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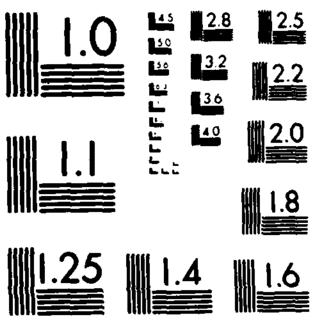

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FINAL REPORT

to the

Air Force Office of Scientific Research

# DYNAMICAL PHENOMENA IN SUNSPOTS

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Academic Rank: Assistant Professor

Department and University: Mechanical Engineering Department, Rochester Institute of Technology

Date: October 29, 1982

Contract Number: ~~AS~~AFOSR-82-0124

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER AFOSR-TR- 83-0197 | 2. GOVT ACCESSION NO. A126931 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) DYNAMICAL PHENOMENA IN SUNSPOTS | | 5. TYPE OF REPORT & PERIOD COVERED Final 01 Mar 82 - 31 Jul 82 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Dr. Alan H. Nye | | 8. CONTRACT OR GRANT NUMBER(s) AFOSR-82-0124 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Rochester Institute of Technology Mechanical Engineering Department Rochester, NY 14623 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2311/D9 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NP Bolling AFB, Bldg. #410 Wash DC 20332 | | 12. REPORT DATE 29 Oct 82 |
| | | 13. NUMBER OF PAGES 24 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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by

Alan H. Nye

## ABSTRACT

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## I. INTRODUCTION

During the latter part of August, 1980, an observational program was carried out at the Sacramento Peak Observatory which was intended to provide comprehensive information about dynamical phenomena in sunspots. The observations consisted of high spatial resolution measurements in long time series taken at two levels in the sunspot atmosphere. The observations and initial data reduction and analysis were described in the final report to the 1981 USAF-SCEEE Summer Faculty Research Program. The final data reduction of the August 21, 1980 data and the thorough analysis of the data from both August 18 and 21, 1980 was supported by Air Force Office of Scientific Research Grant Number AFOSR-82-0124.

There were three basic objectives of the proposed work. The first was to analyze the August 21, 1980 data in terms of velocity, intensity, and magnetic field information. Any relationships between oscillations at the two levels (photosphere and chromosphere) or between observations from the two days would be investigated. The umbral oscillations and umbral flashes observed in the chromosphere are shown to be the same phenomena with different amplitudes. This is discussed in Section IV. There does not appear to be any connection with the photospheric oscillations. However, the photospheric five-minute oscillation signals definitely come from the sunspot umbra and are measured on both days. They seem to be a passive response of the sunspot to the velocity field in the surrounding quiet photosphere. This is discussed in Section V. A reanalysis of the data from August 18, 1980 has greatly added to and improved on the information reported earlier regarding the moving magnetic feature (Section III).

The second objective was to study the theoretical consequences of the observational results. This has turned out to be the most important aspect of the work. Section IV outlines a technique which, in theory, will allow one to determine the structure of a sunspot below the visible surface. This is based on the passive response of the sunspot to the global solar five-minute oscillations acting as a selective filter at different depths. The particular modes of oscillation observed at the surface depend on the subsurface geometry much like the study of terrestrial seismology.

Finally, the last objective was to make suggestions for future work. Section VII details refinements in both observations and theory which could greatly improve the basic understanding of the nature of sunspots.

## II. OBSERVATIONS AND DATA REDUCTION:

The observations were made with the Vacuum Tower Telescope and Echelle spectrograph at Sacramento Peak Observatory. The final data reduction and analysis was carried out on two spectral lines: Fe 6303, formed in the sunspot photosphere and Calcium II, formed in the sunspot chromosphere. The observations consisted of a seventy minute time series of exposures made at a 20 second rate with the slit at a fixed spatial location crossing the darkest part of the sunspot umbra. The same sunspot was observed on August 18 and August 21, 1980 when it was located at radius vectors 0.56 and 0.185 respectively.

The photographic spectra were digitized using the fast microphotometer at Sacramento Peak Observatory. The measured densities were converted to relative intensities using standards exposed on the film when the original observations were made.

Each observation in Fe 6303 consisted of two images: the left and right hand circular polarizations. The polarization images for each frame were registered in space using a hair line and in wavelength using an $O_2$ telluric line that lies close to Fe 6303. By adding and subtracting the two polarization images, Stokes intensity (I) profiles and circular polarization (V) profiles were obtained.

Several different quantities were calculated from the I and V profiles for each spatial point at each time. The continuum intensity was determined by averaging points outside the spectral lines in the I profile. The position of the center-of-gravity of the I profile was located to measure velocity. The residual intensity of Fe 6303 was calculated by dividing the central intensity of the I profile by the continuum intensity. From the V profile, the positions and values of the extrema, $V_{max}$ and $V_{min}$, were determined together with the equivalent width of the profile V . These quantities were then used to derive several parameters, including the magnetic field intensity (from the separation of the extrema) and the Doppler shift. The line-of-sight projection magnetic field and a Doppler shift were also determined from the positions of the centroids of the I $\pm$ V profiles. Each frame was then registered spatially into a time series by cross-correlating it to the mean of the data. It is important to note that the velocities, as determined from the V profile, are not corrupted by photospheric scattered light. Since the velocities come from magnetic information, they clearly represent motions in the sunspot.

The study of the Calcium II resonance lines was based on the total intensity of the emission core and the shift of its centroid. The line center was determined from the centroid of the spatially averaged profile at each time step. If there were any oscillations which were in phase over the entire 40 arc seconds of the slit they would be removed by this approach. One must be cautious in interpreting the position of the centroid as a velocity signal since the emission core exhibits asymmetries and reversals which contribute to the net shift in a very complex way.

## III. MOVING MAGNETIC FEATURE:

After the data from the 21 August, 1980 observations was reduced, a thorough analysis was performed which included reworking the 18 August, 1980 data. It was found that some errors had been made regarding the moving magnetic feature which was discussed by Nye et. al. (1981). Also, additional information regarding the evolution of this feature was obtained.

Moving magnetic features around sunspots were first reported by Sheeley (1969) who observed them in a time lapse sequence of high-resolution CN spectroheliograms. They appeared as a radial outflow of bright points from two sunspots. Since that time other observers (Vrabec, 1971; Harvey and Harvey, 1972, 1973; Chapman, 1973) have seen these moving magnetic features (MMF's) and given a general description of their properties. Although a few features have been observed moving radially inward toward the sunspot, by far most of the observations have been of outflowing features, crossing the moat (a region surrounding mature sunspots which has no permanent magnetic fields). According to Vrabec (1974) only a small fraction of the moving magnetic features persisted long enough to cross the moat and merge with the surrounding network fields. The rest disappeared during their transit of the moat.

