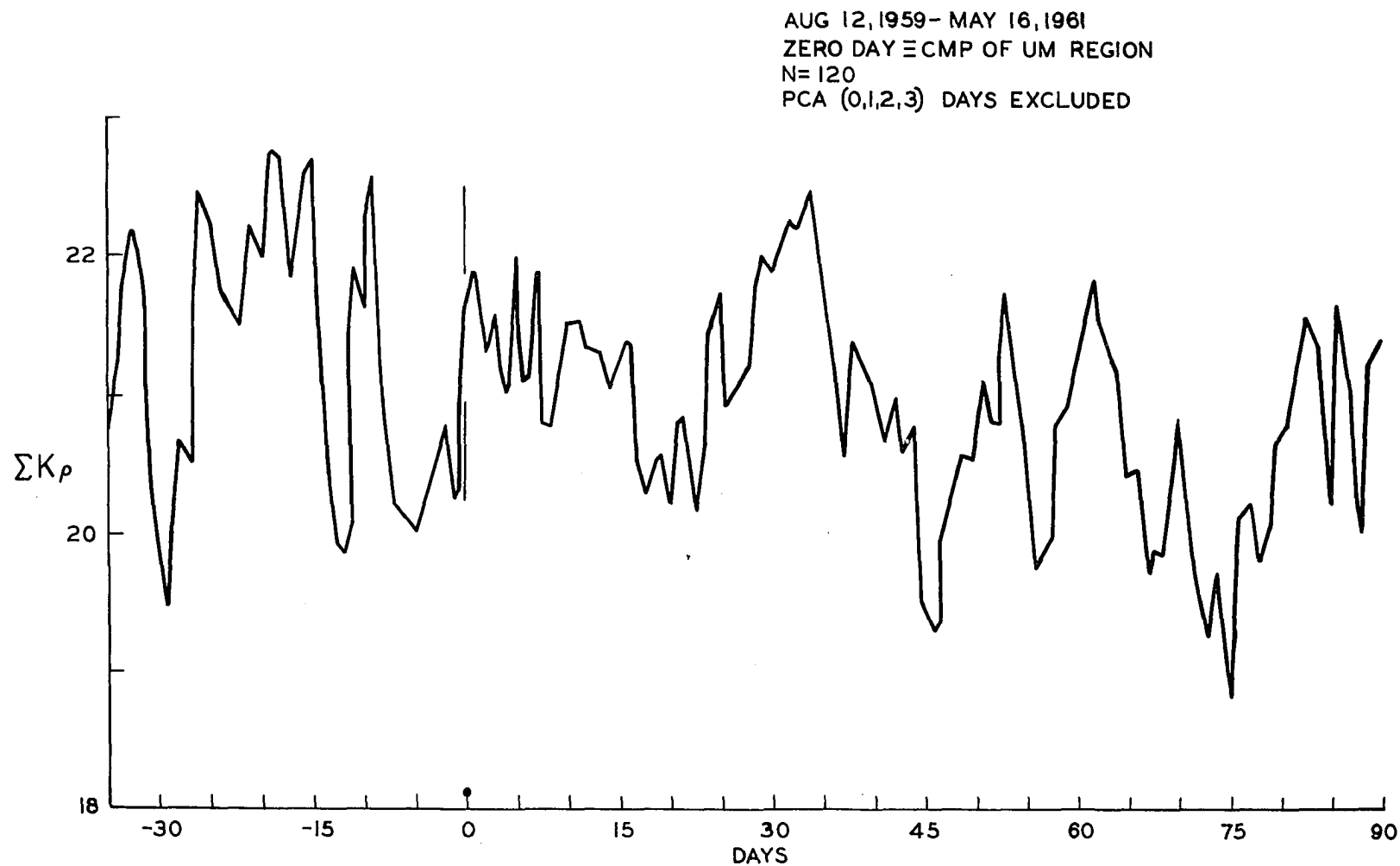


Fig. 31. The relation of ΣK_p to unipolar magnetic regions on the sun as determined by the superposed epoch technique. To be compared with Fig. 28.

available in the form of the Mariner 2 plasma data. Snyder, Neugebauer, and Rao (1963) found a high correlation between the observed daily mean plasma velocity and ΣKp , the value being 0.73 ± 0.04 for the entire period of observation from August through December 1962. The direct measurements of the solar plasma made by Mariner 2 provide a standard against which absorption and Kp can be compared, so correlation coefficients were calculated and are given in Table 6. For these calculations, average absorption and ΣKp were both computed for the UT day, as was the mean plasma velocity. However, there were 11 days for which there was not sufficient absorption data to use in computing an average value, so the N for the correlation calculation was 104 instead of 115. The exclusion of these 11 days did not change the value of the correlation coefficient between plasma velocity and ΣKp , since in both cases it was found to be 0.73.

TABLE 6

Correlation coefficients for 104 simultaneous values of daily average absorption, ΣKp , and daily mean plasma velocity.

Absorption and Plasma Velocity	ΣKp and Plasma Velocity	Absorption and ΣKp
0.71	0.73	0.83

As can be seen from Table 6, this was a period of unusually high correlation between absorption and Kp , and from Fig. 20 in Chapter 5 it is apparent that this was also a period with well-developed M-type disturbances. Thus, the nearly identical correlation coefficients are not surprising, and it must be concluded that during the period examined, absorption and Kp were equally responsive to the solar plasma. It would have been interesting to compare the correlations during a period, such as 1959 or 1960, when

absorption and Kp showed a much less similar behavior and M-regions seemed to be better defined in terms of absorption than by Kp.

Another means of demonstrating the relation of absorption and plasma velocity is by the scatter diagram shown in Fig. 32. This figure should be compared to Fig. 3 of Snyder, Neugebauer, and Rao (1963) who found by a least squares analysis using Kp that the best fit was given by the equation

$$V(\text{km/sec}) = 8.44 \Sigma Kp + 330.$$

It should be noted that the intercept in Fig. 32 shows zero absorption to correspond to a plasma velocity of 400 km/sec whereas 330 km/sec is the threshold velocity as defined by Kp. However, velocities lower than 400 km/sec were observed to generate absorption. In one case with low velocity the daily average absorption was found to be greater than 1 db, which is a disturbed day as defined in Chapter 5; and December 9, the least disturbed day observed in the entire period with an average absorption as close to zero as can be measured within the limitations of the technique, had a mean plasma velocity of only 343 km/sec. It is felt that not too much significance should be attached to the actual magnitude of this background velocity as defined by either absorption or Kp since there is obviously considerable scatter about the computed lines in both cases. The significant fact is that a threshold velocity does exist and is in the range of 300-400 km/sec. It is also important that absorption is as closely related to the solar plasma velocity as Kp even though it is defined by only one station. Presumably the scatter in Fig. 32 could be reduced somewhat by using an absorption average compiled from a network of auroral zone stations in both hemispheres, but the scatter is probably more a result of the spatial separation between the space-craft and the

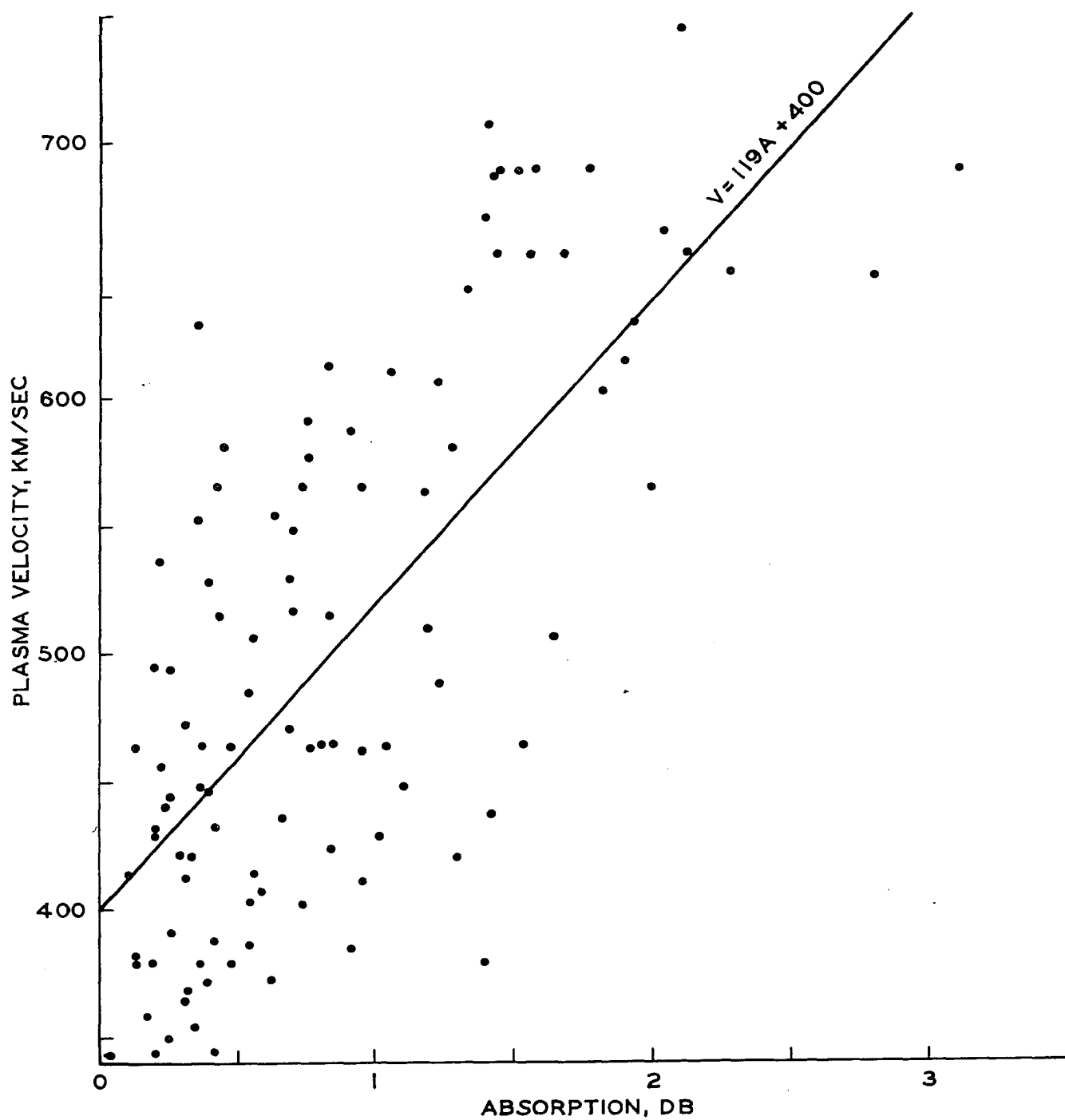


Fig. 32. Scatter diagram of daily mean plasma velocity and daily average absorption. The line represents the least squares fit to the points and is defined by the equation $V(\text{km/sec}) = 119A + 400$ where A is the daily average absorption in decibels.

earth, and of some plasma property other than velocity which is as yet unmeasured but which contributes to terrestrial disturbance.

