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THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Electrical Engineering
Space Physics Research Laboratory

Final Technical Report

EMPIRICAL MODEL OF POLAR THERMOSPHERE STORM

Prepared by:
D. R. Taeusch

Under Contract with:

National Aeronsutics and Space Administration
Marshall Space Flight Center
Contraft NAS8-26243
Huntsville, Alabama 3581

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Section 1

INTRODUCTION

Contract NAS8-26243 called for a study of the OGO-VI satellite Neutral Atmosphere Composition experiment data during the period from September 27 through October 5, 1969, a period of substantial geomagnetic activity. The points to be discussed in this report, within the limits of the available data, are the following:

1. The latitudinal extent of the neutral response to the storm (i.e., are the responses confined to the auroral oval).
2. The magnitude of the response versus quiet conditions.
3. The longitudinal variations in the auroral oval.
4. The time respones of the atmospheric parameters to the solar activity as indicated by the solar-geomagnetic indices $F_{10.7}$ and a_p.

The second section of this report presents the data which were used to determine answers to the above questions. The third section is devoted to a discussion of the data as they apply to the above questions.

Section 2

DATA

The data presented here were obtained from the OGO-VI Neutral Atmospheric Composition (NAC) Experiment during the period between September 27 and October 5, 1969. During this period, magnetic storms numbered 43, 44, and 45 of 1969 occurred. These data have been reported on at the 1970

Western American Geophysical Union Meeting (Taeusch and Carignan, 1970) and a paper discussing them has been submitted for publication to the Journal of Geophysical Research (Taeusch and Carignan, 1971).

The OGO-VI satellite, launched June 6, 1969, has a perigee of 500 km and an apogee of 1100 km with an inclination of 82°. The NAC experiment is a closed source quadrupole mass spectrometer capable of detecting masses from 50 to 1 AMU, with fixed tuned and sweep mode capabilities. The NAC experiment was mounted in OPEP-2 of the satellite, which allowed the opening to the ion source to be pointed in the orbital plane toward the velocity vector during most of the measurements.

Figure 1 shows the source density versus time of the major constituents measured on September 27, 1969, a geomagnetically quiet period preceding the storms. In reducing these data to ambient values, the O_2 density is considered to be recombined ambient O densities. Also adsorption, desorption, and production of CO, CO_2, and NO are taken into consideration to obtain ambient densities in a process that was not complete at the outset of this work. We are able to obtain useful N_2 data to an altitude of 550 km and useful O data to an altitude of 650 km before the background gases reduce the accuracy of the measurement to an unaccceptable level. For this report, we avoided using true ambient densities by using the quiet day data as the quiet standard, to which all subsequent data were normalized during the seven day period of the storm. We also normalized these data to a constant altitude of 500 km using standard hydrostatic equilibrium techniques, and used the Jacchia (1970) equation for correcting the data for 10.7 cm solar flux variations during the period. Thus we have attempted to eliminate the geophysical factors which are not related to magnetic activity, and therefore variations or residuals during the period are associated only with the geomagnetic storm.

Figure 2, one of a series of nine, shows the type of normalized data described. $R(N_2)$ and $R(O)$ are the ratios of the data to a best fit exponential, fitted to data of September 27, 1969 at 1550 GMT (60° magnetic latitude times). The Norm Orbit data for N_2 fit the exponential with a standard deviation of 4.2% (dots and solid curves) for data points below 550 km, and the O data fit with a standard deviation of 3.2% (x's and dashed curves) for data points below 650 km. These ratios are plotted on a logarithmic scale versus magnetic latitude from 90°N to the equator To the right of the plots are given the a_p values for the three hour period in which the data were obtained.

In these first seven orbits, some variation in the N_2 and O densities are noted up to a factor of 1.6 in both cases with values of a_p up to 22. However, Figure 3 shows the dramatic effect of the onset of the storm, which was at about 1100 to 1130 GMT according to College magnetograms. The maximum enhancement of N_2 and O is at about 82°N, with $R(N_2)$ about 21 and $R(O)$ about 3.5. The equatorial enhancement was about the same (1.25) for O and N_2. The enhancement of N_2 at 82°N would correspond to a Jacchia (1970) temperature increase of about 450°K. Assuming no turbopause change, the increase in O corresponds to a Jacchia (1970) temperature increase of about 325°K. The equivalent temperature changes at the equator would be 25°K for N_2 and 45°K for O. The question arises as to whether this is a lack of thermal equilibrium or, more likely whether there are fast changes in the effective turbopause level, an increase in the northern latitudes in this case, to decrease the O/N_2 ratio at 500 km.