MMF's have come in a wide range of properties which were summarized by Vrabec (1974). Their size varied between $0.6\widehat{\pi}$ (estimated by Harvey et. al, 1972) and $5\widehat{\pi}$ (these appeared to be clusters of features) with a typical size less than $2\widehat{\pi}$. The magnetic field strength (longitudinal) was measured at 300 g by Harvey and Harvey but Beckers and Schroter (1968) calculated field strengths of up to 1400 g correcting for scattered light and field inclination. The true magnetic field strength is difficult to determine due to instrumental resolution. The magnetic flux ranged from $6(10^{17})$ Mx to $8\ (10^{19})$ Mx with the average about $10^{19}$ Mx. The lifetimes of MMF's were reported to vary from less than one hour up to eight hours. Vrabec listed a characteristic lifetime of two to three hours with some reservations.

After reducing the data from the sunspot observations of 18 August, 1980, one of the most obvious features was seen in the space-time plot of magnetic field (Figure 1). There was an opposite polarity feature on the left side of the plot which moved radially away from the sunspot, expanding as it went. It first appeared 10 minutes after the beginning of the observations and disappeared at about 55 minutes. This seemed to be a typical MMF as discovered by Sheeley.

The horizontal velocity (proper motion) of the MMF was 0.6 km/s when measured at the centroid of the feature. This compared with reported velocities from a few tenths to over two km/s. Because the feature expanded as it travelled, the leading edge had a velocity of 0.8 km/s. The magnetic field strength was initially about 2000 g which was higher than that measured by Harvey and Harvey but on the order of that calculated by Beckers and Schroter. The size of the feature was measured by its width along the slit. This varied between $1.25\widehat{\pi}$ and $2.66\widehat{\pi}$, which was well within the range reported earlier. Assuming that the feature had a circular geometry, then the MMF had a magnetic flux of $1.4(10^{19})$ Mx which was close to the average reported value. This value of flux was an upper limit because the slit may not have passed through the center of the feature in which case the area would have been underestimated.

The MMF was visible in the magnetic field space-time plot for approximately 45 minutes and seemed to disappear during its transit of the moat. The observations were probably showing the actual disappearance of the MMF as opposed to its moving out of the entrance slit because of the shape of the feature in the space-time plot. If the MMF had moved off the slit, it would have become thinner with time in Figure 1. Instead it was a symmetric feature up until the time it disappeared implying that it was still in the center of the slit.

This appeared to be a typical moving magnetic feature but the observations have added some new information on the morphology of MMF's. The vertical velocity in the photosphere was determined from Fe 6303 and presented in a space-time plot (Figure 2). There was a downflow centered in the MMF of approximately 400 m/s.

In addition to seeing the MMF in magnetic field and velocity in the photosphere as measured by the Fe 6303 line, the feature was visible at other heights. The MMF could be seen quite clearly in the space-time plot of intensity measured in the H line-wing but it was not distinguishable however in the intensity of the H line core. This implied that the moving magnetic feature was a low lying feature. Harvey and Harvey (1973) concluded that the magnetic field in a MMF was vertical because they could not see any line of sight magnetic field at the limb. This could have been due however to the fact that at the limb one is looking higher in the solar atmosphere.

The signature of the moving magnetic feature was seen in several of the observations; magnetic field and velocity measured in the photosphere, residual intensity of Fe 6303, and intensity in the H line wing (but not the core). The lifetime of MMF's as reported by Vrabec (1974) was based on observations of the magnetic field. Using this definition, the 18 August 1980 MMF lived for 45 minutes. However, the MMF was visible in other signatures for longer periods. The probable reason that the MMF disappeared from the magnetic field plot was due to resolution. Assuming conservation of flux, the magnetic field had been reduced to about 450 gauss due to spreading. The limit of resolution was 500 gauss. Therefore, the MMF had not gone away, it had simply spread to the point that its magnetic field was no longer visible, but it still existed as a MMF as evidenced by its other signatures. Thus, the lifetime of a MMF is a strong function of the manner in which the feature is observed.

## IV. CHROMOSPHERIC OSCILLATIONS:

When the data was analyzed for an oscillatory signal, the umbral oscillations and umbral flashes were visible in the sunspot chromosphere throughout both observing runs. A visual inspection of the Calcium II film showed the umbral flashes occurring at several locations in the umbral chromosphere. The flashes would appear and repeat several times then disappear. The intermittent nature of the flashes should have shown up as power at low frequencies of a power spectrum. Figure 3 shows the power spectrum of the intensity in the Calcium II emission peak for the umbra of the 21 August 1980 observations. The peaks occur at periods of 194 s, 171 s, 155 s, 139 s, and 125 s. These fall in the typical range of periods for umbral oscillations (120-180 s) given in a review paper by Moore (1981). It seems well established now that umbral flashes are simply larger than normal amplitude umbral oscillations caused by the superposition of two oscillations with slightly different frequencies. This would give a "beating" effect with periods of large amplitude and periods of low amplitude. The "flash" is probably due to saturation of the film on which the observations were taken.

The data from the 21 August 1980 observations also revealed an interesting Z pattern associated with the umbral oscillations. The Calcium II profiles at five locations in the umbra are plotted as time series in Figure 4. The Z pattern which can be seen at each of the locations represents a blue shifted flash followed by a decay of the emission peak as it shifts to the red. This is followed by another blue shifted flash and the process repeats. This combination of intensity and velocity is asymmetric and would imply a net upward flow as pointed out by Phillis (1975). The pattern appears to be a characteristic signature of umbral oscillations and umbral flashes and in fact, could have been predicted from the line profiles published by Beckers and Tallant (1969).

It was hoped that some connection would be found between the chromospheric umbral oscillations and the velocities measured in the sunspot photosphere. However, in comparing power spectra from Fe 6303, Figure 5a, with that from Calcium II, Figure 3, there is only one period which has a peak in power at both heights. That is at 197 seconds. This appears to be due to coincidence instead of some physical connection, since a plot of cross-correlation between the velocities as a function of frequency looks like a scatter diagram. This means that if the umbral oscillations are excited in the convection zone below the photosphere and propagate upward, then the velocity amplitude is so small in the sunspot photoshpere that it is completely masked by other velocity oscillations there. The power spectrum of velocities measured in the photosphere has provided some very interesting information however, which is discussed in the following section.

## V. FIVE MINUTE OSCILLATIONS:

The power spectra of velocities measured in the sunspot photosphere showed power in a range of periods around five minutes, the dominant period of oscillation of the quiet photosphere. The observing and data reduction techniques used in this program have eliminated the usual problems of scattered light and velocity reference thereby insuring that the origin of the signal is the sunspot umbra.