Even if Table 6 did not show absorption to be as closely related to the solar plasma as K_p , absorption would still be a unique and thus valuable indicator since it shows the behavior of that particular element of solar "disturbance" which is responsible for the actual precipitation of particles into the auroral zone. That this is not always true for K_p is made clear in Table 5. This investigation was undertaken not only in the hope of shedding light on the general subject of solar-terrestrial relations, but also with the belief that an understanding of high latitude radio wave absorption, especially for purposes of predicting propagation conditions, rests fundamentally on the relation of absorption to solar phenomena. Thus it is felt that the results have an intrinsic value irrespective of the validity of the assumption stated in Chapter 3 that daily average absorption is a more quantitatively accurate index of solar corpuscular influx than ΣK_p .

6.2 SOLAR-TERRESTRIAL RELATIONS

So far this work has been concerned with discussions of both the general nature of solar corpuscular emission processes and their effects observed on the earth and the specific relation of ionospheric radio wave absorption events to occurrences on the sun. This and the following section will summarize the earlier information in an effort to unify the presentation. The next section will contain the conclusions about PCA and auroral absorption events and their respective behaviors in relation to solar phenomena, but first there is a need for a concise description of

the general field of solar-terrestrial relations and a discussion of what new insights the present work has given into this field.

The essence of the previous discussions on solar-terrestrial relations are contained in the simple schematic diagram in Fig. 33. The concept of electromagnetic wave radiation and the effects of its many components ranging from radio waves through gamma rays are not germane to the present study and so are not elaborated in the diagram. However, it is included for the sake of completeness. Except for electromagnetic waves, the only available carriers for solar energy are corpuscles which can contribute not only their own kinetic energy but are also capable of transferring "frozen-in" magnetic fields. The division between energetic nuclei and plasma is made on the basis of both energy and composition. Energetic nuclei are of course all positively charged and consist mostly of protons but with a few alpha particles and heavier nuclei. A plasma is ionized, although not necessarily completely, but is macroscopically neutral, containing positive and negative charges in equal abundance and with the same velocities. Energetic nuclei are divided between solar cosmic rays with energies from about 1-20 Bev and solar sub-cosmic rays with energies from about 30 Mev to several hundred Mev. These particles are all accelerated during solar flares and of course have a continuous energy spectrum which varies greatly in slope and extent from one flare to another. Particles in solar plasmas are generally believed to have energies in the range from a few electron volts (for electrons) to about 10 or more kev (for protons).

Solar plasmas are divided in Fig. 33 into 3 types according to differences in their origin and spatial extent. The term solar wind is used

SOLAR-TERRESTRIAL RELATIONS

VEHICLES FOR TRANSFERRING SOLAR ENERGY TO THE EARTH

TERRESTRIAL EFFECTS

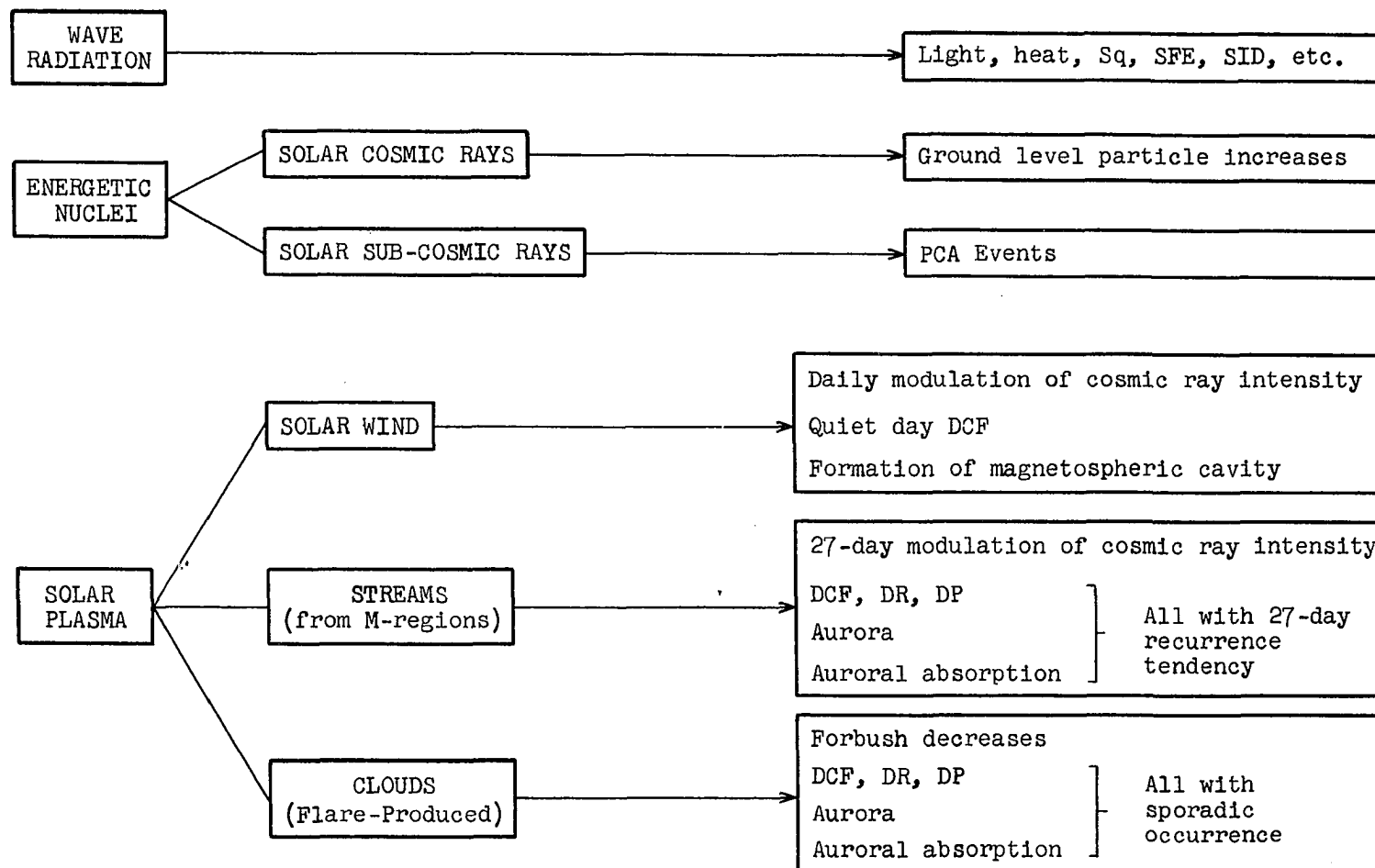


Figure 33. Schematic diagram of solar-terrestrial relations.

ambiguously by many authors to include all types of solar plasma flow, but the concept as it is used here refers to the steady-state streaming from the undisturbed sun as it was visualized by Parker (1958b) when he first discussed the continuously expanding solar corona. A comprehensive review of this concept is given by Parker (1963). The velocity of this background plasma flow was measured by Snyder, Neugebauer, and Rao (1963) to be approximately 300-400 km/sec. It should be noted that the solar wind as so defined is not believed to have any significant relation to geomagnetic or auroral phenomena.

The term stream is employed to describe those plasma emissions whose cross-sectional dimensions are much less than their length. These streams are quasi-permanent features, lasting in some cases for many months and they are twisted into a spiral shape by the sun's rotation. However, only the envelope is twisted. The individual particles travel in straight lines essentially radially. On the basis of their longevity, these streams are defined as emanating from M-regions. Clouds, or shells as they are sometimes called, have cross sectional dimensions at least as great as and sometimes much greater than their length (defined in the direction of propagation), and they are ejected sporadically from centers of activity during some solar flares. Although they have different shapes and origins, clouds and streams travel on the average at about the same velocity of approximately 600 km/sec since their travel times are both observed to be about 3 days (Saemundsson, 1962). The plasma velocity in the streams encountered by Mariner 2 were also observed to have about this average velocity (Snyder, Neugebauer, and Rao, 1963). It should be noted, however, that great magnetic storms follow about one day after large flares (Allen, 1944; Newton, 1943, 1944; Bell, 1961) which requires a velocity of about

1740 km/sec. For smaller flares the velocity tends to be lower, so the average of 600 km/sec reflects the scarcity of these large events.

An explanation of the symbols for geomagnetic disturbance used in Fig. 33 can be found in Chapman (1963). He divides the disturbance (or D) field into the components DCF, DR, and DP each having a different physical origin. The DCF field (CF for "Corpuscular Flux" or for "Chapman-Ferraro") is produced by the plasma pressure on the earth's main field at a distance of approximately 10 earth radii. The DR field is the ring current field generated by the collective motions of charged particles around the earth in the outer radiation belt. The DP field (P for polar) is produced by ionospheric current systems in the auroral zone and polar cap of both the northern and southern hemispheres. This work by Chapman (1963) contains some of the best detailed discussions of solar-terrestrial relations to be found in one collection anywhere in the open literature.