As we move on in time, the character of the enhancements changes, and a wavelike structure appears. Also, the low latitude data show increases to about a maximum value of 1.8. Of interest in the low latitude data is the fact that $R(N_2)$ and R(O) are about the same, indicating a reversal of what happens at high latitudes, but with a much smaller magnitude. Note that the time difference between the storm beginning at 1142 on 9/28 and the maximum low latitude density at 1825 on 9/28, is 6 hours 50 minutes, a characteristic time often heard in geomagnetic activity versus neutral atmosphere discussions.

The orbits at 2325 on 9/28 and at 0101 on 9/29 show, in this case, a remarkably fast decay in $R(N_2)$ and R(O) as the a_p drops from 48 to 15. Also note the dip in R(O) in the polar regions, a characteristic that is repeated throughout the storm.

Figure 4 continues with orbits showing polar enhancements with decreasing O/N_2 ratios, wave structure, and equatorial enhancement with approximately constant O/N_2 ratios and polar dips in O, during a period of considerable magnetic activity.

Figure 5 shows the orbit at 0016 on 9/30, the peak of the storm. At 70° magnetic latitude $R(N_2)$ equals 15.5 and R(O) equals 2.4 and the equatorial values are approximately equal at 1.5. By using the calculations previously described for T_∞, we get $\Delta T(N_2)$ equal to 390°K and $\Delta T(O)$ equal to 200°K for the 70° magnetic latitude data.

Continuing, we see structures suggesting waves, and R(O) changing from a value apparently constant with latitude to values of less than 1 in the polar regions at 2152 and 2330 on 9/30, when the a_p drops to 12. Note, that in this case we do not see the fast decay in $R(N_2)$ when a_p drops, as we did in Figure 3.

Figure 6 shows eight more orbits, during which the a_p went from 32 to 12 to 22 and stayed constant for the next 12 hours. R(O) has settled considerably, but $R(N_2)$ continues to show polar enhancements, and shows a dip at 1244 on 10/1 at about 50° magnetic latitude.

Figure 7 shows eight orbits following the preceding ones, during which a_p increases from 15 to 56. Evident are the polar enhancements in $R(N_2)$ with a lesser increase of R(O), followed in time by equatorial increases in O and N_2

with R(O) and R(N_2) equal or R(O) larger, followed by polar decreases in R(O).

Figure 8 shows eight more orbits, during which a_p dropped to a minimum of 7 and increased to 27. The minimum R(N_2) at 1252 on 10/3 was 0.68. Again, the polar values of R(N_2) do not decay as was noted in Figure 3, but the polar values of R(O) remain near 1 or less.

Figure 9 shows that a_p has settled to a low level, and that the atmosphere is settling to somewhat the norm value, with a few oscillations left.

Figure 10 shows the last seven orbits of this series of data. The minimum value of the R(N_2) dip at 1527 on 10/4 is 0.60.

Figures 11 and 12 show the values of R(N_2) and R(O) at fixed magnetic latitudes versus time from September 27 to October 3, 1969. Note the general decrease in R(N_2) as we go southward. The amplitude of R(O) up to 60° magnetic latitude stays about constant, with some shifts in phase and changes in character. At 30° latitude R(O) and R(N_2) are about equal in amplitude and remain so down to the equator. The maximum value for R(N_2) and R(O) from 30° to the equator is about 2.

Figure 13 shows the 60° and 0° values of R(N_2) and R(O) of Figures 11 and 12 with a_p and the College magnetic field values versus time. There are some obvious correlations between the ratio data and the geomagnetic field variations. Note the first peak at 60° latitude where the R(N_2) is equal to 4.4. Associated with this is the first large amplitude variation in the a_p and the College magnetic field with a time delay at 60° latitude in the ratio data of less than one hour. The apparent time delay in the 0° latitude ratio data is about 3.5 hours from the first peak at 60° latitude.

Section 3
DISCUSSION

We believe the $R(N_2)$ enhancements are due to a temperature increase of the neutral atmosphere. Typically, during this magnetic storm, the temperature increases were small (<50°K) from the equator up to about 30° magnetic latitude. The $R(N_2)$ enhancements increased from 30° magnetic latitude up to maximum values corresponding to approximately a 450°K increase in temperature between 60° and 80° magnetic latitude. This indicates that the source must deposit its energy in the polar regions, whether by Joule heating (Cole, 1962a, 1962b, 1966), corpuscular heating (Jacchia 1959), or other dynamical processes (Dessler, 1958; Hines, 1965a, 1965b; Jacchia 1965b). Also, if a_p is an indicator of the energy magnitude and temporal variation, the time lag for atmospheric response to these energy depositions is very short at high latitudes. This is contrary to the belief of many authors (Jacchia, 1967; Lew, 1969; Roemer 1967, 1970), and may only be the result of this one storm. However, Volland (1969) suggests that the time lag is dependent on the impulse width of the storm, with the time lag being very short for small impulse widths. This is compatible with the data presented in Figure 13, where the first two peaks in $R(N_2)$ at 60° magnetic latitude are correlated with the short impulses in a_p with short time lags. However, the large impulse and sustained magnetic activity on October 30 can be correlated with a shift in the $R(N_2)$ maximum value of 8 to 9 hours.