Figure 5 shows the mean power spectrum of the velocity field for the portion of the umbra covered by the entrance slit, for each of the two runs (18 and 21 August 1980). Each power spectrum has three conspicuous peaks clustered around a five-minute period. Given the frequency resolution of the observations, the periods of these three peaks for both runs are consistent with nominal values of 265 s, 300 s, and 360 s. Another conspicuous peak near 200 s in both runs is more likely associated with a resonant mode of the sunspot itself. The greater power in the peaks in 21 August, when the sunspot crossed the central meridian of the sun, indicates that the velocity is predominantly vertical in the photosphere. The total power at periods near five minutes implies an rms vertical velocity of about 50m/s in the umbra, at least a factor of five smaller than for the five-minute oscillation in the quiet photosphere.

Because of the limited temporal and spatial extent of the data (70 min time series with a 20 s sampling interval, over about 13 Mm in the umbra) there is statistical noise in the power spectrum. The noise level may be estimated in three ways: from the high-frequency limit of the power spectrum, from the statistics of the distribution of individual power spectra that are used to form the mean power spectrum for the entire umbra, and from the estimated number of degrees of freedom (- 20) using Edmond's tables (1966). All three of these methods indicate that the 50% confidence level for each peak corresponds to roughly 25% of the peak amplitude. Any peak that is four times the noise level is marginally significant (50% confidence level), with greater confidence for higher peaks. Thus, in Figure 5, the peaks near 360 s, 300 s, 265 s, and 200 s are all significant at well above the 50% confidence level. Note that the noise level is about the same on the two days while the signal increases in power on 21 August as the line-of-sight velocity becomes more nearly vertical.

The existence of five minute oscillations in the umbra had not been conclusively shown previously. They would seem to be a passive response of the sunspot to the surrounding velocity field in the quiet photosphere since a sunspot has no theoretical resonances in the five minute range. The splitting of the temporal power spectra into several peaks around five minutes is very similar to the ridge structure of the five minute p-mode global oscillations of the solar convection zone. These are acoustic waves with a wide range of horizontal wavelength and moderate variation of frequency. They buffet and squeeze the sunspot with their characteristic frequencies thereby forcing a response within the sunspot umbra at the same frequencies. This passive response can, in theory, be used as a subsurface probe of sunspot structure, as discussed in the following section.

## VI. SUBSURFACE SUNSPOT STRUCTURE

The observation of separate modes of five minute oscillation in a sunspot umbra provides, in theory, a means of determining the structure of the sunspot below the visible surface. The observed modes represent the passive response of the sunspot to several of the multitude of trapped p-mode acoustic waves in the solar convection zone. The various p-mode waves are trapped at different effective depths below the photosphere depending on horizontal wavelength, frequency, and the number of nodes in the radial direction. The interaction between the sunspot and the p-mode waves is geometry dependent and thus the particular modes observed in the sunspot give information about the geometry of the sunspot at different effective depths.

It is well established that the solar five minute oscillations are global in character and consist of the superposition of many trapped modes of pressure waves (p-modes or acoustic waves). Observations by Deubner et.al. (1979) with sufficient resolution in wavenumber and frequency show ridges in a $k$-$\omega$ diagram (Figure 6) corresponding to p-modes with different numbers of nodes in the radial direction. The three peaks in the power spectra of sunspot velocity oscillations are plotted in Figure 6 as horizontal lines. The three lines cross all the modes in the $k\cdot\omega$ diagram but presumably represent the response of the sunspot to three consecutive modes of p-mode oscillation. Each possible set of three crossings corresponds to a set of three horizontal wavenumbers and therefore a set of three horizontal wavelengths.

One might expect some relationship between the diameter of the sunspot umbra and the horizontal wavelength of the p-mode most likely to interact with the sunspot. Space-time plots of the umbral velocity field show a characteristic "herringbone" structure with phase varying across the umbra. At any instant, diametrically opposite points at the edge of the umbra tend to be 180° out of phase and the center of the umbra appears to be a node in the velocity field. This suggests that the peak response is occurring at a wavelength equal to roughly twice the umbral diameter, so the assumption is made that the peak response is at a wavelength equal to exactly twice the local diameter. As discussed above, the various sets of three consecutive mode crossings in Figure 6 predict alternative sets of three horizontal wavelengths and hence sets of three values of sunspot diameter. Each diameter corresponds to a different p-mode (different value of n) which probes a different effective depth. Values of the effective depth for the p-mode eigenfunctions have been calculated by Ulrich et.al. (1979). The effective depth varies with horizontal wavenumber as well as radial mode number. For any set of mode crossings in Figure 6 an effective depth is assigned to each of the three values of sunspot diameter, thus obtaining a plot of sunspot radius versus depth, assuming a circularly symmetric sunspot flux tube.

The results of these calculations are combined in Figure 7, where sunspot radius is plotted as a function of depth for each of the possible sets of mode crossings. The limited resolution in frequency (due to finite time series) and the spread of power in the ridges on the k-$\omega$ diagram gives the uncertainty in calculated sunspot radius, and the uncertainty in k and $\omega$ gives the uncertainty in effective depth. For any given set of points in Figure 7, the uncertainties mask the depth variation of sunspot radius, making each set of three points equivalent to a single piece of information about the subsurface sunspot geometry. The individual sets of three points in Figure 7, corresponding to sets of three consecutive mode crossings, are definitely distinct from each other, allowing a selection of the most likely set based on theoretical arguments about the expected depth variation of sunspot radius. For example, the theoretical model of Deinzer (1965) is plotted in Figure 7 for comparison. It passes through the set of points corresponding to p-modes n = 3,4, and 5. This is only an illustration of the method and not a specific prediction for this sunspot. However, it is interesting to note that, for the range of wavenumbers under consideration, modes n = 3,4, and 5 have the most power in their ridges; they might be chosen on this basis as well.

The development of this technique to probe below the visible layers of a sunspot was reported by Thomas, Cram, and Nye (1982). It is similar in nature to the methods used by seismologists to study the earth's interior.

## VII. FUTURE WORK

The ability to probe below the visible layers of the solar surface offers scientists the possibility of answering some basic questions concerning the nature of sunspots and their effect on energy transport. There is no general agreement as to the geometry of a sunspot below the visible surface and in fact there are two totally divergent viewpoints. One theory is that the magnetic flux is confined in a symmetric tube to the base of the convection zone (Meyer et.al, 1974). The alternative is that the magnetic flux separates into many individual bundles just below the surface (the "spaghetti" model of Parker, 1979). The results presented in Section VI tend to support the Meyer et.al. model but better observations and theoretical work are required before any definitive statement can be made.

In order to improve the observational results, a longer time series is required to give better frequency resolution. Two dimensional observations of the sunspot umbra would give a better picture of the wave mode and therefore the nature of the interaction between the trapped p-modes and the sunspot umbra.