One of the basic unanswered questions about the relation of geomagnetic and auroral disturbances to the solar plasma is whether the plasma protons and electrons are captured by the earth's main field and forced to participate directly in the disturbance processes (and if so, how) or whether the plasma only perturbs the earth's environment in some way which accelerates resident particles with previously undetectably low energies and causes them to partake in the disturbance reactions. A possible answer to this question has been suggested by Akasofu and McIlwain (1963) and Akasofu (1964a) who propose energetic neutral hydrogen atoms as a source of the ring current particles. The beauty of their suggestion is that no complicated injection mechanism is required to get particles from the plasma into the magnetosphere. It also explains why

there is no disturbance produced by the background solar wind, since Akasofu (1964b) noted that, according to the theory of the solar wind as an expansive motion of hot coronal gas, it would contain very little neutral hydrogen. However, one minor limitation of the neutral hydrogen theory is that it so far has no provision to explain the delay between the onsets of the initial and main phases of magnetic storms. The initial phase is well understood as an effect of ionized plasma. If the onset of the main phase is to be interpreted as due to the arrival of neutral hydrogen, then there must be some explanation of why there should be an abrupt transition between fully ionized gas at the front of a cloud or stream, and only partial ionization elsewhere.

Before proceeding in the next section with the discussion of the specific conclusions reached in this work, some of the insights gained into the general subject of solar-terrestrial relations should be mentioned. One of the features that distinguishes this work from previous investigations is the use of PCA events to separate the effects of active regions from the effects of M-regions. There is no corresponding straightforward criterion for separating magnetic storms according to whether they are related to flares or M-regions. One possible technique is to exclude storms with sudden commencement, but not all SC storms are flare-produced and not all gradual commencement storms are attributable to M-regions. Another practice is to restrict the investigation to years of low sunspot number when the relative absence of flare-storms makes the M-region effects seem more prominent. However, this practice has given rise to what is probably a mistaken notion that M-regions only exist during years near sunspot minimum. The results in Chapter 5 show that M-regions are detectable at least within a year after sunspot maximum although their effective

lifetime is shorter during these years of high activity. It is not meant to imply that all non-M-region effects have been eliminated by excluding PCA events, but at least a rigorously defensible criterion has been established which prevents a large measure of contamination that previously would have been unavoidable in studies of M-region effects.

Two important general principles must be borne in mind in studies of solar-terrestrial relations. These are: 1) A cause and effect interpretation of M-type phenomena must be consistent with transit times from sun to earth of from one to five days; and 2) Any effect which is attributed to M-regions must exhibit a strong 27-day periodicity. Transit times longer than five days are unacceptable because they are inconsistent with the Mariner 2 observation that the plasma velocity must be greater than about 330 km/sec in order to have any geomagnetic effect. It is likewise not acceptable to invoke a non-radial emission of particles to account for longer or shorter transit times of M-region particles. Although there is as yet no observational data of the precise direction of the plasma flow, Explorer 10 placed the direction within a window of about 20° by 80° which contained the direction pointing radially away from the sun (Bonetti, et al., 1963). Mariner 2 data can likewise be interpreted as showing that the plasma flow was from a direction within the range from $\sim 15^\circ$ west to $\sim 5^\circ$ to the east of the sun and within $\pm 10^\circ$ of the ecliptic (Marcia Neugebauer, private communication). Also, although it is not exactly relevant to the M-region problem, an essential feature of the solar wind, as it is envisioned by Parker (1963), is that it blows radially from the sun. The 27-day periodicity is the single defining characteristic of M-region effects, so it is imperative that this periodicity be demonstrated before any observed behavior can be rightfully interpreted as an M-region effect.

It was for this reason that a long time span, usually from -35 to +90 days, was used in the present work, and it is felt that the improved perspective gained thereby has allowed the truly significant features to be recognized more easily here than was possible in previous works with more limited time scales. A review of Mustel's work (see section 1.7) in the light of the two above-mentioned principles shows that neither is adhered to and so weakens his argument that centers of activity are the sources of M-regions particle streams. His interpretation of the maximum at +6 days requires an average particle velocity of less than 300 km/sec, and the limited time span of his diagrams (from -15 to +15 days) precludes the possibility of ascertaining which (if any) of the features he observes has a tendency for 27-day recurrence.

6.3 PHYSICAL ASPECTS OF THE RELATION OF ABSORPTION TO SOLAR PLASMA

Since an empirical approach has been employed throughout this work it is important to give some consideration to the physical processes through which the sun's corpuscular radiation effects absorption. Of course there are many problems to be dealt with, including the physics of the different solar corpuscular emission processes, the propagation of particles through interplanetary space, and the mechanism by which energy is transferred from the solar plasma into the earth's magnetosphere. Because terrestrial data have formed the basis of this work, the later subject has been chosen for a brief development in this section.

6.3.1 Physical properties of the solar plasma

The basic parameters describing a field-free neutral plasma are T , the temperature, N , the number density, V the bulk velocity, and M the mass of the ions. From these fundamental parameters several other

important quantities can be derived to describe the physical nature of the plasma (Spitzer, 1962). The basic plasma parameters in interplanetary space are still not known precisely. Their values have been predicted theoretically by a number of authors (see discussion in Parker, 1963) and have been measured experimentally by Explorer 10 (Bonetti, et al., 1963) and Mariner 2 (Neugebauer and Snyder, 1962). The measured values are listed in Table 7. The Explorer 10 measurements were made during a 40 hour period at a distance from the earth of from 22 to 42 earth radii. Because of this short period of observation and the possibility of confusion due to proximity of the earth (for instance, by a shock wave in front of the magnetosphere), the calculations in this section will be based on the Mariner 2 results only.

Table 7.

The temperature, density, and bulk velocity of the interplanetary plasma as measured by Explorer 10 and Mariner 2.

	T(°K)	N(cm ⁻³)	V(km/sec)
Explorer 10	6 x 10 ⁵	7	280
	3 x 10 ⁵	4	280
Mariner 2	1.9 x 10 ⁵	2.5	460
	7.4 x 10 ⁵	4.5	8.0

The Mariner 2 data for V = 460 km/sec represent very nearly average (but not quiet) conditions (Snyder et al., 1963). Unless otherwise noted, the calculations in this section will refer to these average values. In some cases, when values are considered other than the two sets listed, a linear interpolation or extrapolation is required. In all cases the plasma

is assumed to be made up of ionized hydrogen, so M is taken as the mass of a proton, 1.67×10^{-24} g.

The minimum distance over which the plasma can be considered electrically neutral is called the Debye shielding distance or the Debye length and is given by

$$h = \text{Debye length} = \left(\frac{kT}{4\pi N e^2} \right)^{1/2} = 6.90 \left(\frac{T}{N} \right)^{1/2} \text{ cm} = 19 \text{ m.}$$

An ionized gas is called a plasma if h is small compared with other distances involved, such as the container size in a laboratory or the mean free path. This latter distance is the ratio of the mean thermal velocity to the collision frequency. The collision frequency is a complex concept in an ionized gas, but for the case of proton-proton Coulomb collisions it can be shown to be

$$\nu = \text{self collision frequency} = \frac{5.71 \pi N e^4 Z^4 \ln \Lambda}{M^{1/2} (3kT)^{3/2}} = 0.0877 \ln \Lambda N T^{-3/2}$$

Λ is the ratio of the Debye length to the distance of closest approach of the colliding particles, and for T less than about 4×10^5 °K it is given by

$$\Lambda = \frac{3}{2Z^2 e^3} \left(\frac{k^3 T^3}{\pi N} \right)^{1/2} = 1.24 \times 10^4 \left(\frac{T^3}{N} \right)^{1/2} = 6.49 \times 10^{11}$$

For higher temperatures this equation must be multiplied by $(4.2 \times 10^5/T)^{1/2}$ because of quantum mechanical effects. The function $f(w)$ giving the number of particles per cubic centimeter per unit interval of thermal velocity (w) is given by assuming a Maxwell-Boltzmann distribution

$$f(w) = 4\pi w^2 N \left(\frac{M}{2\pi kT} \right)^{3/2} e^{-\frac{Mw^2}{2kT}}$$

The mean thermal velocity (\bar{w}) for protons is then defined by

$$\bar{w} = \frac{\int_0^\infty wf(w)dw}{\int_0^\infty f(w)dw} = \left(\frac{8KT}{\pi M} \right)^{1/2} = 1.45 \times 10^4 T^{1/2} \text{ cm/sec}$$

Thus the mean free path between proton-proton collisions in the average solar plasma is

$$\lambda = \frac{\bar{w}}{v} = \frac{1.66 \times 10^5 T^2}{N \ln \Lambda} = 8.82 \times 10^{13} \text{ cm} = 5.88 \text{ a.u.}$$

The plasma must therefore be considered collisionless in its interaction with the earth's magnetic field.

The kinetic energies of the individual plasma particles are given by the relativistic formula

$$E = \text{kinetic energy} = MC^2 \left[\left(1 - \frac{v^2}{c^2} \right)^{-1/2} - 1 \right]$$

which because of the relatively low velocities can be reduced by means of a binomial expansion to

$$E = MV^2 \left(\frac{1}{2} + \frac{3}{8} \frac{v^2}{c^2} \right)$$

Actually, even the second term is negligible for velocities less than about 10^4 km/sec. The electron and proton energies corresponding to the range of interplanetary velocities discussed in this work are listed in Table 8. Some of these travel times refer to plasmas and others to solar cosmic rays on sub-cosmic rays.

Table 8.

The particle energies corresponding to the range of observed sun-earth travel times.