The R(O) enhancements are not compatible with a hydrostatic equilibrium, static diffusion view of atmospheric behavior. The increases in R(O) in the polar region are not as large as would be expected for the temperature increases indicated by the values of $R(N_2)$. However, if we introduce vertical winds caused by the energy deposition (Cole, 1962), we get a decrease in the O/N_2 ratio with an upward flow in the polar regions and an increase in the O/N_2 ratio with a downward flow at the equator. This is compatible with the recent circulation theories of Mayr and Volland (1970) and Hays (1970).

The particular orbit and season for the study presented here did not allow helium measurements near the poles, due to the very low densities of that constituent. However, Reber (1970) has reported data for other times which show the helium densities to decrease during such N_2 enhancements, which is also compatible with the wind theories.

Of passing interest at this time, which we would like to note, are the apparent 12 and 24 hour periodicities seen in the ratio data. These periodicities may be due to a spatial or longitudinal effect of the storm on the density data, or they may be due to the magnetic field variations themselves being periodic with periods of 12 and 24 hours.

Answers to the specific questions to which this study was directed will be taken in turn.

1. The latitudinal extent of the neutral response to the storm (i.e., are the responses confined to the auroral oval); and

2. The magnitude of the response versus quiet conditions.

The response of the neutral atmosphere to a magnetic storm is at least as complex as the storm itself. How the energy is transferred to the neutral atmosphere and what portion is expended in heating and what portion goes into dynamical processes is not yet known. However, the data shown here indicate that the energy deposited in the neutral atmosphere peaks above 60° latitude and is either nonexistent or constant from 30° latitude to the equator. At 500 km altitude, the N_2 densities are seen to increase at 60° to 80° latitude by factors of 15 to 20 during large disturbances of the magnetic field. At latitudes below 30°, the increase in density of N_2 and O appears to be no greater than a factor of 2. The corresponding maximum temperature increase in the polar region is about 400 to 500°K.

The atomic oxygen enhancements appear fairly constant with latitude, with only slightly greater increases at times in the high latitudes. This is believed due to the dynamical processes which are initiated and not due to a latitudinal independence of the effect of the storm on atomic oxygen.

3. The longitudinal variations in the oval.

This point was partially discussed during the description of the data presented in Figure 13. Since the satellite orbit provides us with data for essentially fixed local times, we obtain data for all longitudes during each 24 hour period. Any 24 hour periodicities in the data could lead one to believe that the densities measured were exhibiting longitudinal variations. However, in looking at the College magnetogram in Figure 13, one can also see 12 and 24 hour periodicities which we could also infer caused the density variations noted. Therefore, which longitudinal variations are present in these data cannot yet be resolved. Hedin, et al., (1970) showed data from the same experiment over the south pole during a period of quiet magnetic activity (K_p < 2) in late August 1969. These data indicated an enhancement in N_2 of about a factor of 5 which persisted at a fixed longitude for several days. More data will be used to study this problem in the near future.

4. The time response of the atmospheric parameters to the solar activity as indicated by the solar geomagnetic indices $R_{10.7}$ and a_p.

In the process of normalizing the data we also corrected for the 10.7 cm flux variations during the period by using the Jacchia (1970) equation for variation with solar activity. During this period the $F_{10.7}$ varied from a maximum value of 158.9 on September 26, 1969, the value used for September 27 data (1 day delay), to a minimum of 133.9 on October 1, 1969. The correction to the October 2 data was -45°K with a base of 1100°K, which provided a correction factor of 1.52 to $R(N_2)$ and 1.24 to R(O) at 500 km. These corrections appeared to provide the proper base line for the ratio data (R(O) and $R(N_2)$ = 1 is base line). However, a longer period of data must be used to determine how well the Jacchia (1970) equation fits the real atmosphere. We plan to do this as more data become available.

The time response of the atmosphere to geomagnetic activity, or a_p, appears to be very short for short impulse duration. For the data shown in Figure 3 on 9/28 at 1142 GMT, the response at high latitudes appears to be on the order of 1 hour or less, and if compared with the College magnetogram on Figure 13, appears almost instantaneous. The low latitude data of Figure 13 shows a lag of 3 to 4 hours. It is felt that the data agree better with the theory of Volland (1969) in that the time lag is probably a function of impulse width and previous history during the particular magnetic disturbance. Also, the time lag appears to be a function of latitude, which is compatible with the conclusion that the bulk of the energy is deposited at high latitudes.