More theoretical work needs to be done on the effective depth of the trapped p-modes in the presence of magnetic flux. The interaction of the p-modes and the magnetic field needs to be studied theoretically as well as observationally. Each of these improvements would serve to reduce the error bars in Figure 7 and select the appropriate set of mode crossings, giving a plot of sunspot diameter as a function of depth. In effect, one could see whether the magnetic field spread out or stayed together below the surface, answering at least one of the fundamental questions concerning sunspots.

This work was performed in collaboration with Dr. John H. Thomas of the University of Rochester and Dr. Lawrence E. Cram of Sacramento Peak Observatory. A portion of this research was published in Nature, Volume 297, Number 5866, p. 485. This paper, titled "Five-Minute Oscillations as a Subsurface Probe of Sunspot Structure", was co-authored by John H. Thomas and Alan H. Nye. A comprehensive paper covering all aspects of sunspot dynamics is in preparation by the same co-authors. An oral presentation was made by Alan H. Nye titled, "High Resolution Observations of a Moving Magnetic Feature", at the 160th meeting of the American Astronomical Society, held in Troy, New York, from June 6-9, 1982.

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## FIGURE CAPTIONS

Figure 1 Time series of the magnitude of the magnetic field in the August 18, 1980 sunspot, determined from the separation of the maximum and minimum of the V profile. The gray scale saturates at plus and minus 1600 gauss.

Figure 2 Time series of Doppler shift in the August 18, 1980 sunspot, measured in the V profile. Note the velocity pattern associated with the moving magnetic feature. The gray scale extends from plus to minus 2000 m/s.

Figure 3 Power spectra of intensity variations in the umbra of the August 21, 1980 sunspot as measured in the Calcium II H line. The peaks represent umbral oscillations and flashes.

Figure 4 Time series of umbral oscillations at five points in the umbra of the August 21, 1980 sunspot as measured in the Calcium II H line. Note the conspicuous "z" pattern which is a signature of the umbral oscillations.

Figure 5 The mean spectrum of line-of-sight motions in the umbral photosphere for two runs: 21 August 1980 (Figure 5A) and 18 August 1980. The labeled peaks have the following periods: 21 August, (a) $366\pm6$ s, (b) $301\pm4$ s, (c) $269\pm4$ s, (d) $197\pm4$ s. 18 August, (a) $353\pm6$ s, (b) $301\pm4$ s, (c) $263\pm3$ s, (d) $213\pm5$ s. Peaks a, b, and c are interpreted as representing the response of the sunspot to individual p-mode oscillations in the surrounding atmosphere.

Figure 6 Highly refined diagnostic diagram for the solar p-modes, due to Deubner et.al., (1979), showing contours of power on the frequency-horizontal wavenumber plane. Lines corresponding to the nominal periods of umbral oscillations near 5 minutes (360 s, 300 s, and 265s) are drawn to determine their points of intersection with p-modes of different radial mode number n (also shown).

Figure 7 Four possible choices of sunspot radius versus effective depth as determined by four different sets of three consecutive p-mode crossings in Figure 6. The crosses show the estimated error for each set (see text). The solid circle gives the observed surface radius of the sunspot. The open circles are the most likely set of mode crossings. The dashed line gives the variation of sunspot radius with depth for Deinzer's (1965) sunspot model, and is shown for illustrative comparison only.

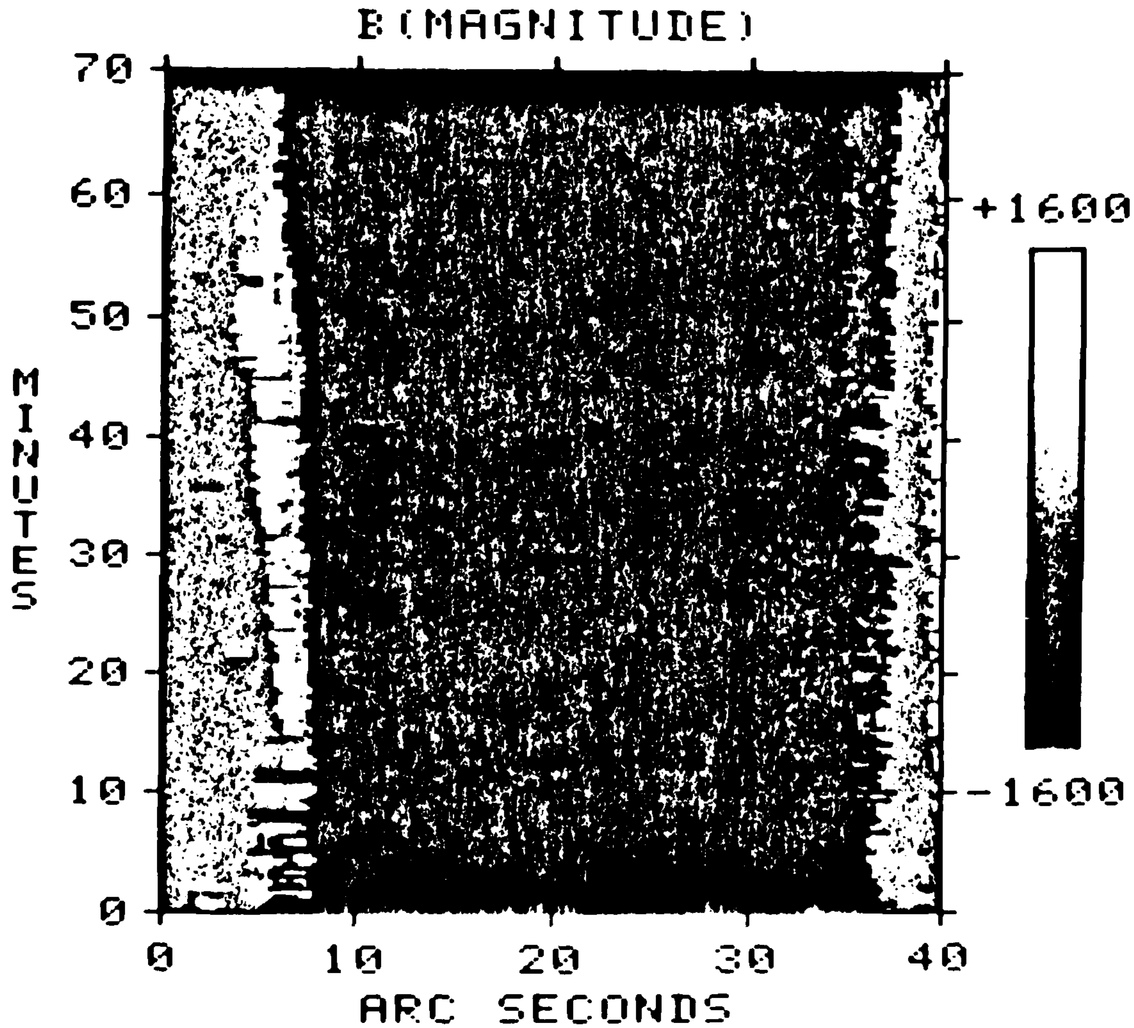
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FIGURE 1