Travel Time	Velocity km/sec	Electron Energy ev	Proton Energy ev
20 min	125,000	50.4×10^3	92.3×10^6
1 hour	41,600	5.00×10^3	9.14×10^6
2 hours	20,800	1.24×10^3	2.26×10^6
5 hours	8,310	197	361×10^3
10 hours	4,160	49.3	90.3×10^3
20 hours	2,080	12.3	22.6×10^3
1 day	1,730	8.53	15.6×10^3
2 days	865	2.13	3.90×10^3
3 days	577	0.950	1.74×10^3
4 days	433	0.535	977
5 days	346	0.342	625
6 days	288	0.236	433

It is important to note in Table 8 that protons which travel to the earth in about one hour or more have an energy less than 10 Mev whereas polar cap protons are observed on the earth to have energies in the range of about 30-300 Mev. This discrepancy is generally explained in terms of a temporary trapping, or storage, of the energetic protons in magnetic fields borne by the flare ejected plasma. On the other hand, the electrons which travel to the earth in about three days have energies less than one ev, which is at least $10^3 - 10^4$ times smaller than the energies of the electrons which cause aurora and auroral absorption. This difference requires that a mechanism

for accelerating electrons within the magnetosphere be an essential part of any auroral theory.

The two most important properties of the plasma in its interaction with the earth are its energy density and frozen-in magnetic field strength. The energy density has two components, kinetic and thermal, given by

$$\text{kinetic energy density} = \frac{1}{2} NMV^2 = 4.42 \times 10^{-9} \text{ dynes/cm}^2$$

and

$$\text{thermal energy density} = \frac{3}{2} NKT = 9.85 \times 10^{-11} \text{ dynes/cm}^2.$$

The thermal pressure is thus sufficiently lower than the kinetic pressure to neglect it except on the nightside of the earth. When the plasma is streaming away from the earth, the thermal pressure alone acts to confine the geomagnetic field to a cavity.

The general interplanetary magnetic field is carried outward from the sun by the continually expanding solar corona, according to the theory of Parker (1963). The fundamental condition which must be satisfied in order for a plasma to transport a "frozen-in" magnetic field is that the kinetic energy density of the plasma must exceed $B^2/8\pi$, the energy density of the field. Coleman, et al. (1962) measured the interplanetary field to be between 2 and 10 gamma. Taking a value of 5 gamma gives $B^2/8\pi = 9.96 \times 10^{-11} \text{ dynes/cm}^2$ which is 44 times smaller than the kinetic energy density calculated above. Although the individual particles stream radially from the sun at all times, the field which they carry takes the shape of an Archimedes spiral because of the sun's rotation. The stream angle, between the field line and the solar radius vector, is shown by Chapman (1929) to be

$$\text{stream angle} = \arctan \frac{\Omega R}{V} = \arctan \frac{430 \text{ km/sec}}{V}$$

Thus the average interplanetary magnetic field is inclined to the solar radius vector by about 45° .

6.3.2 Patterns of particle precipitation

The interpretation of the observed daily and seasonal variations of absorption, as well as of the existence of an auroral absorption zone, in terms of the temporal and spatial variations of particle energies precipitated into the upper atmosphere from the earth's radiation belt was introduced in an earlier paper (Basler, 1963). This interpretation has been confirmed subsequently by satellite observations (O'Brien, 1964; Frank, et al., 1964). It will now be extended to include a discussion of how the gross aspects of absorption, and thus of particle precipitation, are related to the solar plasma. The chain linking absorption to precipitated particles, to the solar plasma and finally to solar M-regions will then be completed.

The depth of penetration of the plasma into the region permeated by the earth's magnetic field can be estimated by computing at what point the plasma energy density, $1/2 NMV^2$, will be balanced by the energy density, $B^2/8\pi$, of the earth's field (Parker, 1958a). Assuming the earth's field to be a dipole whose flux density at any point is given by

$$\vec{B}(R, \theta) = B_0 \frac{a^3}{R^3} (\sin \theta \vec{\theta}_1 + 2 \cos \theta \vec{R}_1)$$

where R is the geocentric distance, θ the colatitude, a the radius of the earth, and $B_0 = 0.312$ gauss. The scalar magnitude, found by taking the dot product of the vector with itself, is

$$B(R, \theta) = B_0 \left(\frac{a}{R} \right)^3 (1 + 3 \cos^2 \theta)^{1/2}$$

The balance condition is then

$$\frac{1}{2} NM V^2 = \frac{B_o^2}{8\pi} \left(\frac{a}{R} \right)^6 (1 + 3 \cos^2 \theta)$$

or

$$\frac{R}{a} = \left[\frac{B_o^2 (1 + 3 \cos^2 \theta)}{4\pi NM V^2} \right]^{1/6}$$

The latitude, ϕ_o , at which this balance point is projected onto the earth's surface, is calculated using the field line equation ($R = a \cos^2 \phi_o$) to be

$$\phi_o = \arccos \left[\frac{B_o^2 (1 + 3 \cos^2 \theta)}{4\pi NM V^2} \right]^{1/2}$$

For plasma streaming radially from the sun and penetrating along a radius vector to the center of the earth, the angle θ will vary during the year between extremes of 55° and 125° . However, this variation has a very small effect on the value of ϕ_o . For penetration in the equatorial plane, i.e. for $\theta = 90^\circ$, the values of ϕ_o are given in Table 9 for the extremes of the plasma energy density as inferred from the previous discussions of observed travel times and Mariner 2 data.

Table 9.

The geomagnetic latitude, ϕ_o , at which the energy density in the earth's magnetic field balances the plasma energy density during very quiet and very disturbed conditions.

$N(\text{cm}^{-3})$	$V(\text{km/sec})$	ϕ_o
1.6	300	74°
4.5	810	68°
9.8	1740	63°

The maximum of the auroral absorption zone was at 65° and the auroral zone maximum was at 67° during the I.G.Y. Thus it is reasonable to associate the location of terrestrial disturbance patterns with the region in the magnetosphere at which the plasma energy density is equal to the magnetic energy density. Table 9 shows that particle precipitation should occur further south during larger disturbances, which agrees with observations although the magnitude of the calculated shift is smaller than what is observed. Another discrepancy is that a ring current will usually exist at 5 earth radii or less during great disturbances. This ring current decreases the total field within its perimeter and increase it outside, so the energy balance with the solar plasma should occur further from the earth, that is, at a higher value of ϕ_0 . Obviously there cannot be a direct connection between plasma penetration depth and particle precipitation patterns, but the agreement is sufficiently good to support a general cause and effect interpretation. In actuality, the plasma does not penetrate into the field but rather compresses it until the magnetic pressure of the compressed field equals the pressure (both kinetic and thermal) of the solar plasma. Because of the resulting distortion of the field lines, ϕ_0 cannot be accurately calculated, as was done, by assuming the equation of a dipole field line.

There are basically three different aspects of auroral absorption which must be explained as solar plasma effects. These are: 1) the latitude variation, 2) the daily variation, and 3) the seasonal variation. The latitude variation gives an auroral absorption zone between $\sim 60^\circ$ - 70° geomagnetic latitude with a maximum at 65° . The daily variation shows a maximum around 1000 local time and a minimum around 2000-2200 local time. The seasonal, or annual, variation shows a well defined minimum in summer (May,

June, and July) which is opposite to the effect which would be expected if photodetachment or photoionization were the controlling processes. The latitude and daily variations can be combined to define a pattern of particle precipitation on the earth's surface, and this has been done by Hartz, et al. (1963) using both Canadian and Norwegian riometer data. They found that absorption appeared on the earth in a pattern fixed with respect to the sun and the geomagnetic pole, and they noted that this pattern was very similar to that predicted theoretically by Axford and Hines (1961).

The Axford and Hines theory postulates that a viscous-like interaction between the magnetosphere and the solar plasma as it streams past the earth causes a convection system to be established in the outer magnetosphere. This convection system is distorted by the effect of the earth's rotation, and when the resulting flow lines are mapped onto the earth's surface along the dipole field lines, the result is quite similar to the observed absorption (particle precipitation) pattern. The salient feature of the daily variation of absorption is its asymmetry about the noon meridian, consisting as it does of a pre-noon maximum and a pre-midnight minimum. This same asymmetry has been noted in several other geophysical phenomena (for instance, Wilson and Sugiura, 1961, 1963; Wilson, 1962) which are all more or less related to particle precipitation, and several authors (Hones, 1963; Axford, 1963; Walters, 1964) have attempted to explain it theoretically.

The seasonal variation of absorption with its well defined summer minimum is one of the most interesting characteristics of auroral absorption, and one which possibly holds the key to understanding the relation of absorption to the solar plasma. Unlike geomagnetic activity, which shows pronounced equinoctial maximums, there is no possibility of explaining the systematic changes of absorption as an effect of narrow-beam corpuscular

sources on the sun combined with the regular changes of the earth's heliographic latitude. It seems most probable that the explanation lies instead in the seasonal change of orientation of the earth's dipole moment with respect to the sun-earth line, i.e. the direction of the solar plasma flow. In order to test this theory the seasonal variation was determined from over 5 1/2 years of data at College. In order that the results would not be affected by the daily variation, only the absorption at geomagnetic noon (≈ 13 -14 hours local time), when the sun was overhead on the College geomagnetic meridian, was taken into account. The average absorption at geomagnetic noon was then determined for each month of the year along with the angle (λ) between the sun-earth line and the earth's magnetic dipole moment at geomagnetic noon on the 15th of the month. The results are shown in Fig. 34. The points can be seen to lie reasonably close to a straight line, defined according to the least squares principle as

$$\text{Abs (db)} = 0.0143\lambda^\circ - 0.428$$

Fig. 34 shows very clearly that absorption is directly related to the orientation of the geomagnetic dipole with respect to the sun-earth line, so it is natural to ask if the observed daily variation is controlled by the same mechanism. Because the earth's magnetic axis is inclined by about 11.5° to the spin axis, the angle λ undergoes a variation of about 23° during the course of each day. The daily variation of absorption can therefore be predicted according to the linear relation defined above by the seasonal variation. The daily variation predicted in this manner and compared with the observed variation is shown in Fig. 35. It is immediately obvious from this figure that the predicted variation is nearly 180° (12 hours) out of phase with the observed, and the magnitude is too small