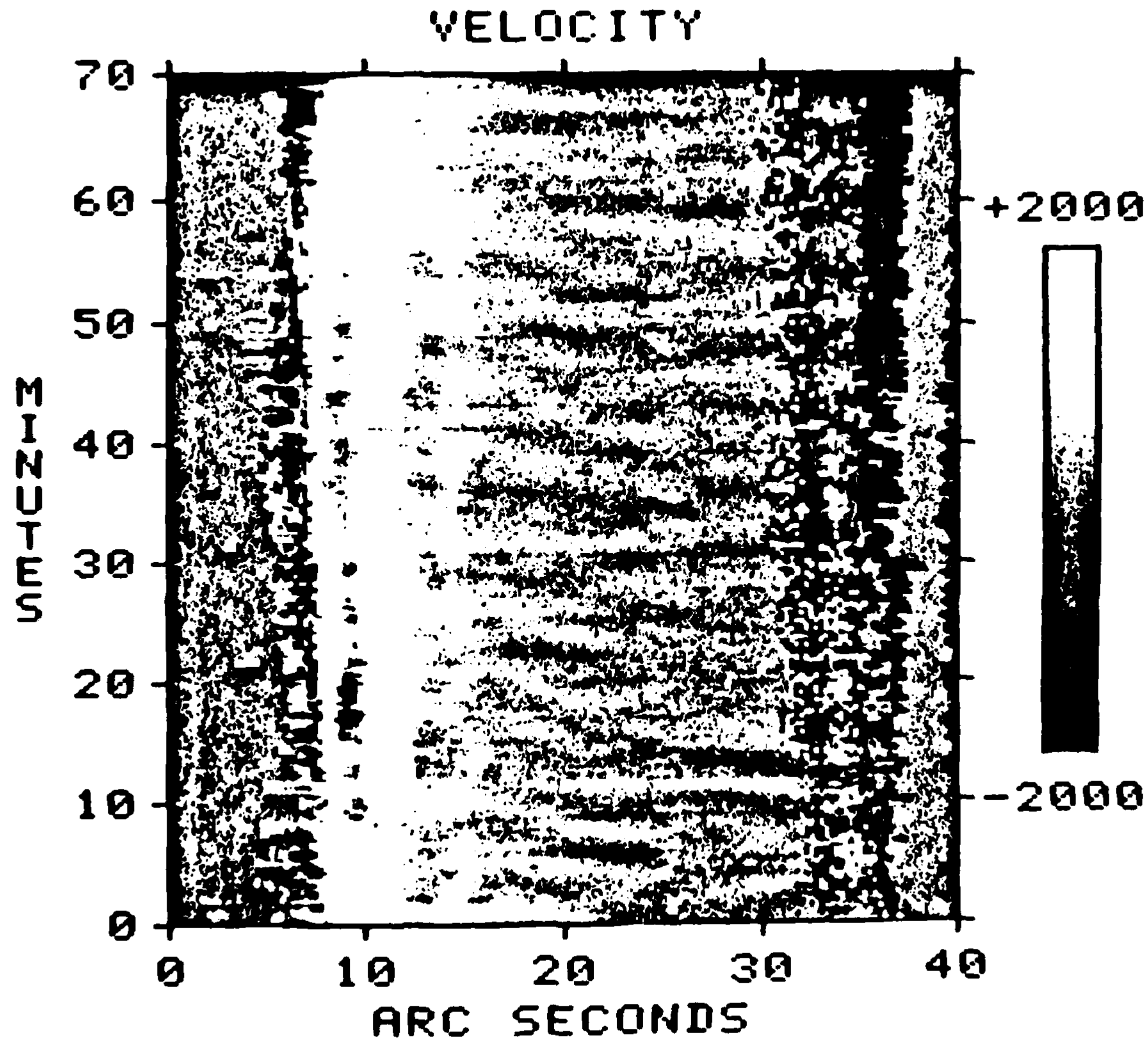
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FIGURE 2