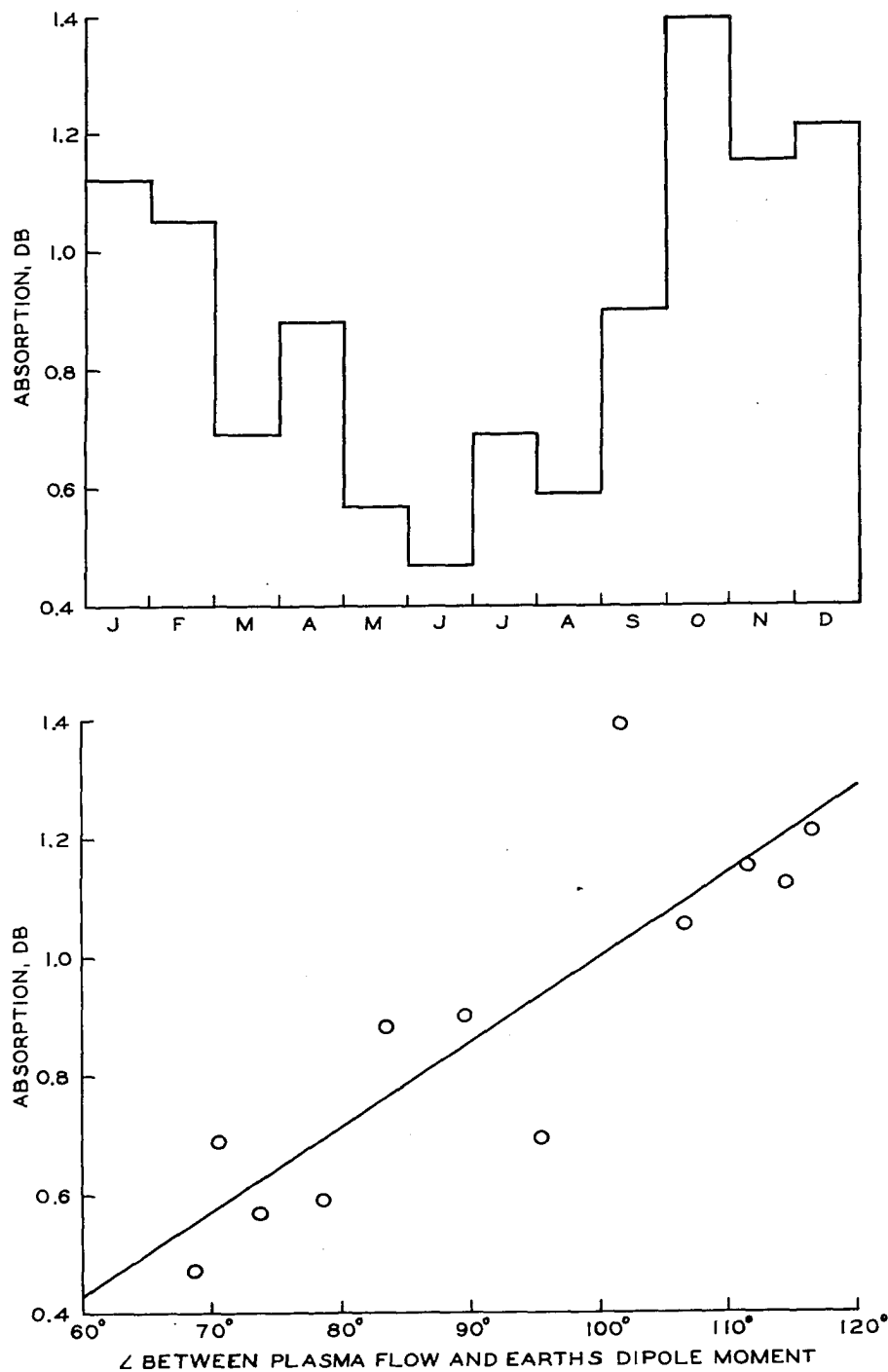


Fig. 34. The seasonal variation of absorption at College at geomagnetic noon on the basis of data from September 1957 through May 1963. The angle (λ) between the direction of plasma flow and the earth's dipole moment can also be interpreted as the sun's geomagnetic declination (δ) according to the relation $\delta = 90^\circ - \lambda$. The straight line is a least squares fit to the points defined by the equation $\text{Abs (db)} = 0.0143 \lambda^\circ - 0.428$.

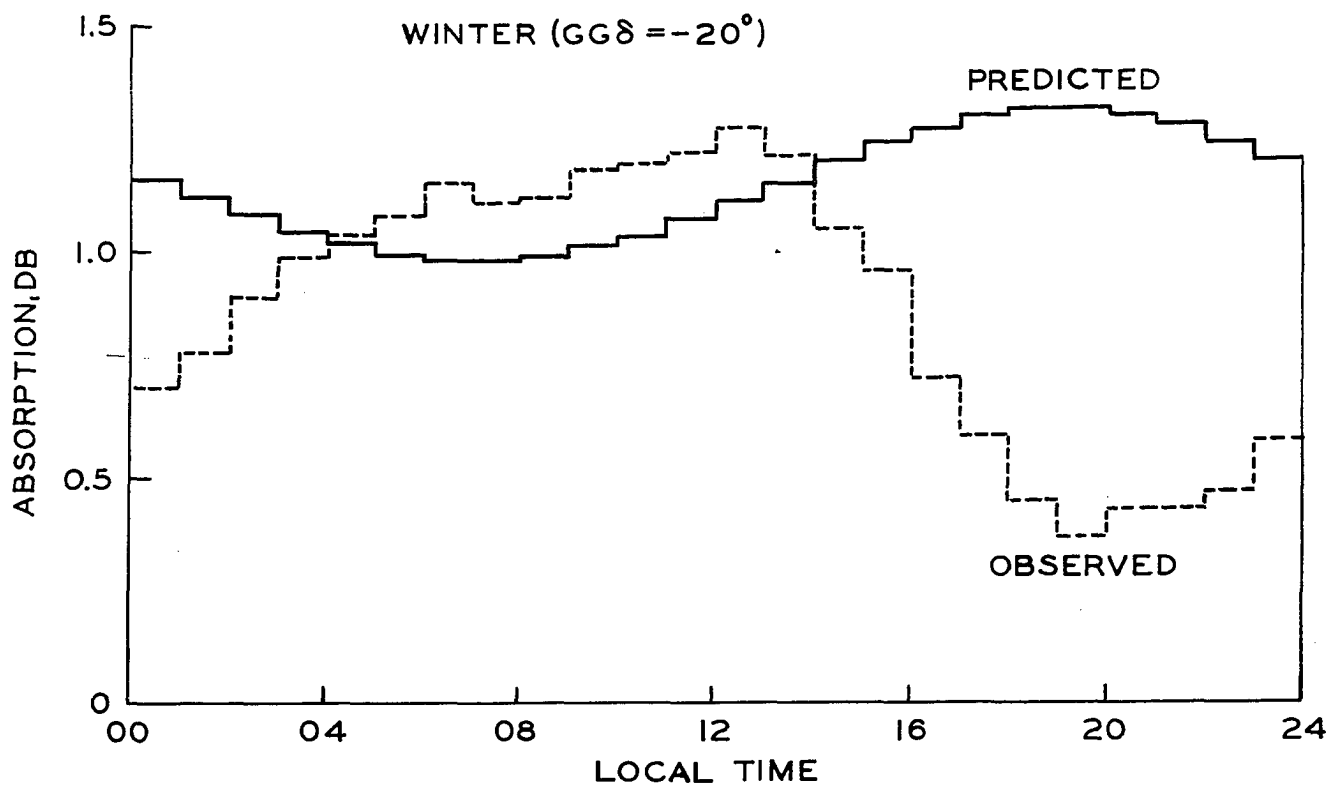
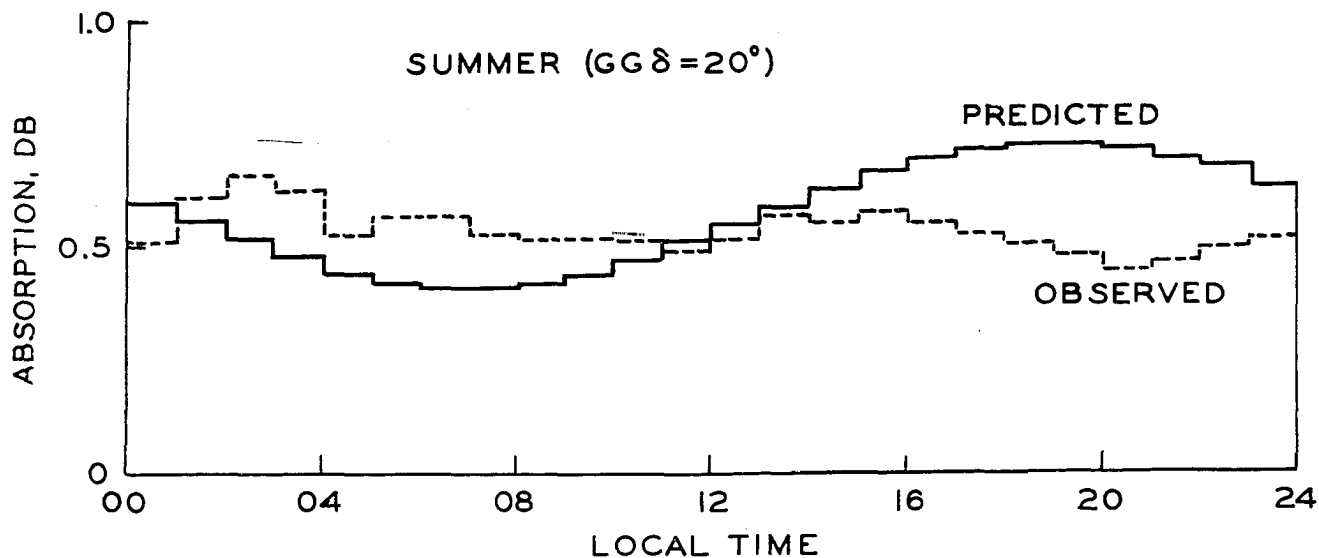


Fig. 35. The observed daily variation of absorption at College for the period September 1957 - June 1962 compared with the daily variation predicted from the relation $Abs (db) = 0.0143 \lambda^\circ - 0.428$. The sun is assumed to have a constant geographic declination of 20° in summer (M, J, J) and -20° in winter (N, D, J).

by more than a factor of three to explain the winter variation. If the λ dependence can be assumed to operate throughout the day in addition to whatever mechanism actually controls the daily variation, then the true daily variation is more accentuated than the observed, and it can be determined by combining the calculated and observed curves.