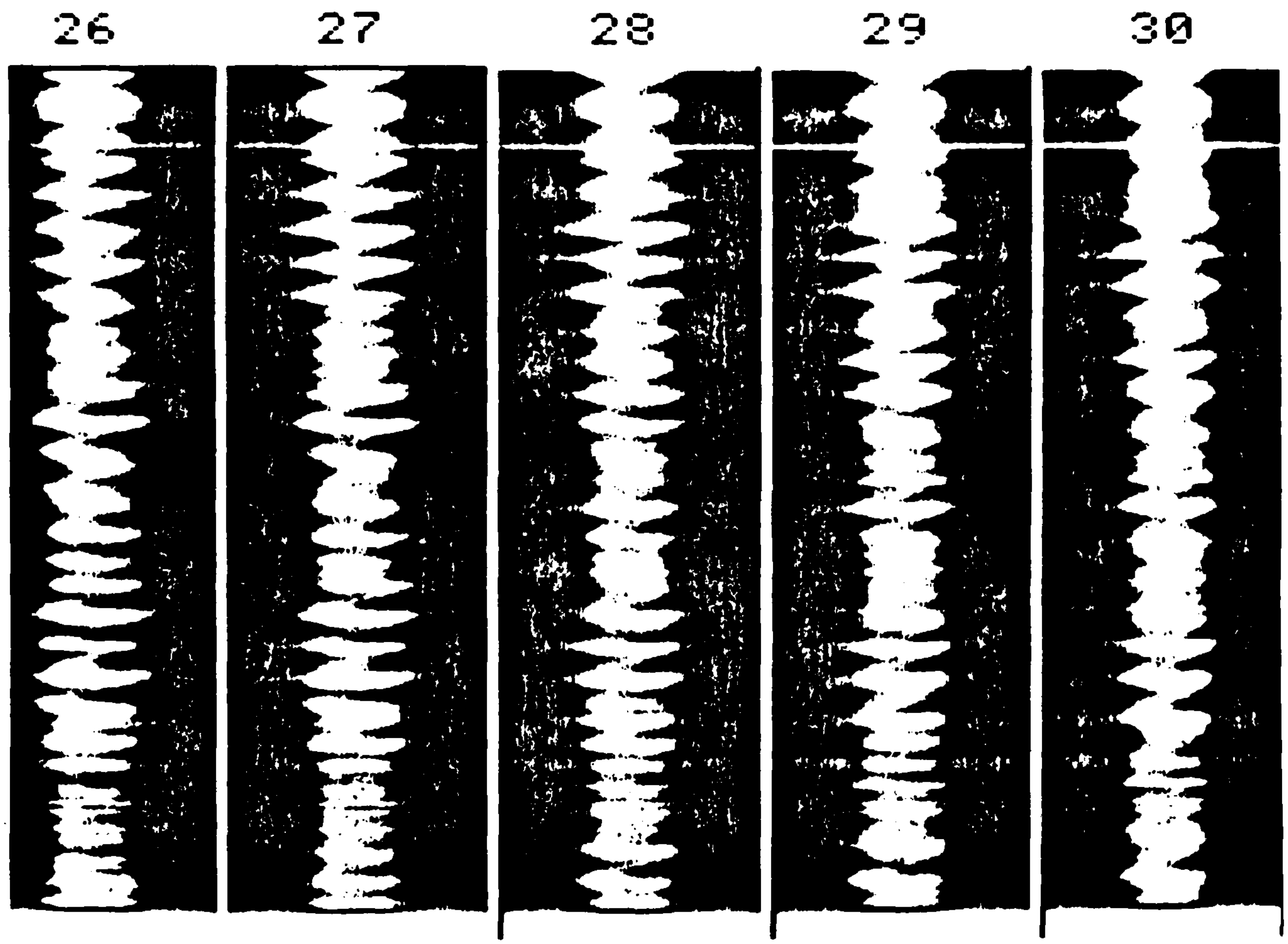


FIGURE 3

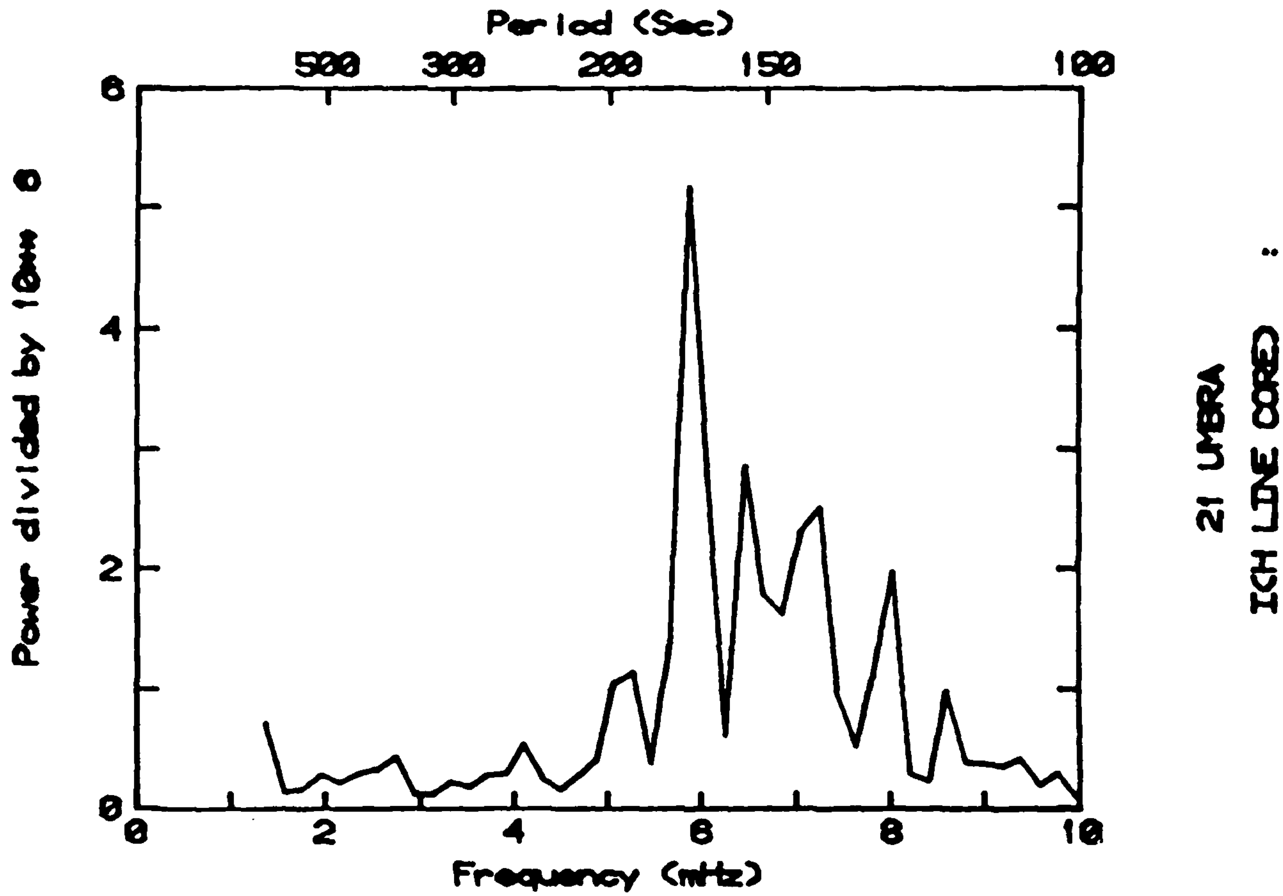
Period (Sec)
500
300
200
150
100
Power divided by 10** 8
0
2
4
6
0
2
4
6
8
10
Frequency (mHz)
21 UMBRA
ICH LINE CORED