The asymmetry about noon of the local time variation of a number of geophysical phenomena (including absorption) is assumed to reflect a basic asymmetry of the magnetosphere, or in general, of the interaction of the solar plasma and the geomagnetic field, with respect to the sun-earth line. In a recent paper, Walters (1964) has suggested that this asymmetry is an effect of the obliquity of the spiral interplanetary magnetic field with respect to the radially streaming solar plasma. He shows that this oblique interplanetary magnetic field causes a deflection of the corpuscles which traverse the standing hydromagnetic shock wave upstream from the earth. The result of this deflection is that the solar plasma flows toward the magnetosphere from a direction west of the sun-earth line. This paper is well written and introduces an interesting concept, but a major weakness seems to be that the predicted deflection decreases when the plasma velocity (and thus the terrestrial disturbance) increases. It has been shown in an earlier paper (Basler, 1963) that strong asymmetry exists under disturbed conditions, but during quiet periods there is little if any detectable asymmetry in the local time variation of absorption. Walters introduces the parameter $\beta = 4 \pi N M V^2 / B^2$, the ratio of kinetic energy density to magnetic energy density in the solar plasma, and he shows that $\Delta\alpha$, the angle through which the solar plasma is deflected in traversing the shock front, decreases for increasing β . This behavior is also mentioned by Dessler and Walters (1964). In order for β to decrease during a disturbance (and thereby

increase $\Delta\alpha$), it is necessary for the interplanetary magnetic flux density, B , to increase more than the plasma velocity and square root density. However, the Mariner 2 data, as they are discussed by Smith (1964) for instance, imply that changes in the magnitude of the interplanetary magnetic field are generally accompanied by corresponding changes in the plasma velocity. In fact, it is necessary for the kinetic energy density to exceed the magnetic energy density (i.e. $\beta > 1$), otherwise the plasma is not capable of transporting a "frozen-in" magnetic field. For this reason, it is felt that Wilson (1962) was mistaken in his conclusion that the solar plasma flow is guided by the extended solar magnetic field. The deflection of the corpuscular flow ($\Delta\alpha$) for $\beta \approx 44$, the "average" defined by the Mariner 2 data discussed previously, is about 7° , which, when added to the 5° deflection caused by the earth's orbital velocity, is too small to account for the observed asymmetry in the pattern of particle precipitation. At least 30° is needed.

It is concluded that a suitable explanation for the daily variation of absorption has not yet been developed, but the mechanisms proposed by Hones (1963), Axford (1963), and Walters (1964) are all steps in the right direction. Possibly a combination of these theories would prove adequate to explain the observations.

6.3.3 Role of the Kelvin-Helmholtz instability

The annual variation of absorption shown in Fig. 34 is believed to be representative of the behavior of absorption all over the world. The June minimum is also found in the Antarctic (Bellchambers, Barclay, and Piggott, 1962), and the behavior is similar to the worldwide variation of f_oF_2 , which is higher in December than in June and also has a more

pronounced daily variation in December than in June (Duncan, 1962; Thomas, 1963; Piddington, 1964b). It is difficult to imagine any explanation for these observations other than an annual variation in worldwide particle precipitation, that is of the influx of solar plasma on the earth. However, the mechanism controlling the annual variation of this influx is still unknown.

One possible explanation might lie in the fact that the earth is about 3.4% closer to the sun on the first of January than it is on the first of July. Assuming an inverse square law, this difference means that the earth receives about 7% more corpuscular (and other) energy at perihelion than at aphelion, but this change is too small to account for the observed difference of a factor of two. Another possible explanation, mentioned by Piddington (1964b), might be that the geographic co-latitude of the south eccentric dipole pole is 15.3° , whereas that of the north is 9.4° . Thus during the December solstice there is a greater daily oscillation of the magnetic field lines, which, through some hydromagnetic process, could result in an increased capture of energy from the surrounding plasma at this time.

It seems unlikely that any second order effect, such as either of the two mentioned, can be the controlling factor in the annual variation of plasma influx. A more credible mechanism lies in a systematic variation of the frictional interaction between the streaming plasma and the earth's magnetic field. Such an interaction has already been proposed by Axford and Hines (1961) to account for the observed daily precipitation pattern, so it is logical to try to extend it to account for the annual effect. One mechanism would then be responsible for all three of the previously

mentioned aspects of absorption which must be interpreted in terms of the solar plasma.

Axford and Hines do not discuss exactly how their assumed frictional interaction is brought about, but Piddington (1964a) suggests that it is caused by an instability of the Kelvin-Helmholtz type at the magnetospheric boundary. Piddington does not elaborate his suggestion, but instead tries to develop a theory of M-region storms which is unfortunately based on the assumption (disproved by Mariner 2) that M-region streams have a lower velocity than the surrounding plasma. The following discussion is presented to show how the Kelvin-Helmholtz instability, which is controlled by the relative orientations of the interplanetary and geomagnetic fields (among other things), might explain the dependence of absorption on the orientation of the earth's dipole moment.

The boundary between the plasma bearing the sun's magnetic field and the earth's field with its trapped radiation can obviously be analyzed as a hydromagnetic discontinuity, and the conditions for its stability can be derived when certain simplifying assumptions are made. Several authors have investigated the stability of the magnetospheric boundary and have come to different conclusions (for example, Parker, 1958a; Hurley, 1961; Sen, 1962). Although there has been some attempt to invoke the Rayleigh-Taylor instability, which requires that the plasmas have no relative velocity tangential to their boundary, as a means of injecting solar plasma into the magnetosphere (Barthel and Sowle, 1964), most studies have considered the Kelvin-Helmholtz instability, for which $V_t \neq 0$, as the means of transferring energy from one medium to the other.

Assuming a plane interface (which is approximated over small distances on the magnetosphere) the stability conditions for incompressible, inviscid, and perfectly conducting fluids are given by Landau and Lifshitz (1960) in their expressions 53.13 to be

$$H_1^2 + H_2^2 > \frac{4\pi\rho_1\rho_2}{\rho_1 + \rho_2} v^2$$

$$(\vec{H}_1 \times \vec{H}_2)^2 > \frac{4\pi\rho_1\rho_2}{\rho_1 + \rho_2} \left[(\vec{H}_1 \times \vec{v})^2 + (\vec{H}_2 \times \vec{v})^2 \right]$$

where the subscripts identify the two sides of the boundary, $\vec{v} = \vec{v}_2 - \vec{v}_1$, and $\rho = \text{NM}$. It is assumed that any change which goes in the direction of violating these stability conditions will serve to increase auroral absorption. This assumption can not be defended rigorously, but it is not unreasonable since the first condition shows that an increase of plasma energy density (which has already been shown empirically, using the Mariner 2 data, to increase absorption) will tend to reduce the stability of the boundary. Since the cross product of two vectors vanishes as the angle between them goes to zero or π , the second stability condition is obviously weakened in proportion to the component of the interplanetary field along the earth's field lines. Of course, the earth's field is three dimensional, so every conceivable orientation with respect to the interplanetary field occurs somewhere, but an "overall" or "effective" field orientation can be considered to be the direction of the dipole moment. Thus, some of the dependence of absorption on the orientation of the earth's dipole moment shown in Fig. 34 can be understood in terms of the Kelvin-Helmholtz instability. However, an obvious weakness of this theory is that it predicts

an equinoctial maximum, i.e. a sine squared dependence, instead of the approximately linear dependence shown in Fig. 34. As has been mentioned previously, planetary magnetic activity maximizes during the equinoxes, which does fit well with the instability theory, but the annual variation of absorption must still be considered as unexplained.

The application of hydromagnetic stability theory to the magnetospheric boundary has so far been too complex a problem to receive an adequate theoretical treatment. One limitation of the Kelvin-Helmholtz instability might seem to be that there can be no mass transfer across the boundary since the normal component of velocity is zero. However, Syrovatskiy (1954) has shown that a continuous transition is possible between a tangential (Kelvin-Helmholtz) disturbance and a magnetohydrodynamic wave disturbance in which there is momentum transfer across the boundary. The pursuit of this subject is outside the scope of the present investigation. It has been introduced to give some measure of physical meaning to the interpretation of absorption as a solar plasma effect.

6.4 SUMMARY OF CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

The purpose of this work has been to show how the corpuscular bombardment which causes the absorption of cosmic radio noise in the auroral and polar ionosphere is related to solar phenomena and to show the significance of this relationship in the context of other studies of the terrestrial effects of solar particles. This work represents the first attempt to use absorption (which is proportional to the total corpuscular energy deposited in the ionosphere) as an index of the solar plasma flux in a study of solar-terrestrial relations. Likewise, the knowledge of

PCA occurrences has been utilized for the first time to systematically separate the effects of centers of solar activity from the effects of M-regions.

The work quite naturally divided itself into two parts, namely the study of PCA and of auroral absorption events. The use of the superposed epoch technique to investigate the recurrence tendency of PCA and the relation of absorption to solar radio emissions revealed a previously unsuspected cycle in solar activity with a period of around 32-35 days. This cycle is even more marked than the tendency toward a 27-day periodicity which is governed by the propensity of discrete solar regions, in particular large and/or magnetically complex sunspots, to generate PCA events. No explanation is offered for this newly observed cycle, and no pretense is made of having conclusively demonstrated its reality. If it is again detected in the PCA occurrences of the next sunspot cycle, it can then be considered as more than a fortuitous relation. In the meantime it would be interesting to examine the occurrence statistics of related solar features (such as flares of various sizes, shapes, and locations) in search of a similar periodicity. A general tendency for PCA flares to prefer the western side of the solar disk, and for western flares to be followed more quickly than eastern flares by the arrival of particles at the earth, supports the idea that solar magnetic fields extend nearly radially into interplanetary space, and, being bent by the sun's rotation, provide a more favorable route to the earth for particles from the western side of the disk than from the eastern. However, the necessary and sufficient conditions for the ejection of energetic nuclei and plasma clouds from active regions on the sun have still not been defined, and the association of PCA events with specific flares is still uncertain in most cases. Although the distinguishing

characteristics of PCA flares have not yet been recognized, it is felt that flare perimeter might be a better criterion for classifying the effectiveness of flares in accelerating and ejecting particles than anything previously used, including size, coverage of sunspot unbras, or explosive development. This suggestion was made by Harry Ramsey after we had decided that a general filamentary appearance was the only common characteristic exhibited by the PCA flares recorded by the Lockheed patrol. An investigation of the usefulness of this suggestion is planned for a future study.

Although the examination in Chapter 4 of the polar cap absorption phenomenon produced some interesting relationships as a result of displaying the old PCA data in a new way using the superposed epoch technique, the most important outcome from the present work has been the new information presented in Chapter 5 on the longstanding problem of the nature of solar M-regions. As was stated in section 1.7, one school of thought contends that the source of M-region particles is in active regions, but two different pieces of evidence weigh against this idea. First, the average conditions on the sun are out of phase with conditions on earth in the sense that terrestrial disturbances of the M-region type occur during periods of solar quiet, and vice versa. In other words, auroral absorption is found to occur after a period of diminished solar activity, and quiet days, i.e. days with little auroral absorption, occur during times of increased disturbance on the sun as measured by the standard indices such as sunspot number, 2800 mc/s flux, coronal line emissions, or flare activity. Second, no significant evidence can be found for an increase of M-type terrestrial disturbance as a result of the CMP of centers of activity on the sun. To the contrary, if attention is restricted to the later half of the declining phase of the sunspot cycle when solar activity has been reduced to the

point where the effects of individual active regions can be separated, these active regions are seen to cause a marked decrease in terrestrial disturbance.

To some extent this conclusion about the negative effect of active regions might appear to support the cone of avoidance theory, but this is not the case. An essential feature of this theory is that a concentration of plasma should occur at the edges of the cone of avoidance and cause two periods of enhanced magnetic activity (or absorption) which occur on either side of the quiet period produced by the cone of avoidance. Taking the average duration of quiet and disturbed periods from section 5.2 to be five days, and assuming the travel time from sun to earth to be three days, the pattern which should be seen following the CMP of an active region (in Figs. 26, 27, or 30, for instance) is a minimum at +3 days preceded by a maximum at -2 days and followed by a minimum of +8 days. This pattern should then be repeated every 27-days. Although the minimums in Figs. 26, 27, and 30 occur at about +3 days the maximums occur at about -10 days and +17 days, much too far removed to be interpreted as effects of a concentration of plasma at the edges of a cone of avoidance. The true picture seems to be that active regions and their associated "cones of avoidance" cause the void channels which recur at 27-day intervals and produce periods of terrestrial quiet, but the M-region streams which cause the disturbances are independent of active regions except in so much as they do not occur within the centers of activity.

Having made the point that M-regions are not active regions the question of what are they remains to be answered, but no definite answer can yet be provided. Unipolar magnetic regions on the sun show a statistical association with M-regions, but a large percentage of UM regions are followed by periods of terrestrial quiet. Thus, some subdivision of UM

regions must be made before a full understanding of M-regions will be achieved. A possible subdivision was suggested in terms of the age of the UM region. According to this suggestion, "young" UM regions, which have only just evolved from BM regions, are embryonic M-regions which will not have any terrestrial effects until they have matured for two or three solar rotations.

There are quite possibly two or more radically different competing processes which sustain long-lived particle emission from the sun. If this were true it would account for some of the difficulty in establishing a simple one-to-one relationship between solar and terrestrial phenomena. The lack of understanding of solar-terrestrial relations does not seem to stem so much from the lack of an adequate terrestrial indicator of solar particles, i.e. from the inability to detect their presence near the earth, as from the lack of any real understanding of the processes on the sun which are responsible for the emission of the particle streams. It is toward improving this understanding that future efforts should be directed.

If the idea of using absorption data as an index of solar plasma flow is to be pursued in future studies, two suggestions can be made for improving the method. First, the daily average absorption should be computed from riometer data obtained at a large number of auroral zone stations in both hemispheres. A network of stations of this sort would remove the error (probably about 20%) imposed by the assumption necessary with only one station that the solar plasma flux does not change during a time interval as short as one day. A world wide index would allow short term global absorption fluctuations of only a few hours, or even minutes, to be detected and compared with the small scale variations measured in the interplanetary

plasma by vehicles such as Mariner 2. A second refinement which could be made in the absorption method is to perform a continuous integration of the daily absorption curve instead of summing the 15-minute values. This would remove the small error ($\sim 2\%$) introduced by the fact that auroral absorption frequently undergoes variations of several db in two or three minutes which are not adequately represented by the 15-minute values. It would be a simple matter to record the cosmic noise intensity at one minute (or shorter) intervals on paper tape or magnetic tape using commercially available equipment. Absorption values and "planetary" absorption indices could then be calculated easily using a simple computer facility.

APPENDIX

NUMERICAL INTEGRATION OF THE DAILY ABSORPTION FUNCTION

In order to calculate the daily average absorption it is necessary to integrate the variable giving absorption as a function of time over a period of one day. As was described in Chapter 3, the riometer records the cosmic noise intensity continuously in terms of a current, I_q , through a noise diode, and the absorption is calculated using the quiet day current, I_q , at the same sidereal time from the relation

$$\text{Abs (db)} = 10 \log_{10} \frac{I_q}{I_d} \quad (1)$$

The standard method of finding the approximate integral of this expression over a given time T is to sum in the manner

$$\sum_{k=1}^N A_k \Delta t_k = 10 \sum_{k=1}^N \log_{10} \frac{I_{qk}}{I_{dk}} \Delta t_k \quad (2)$$

where

Δt_k = time interval in which A_k occurs

N = number of samples taken.

Δt_k is made a constant independent of k , in which case $N \Delta t_k = T$. Of course the total interval of integration, T , is 24 hours when the daily average absorption is to be found.

It has always been a nuisance when dealing with the raw riometer data, I_{dk} , to have to calculate the sidereal time and then take the corresponding quiet day current into account before finding the value of the absorption. Therefore, a unique advantage of calculating the daily average absorption is that the sidereal time need not be considered, and the quiet day currents

can be combined into a single constant, as is evident from the following treatment.

Equation (2) can be rewritten

$$\sum_{k=1}^N A_k = 10 \left[\sum_{k=1}^N \log_{10} I_{qk} - \sum_{k=1}^N \log_{10} I_{dk} \right] \quad (3)$$

When T is taken as 24 hours (or, more accurately, one sidereal day) the

term $\sum_{k=1}^N \log_{10} I_{qk}$ is a constant for all days, and so need only be calculated once. Since the sum of logarithms is the logarithm of a product, equation (3) can also be written

$$\sum_{k=1}^N A_k = 10 \left[\log_{10} \prod_{k=1}^N I_{qk} - \log_{10} \prod_{k=1}^N I_{dk} \right] \quad (4)$$

where again $\prod_{k=1}^N I_{qk}$ is a constant from day to day. If equation (4) is

used to calculate the daily average absorption the computation is faster than with equation (3) since only one logarithm is taken. However, a practical limitation is the size of the product for large N , since it might be too big for even a computer to handle. For instance, for $N = 1440$ (i.e. one minute values throughout a day) the size of the product exceeds 10^{99} , the largest number which can be handled conveniently by the IBM 1620.

In this work the daily average absorption was calculated from values taken at 15-minute intervals throughout the day, that is with $\Delta t_k = 15$ minutes. Since there is a lot of variation in auroral absorption with a time scale of much less than 15 minutes, it is important to determine the

amount of error introduced by this approximate numerical integration. The practical lower limit for Δt_k , imposed both by the instrumental time constants and the chart speed at which the recordings were made, is about one minute. Thus the actual value of the daily average absorption, at least as close as it can be determined from the riometer records available for this study, is calculated from measurements, I_{dk} , taken at one minute intervals. This actual value will be referred to as $A(1)$. The per cent error introduced by calculating the daily average absorption, $A(m)$, from scalings made at intervals of m -minutes, is given by

$$\text{Per cent error} = \left[\frac{A(m) - A(1)}{A(1)} \right] \times 100 = \left[\frac{A(m)}{A(1)} - 1 \right] \times 100 \quad (5)$$

The accuracy of the daily averages calculated from 15-minute scalings is least reliable for disturbed days on which the absorption shows a considerable irregularity in its time variation. In order to place an upper limit on the uncertainty in the daily absorption values used in this work, a study was made of these irregular disturbed days to determine how much the calculated daily average deviated from the true average when the scaling interval, Δt_k , was increased up to as much as one hour. In all, nine days were scaled at one minute intervals and the daily average absorption, $A(m)$, was calculated for each day with m , i.e. Δt_k , taking on integral values from one to fifteen minutes and then proceeding in steps of five minutes up to one hour. The per cent error was then calculated according to equation (5) for each value of m , and the means and standard deviations of the absolute value of the per cent error are shown in Figs 36 and 37.