FIGURE 4

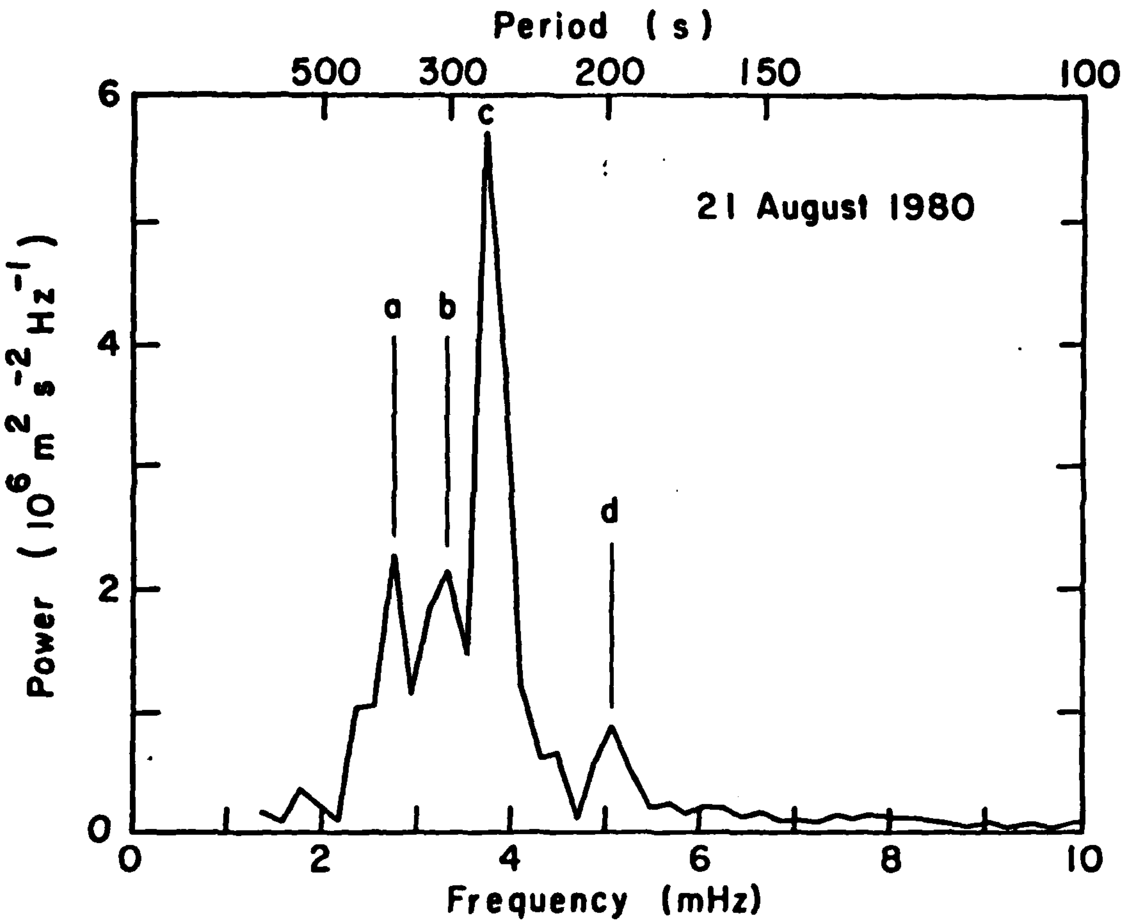
Period (s)
500
300
200
150
100
c
21 August 1980
a
b
d
Power ( $10^6 m^2 s^{-2} Hz^{-1}$ )
6
4
2
0
0
2
4
6
8
10
Frequency (mHz)

Figure 5A

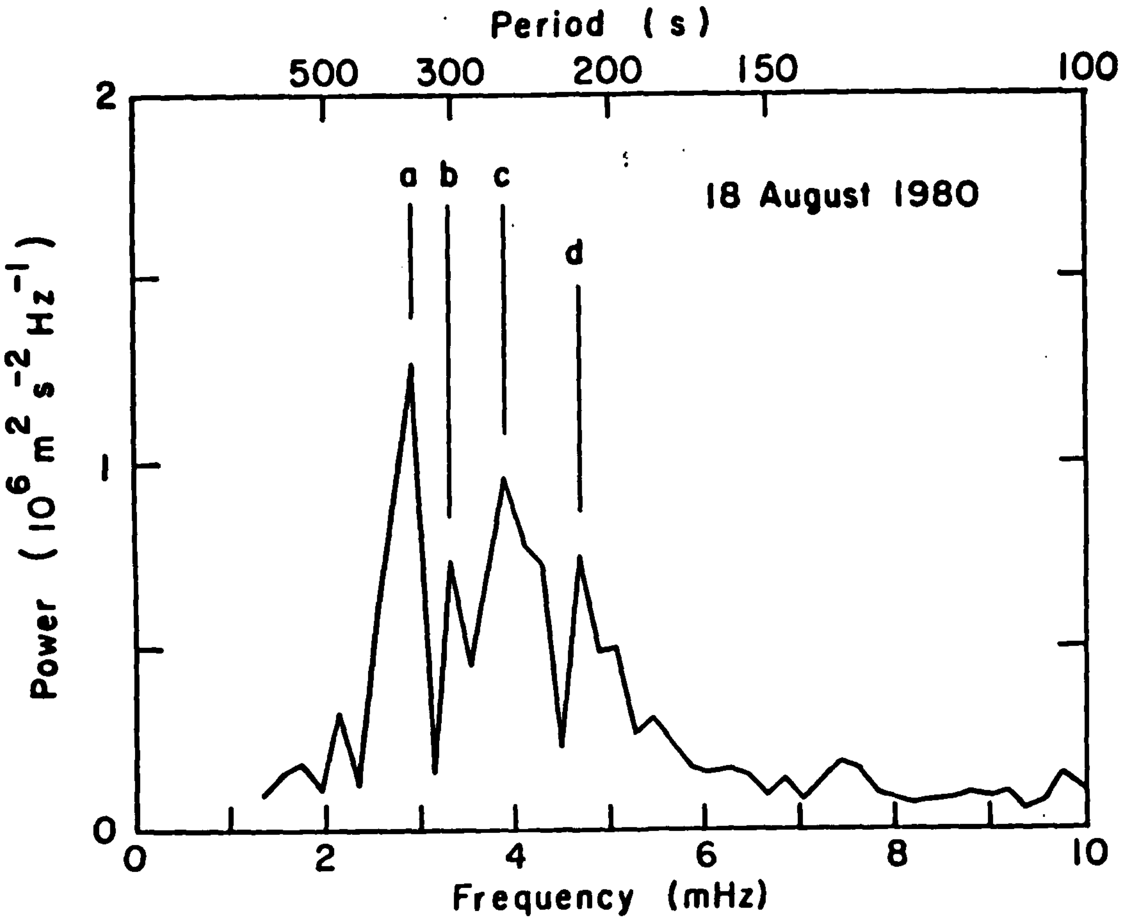
Period (s)
500
300
200
150
100
2
1
0
a
b
c
d
18 August 1980
Power ( $10^6 m^2 s^{-2} Hz^{-1}$ )
0
2
4
6
8
10
Frequency (mHz)