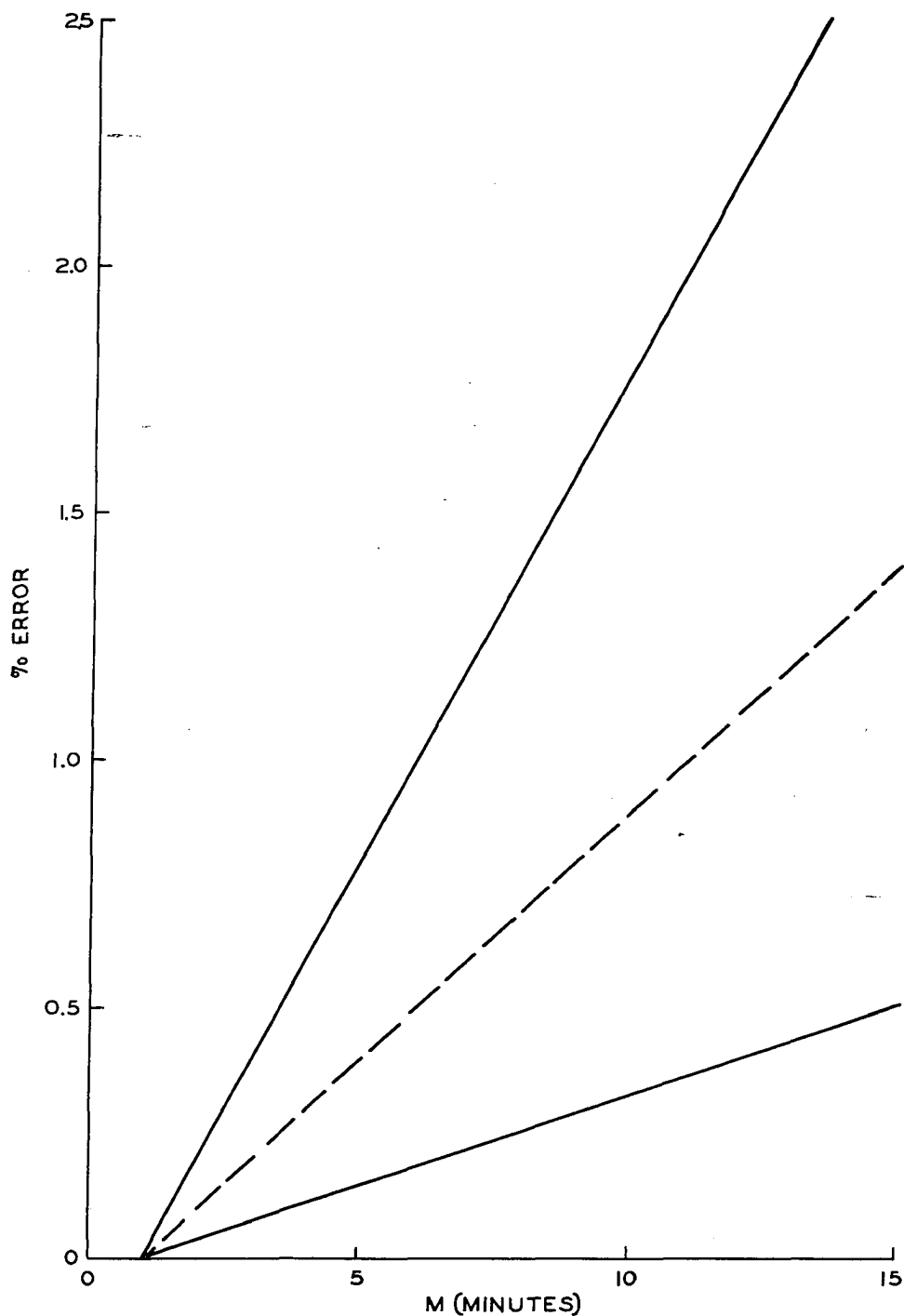


Fig. 36. The absolute value of the per cent error of the daily average absorption, defined in equation (5), as a function of m , the time interval at which the riometer record is scaled. The solid lines show the upper and lower limits of the observed standard deviations. Each of the individual standard deviations was much less than shown by these limits. The dashed line was drawn to pass within the standard deviation of each point and so indicates the average trend.

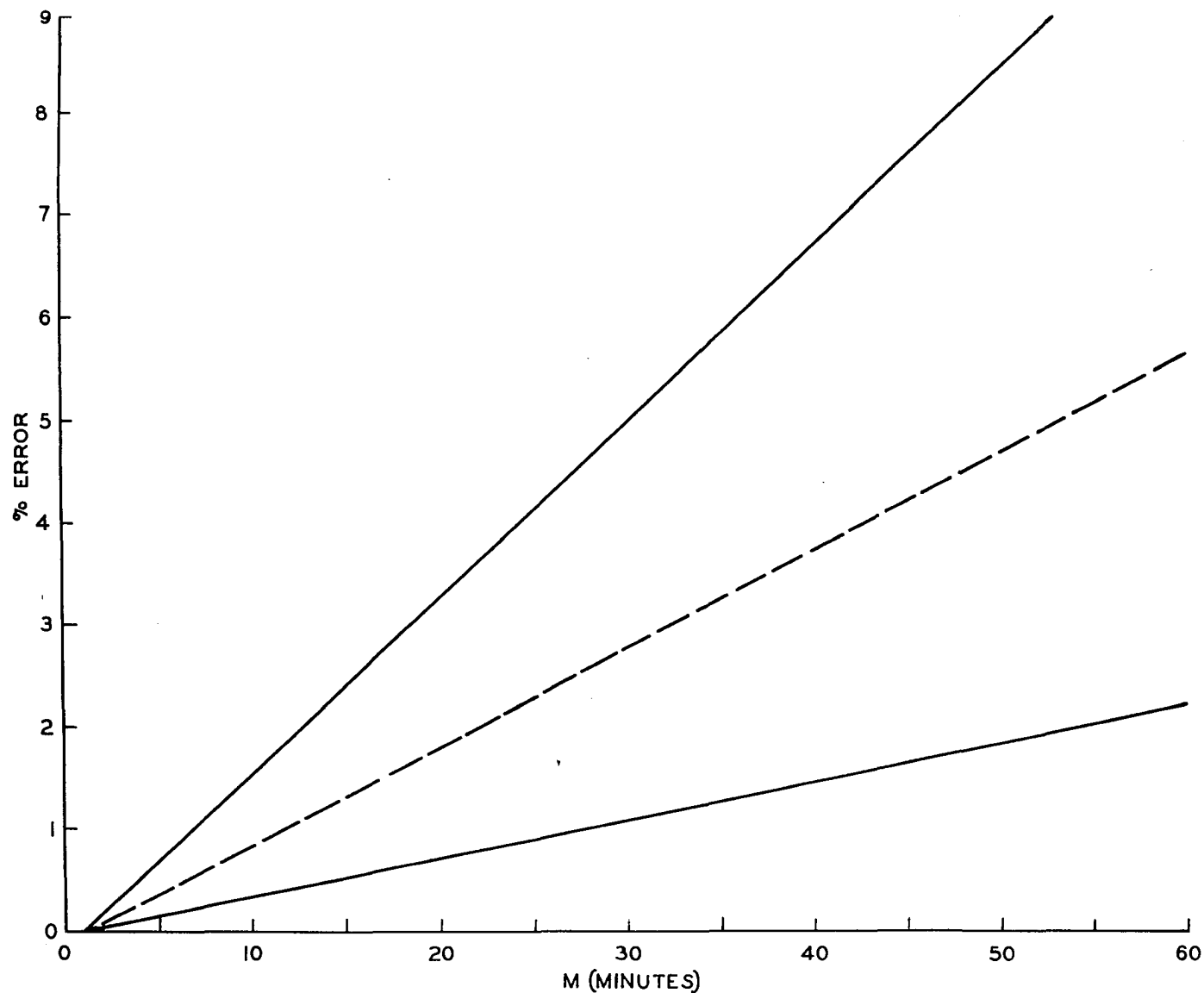


Fig. 37. The absolute value of the per cent error of the daily average absorption, defined in equation (5), as a function of m , the time interval at which the riometer record is scaled. The solid and dashed lines have the same meaning as in Fig. 36. It is apparent that even hourly absorption values can be used to find the daily average absorption to accuracy of about 95%.

It is apparent from Fig. 36 that the error introduced into the daily average absorption by averaging 15-minute absorption values instead of 1-minute values is only about 2% even on irregular disturbed days. On quiet days, or days with smooth, slowly varying absorption, the error will be even less. Since these are disturbed days with an average absorption of about 1-2 db, the error in making the approximate numerical integration is an order of magnitude less than that introduced by uncertainties in the quiet day curve, usually considered to be about 0.2 db. Fig. 37 shows that even when hourly values are used, the error is only about 5%. Thus, it is concluded that no serious uncertainty has been introduced in the results described in this work because of the approximations made in the numerical integration.

ADDENDUM

In the course of the defense of this dissertation Dr. Syun-Ichi Akasofu objected to the part of section 6.3.2 in which it is suggested that the location of the auroral absorption zone can be interpreted as related to that region of the magnetosphere in which the plasma energy density is equal to the magnetic energy density. He said in particular that Mead's work (J. Geophys. Res., 69, 1181-1195, 1964) has shown the magnetospheric boundary to correspond to about 83° geomagnetic latitude and that extreme changes in the plasma energy density only cause the value to vary in the range from about 80°-85°.

The candidate agreed with Dr. Akasofu and admitted that the treatment could certainly not be considered to describe the physical situation precisely or plausibly. The candidate pointed out that he had attempted to emphasize on page 154 the physical limitations of the approach. It was concluded that it is not possible to explain the location of the zone of auroral particle precipitation in the light of the present understanding of the interaction between the solar plasma and the earth's magnetic field.

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