Figure 5B

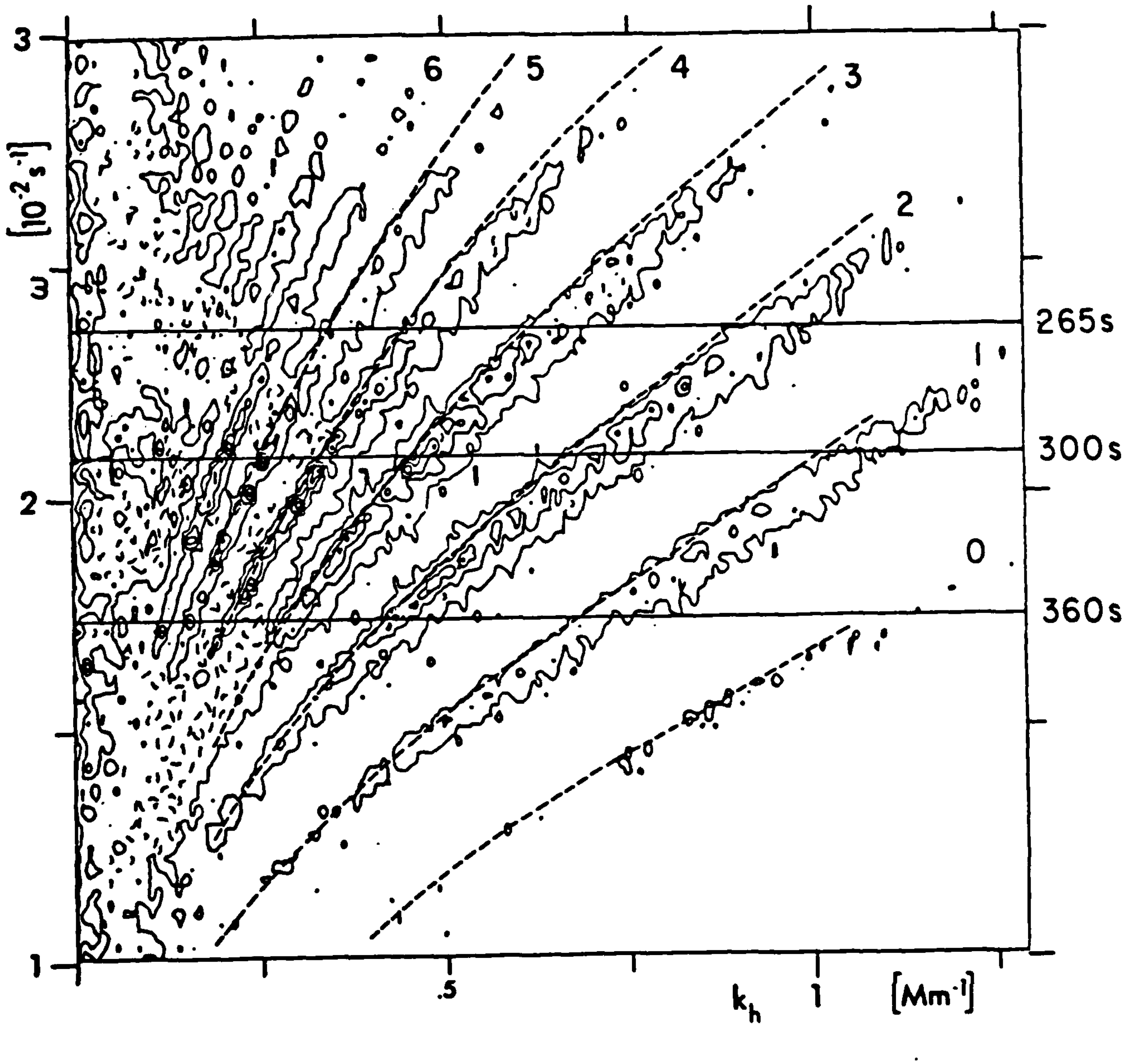


Figure 6

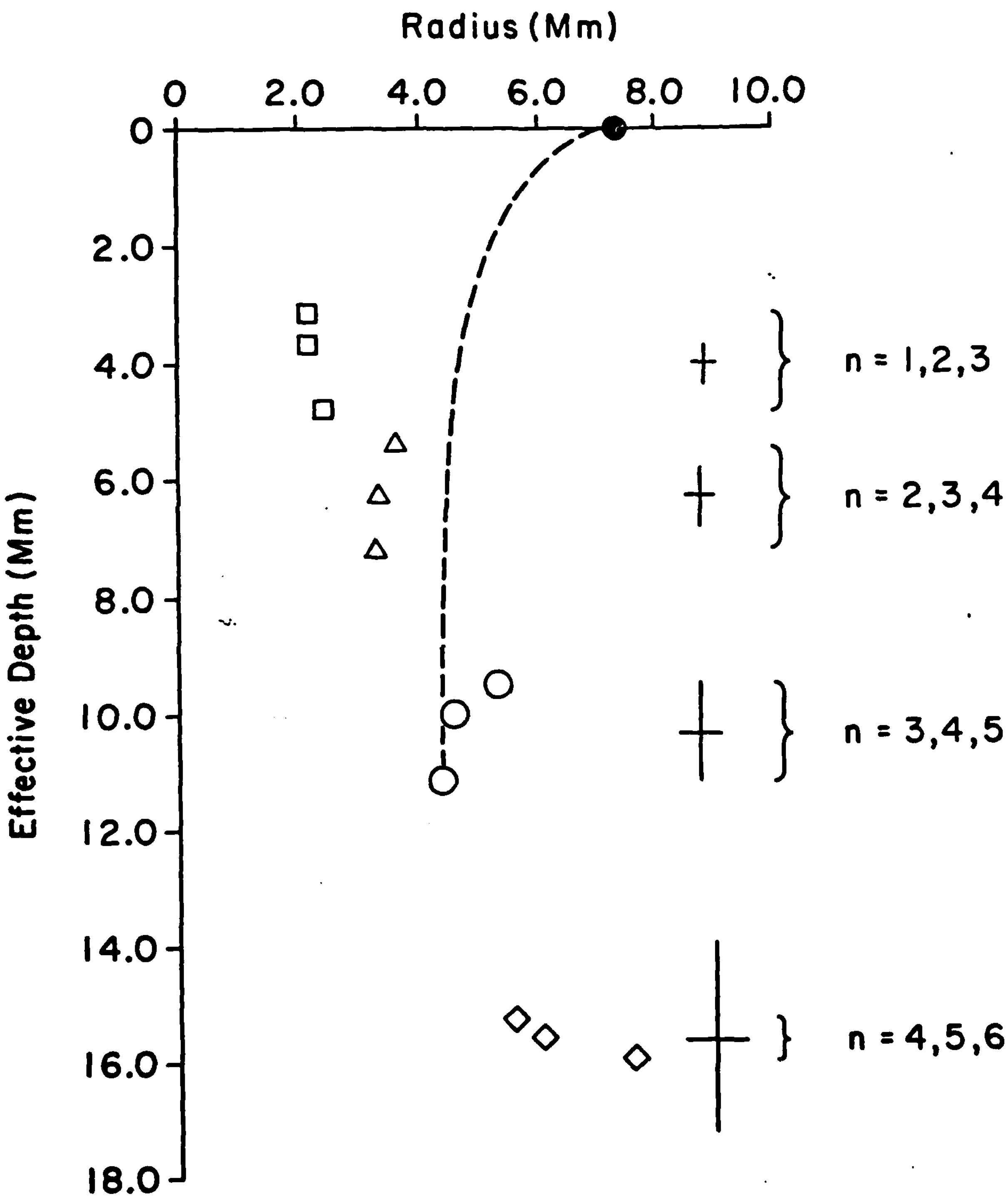
Radius (Mm)
0
2.0
4.0
6.0
8.0
10.0
Effective Depth (Mm)
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
n = 1,2,3
n = 2,3,4
n = 3,4,5
n = 4,5,6

FIGURE 7

n = 1,2,3

n = 2,3,4

n = 3,4,5

n = 4,5,6

END

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