Section 4
CONCLUSIONS

The magnetic disturbances during the period between September 27 through October 5, 1969 may or may not hav been typical. No attempt has been made as yet theoretically to model the neutral atmospheric response to magnetic disturbances since there appears to be a very complex reaction which is a mixture of heating of the atmosphere and circulation of the atmosphere, and which is latitudinally dependent and may be longitudinally dependent. The work of Hays (1970) and Mayr and Volland (1970) is providing a step in the direction of modeling auroral heating effects. These approaches to the problem should be looked at carefully when one is attempting to predict the effects of geomagnetic activity on the neutral atmosphere, especially in the polar regions.

As more data are studied more is sure to be learned. As has been shown by Hedin, et al., (1970), N_2 enhancement and He depletions can be seen at the high latitudes even during periods of quiet magnetic activity, as determined by K_p. As has been pointed out by Cole (1966), $K_p = 0$ does not necessarily mean that geomagnetic disturbances are not present in the polar regions, and indeed there may never be purely quiet conditions. The data that are available will certainly yield a new picture of atmospheric response to geomagnetic activity.

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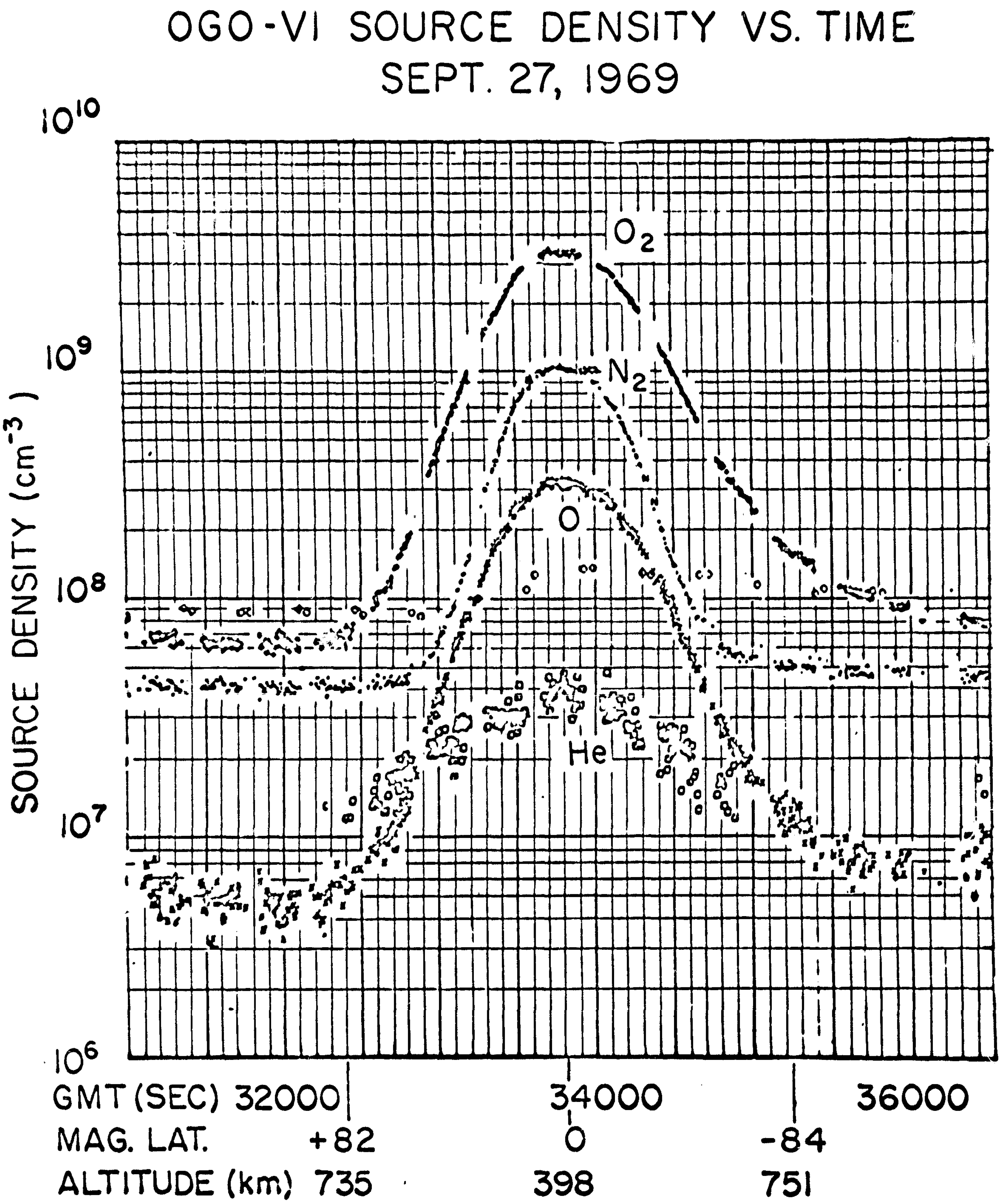
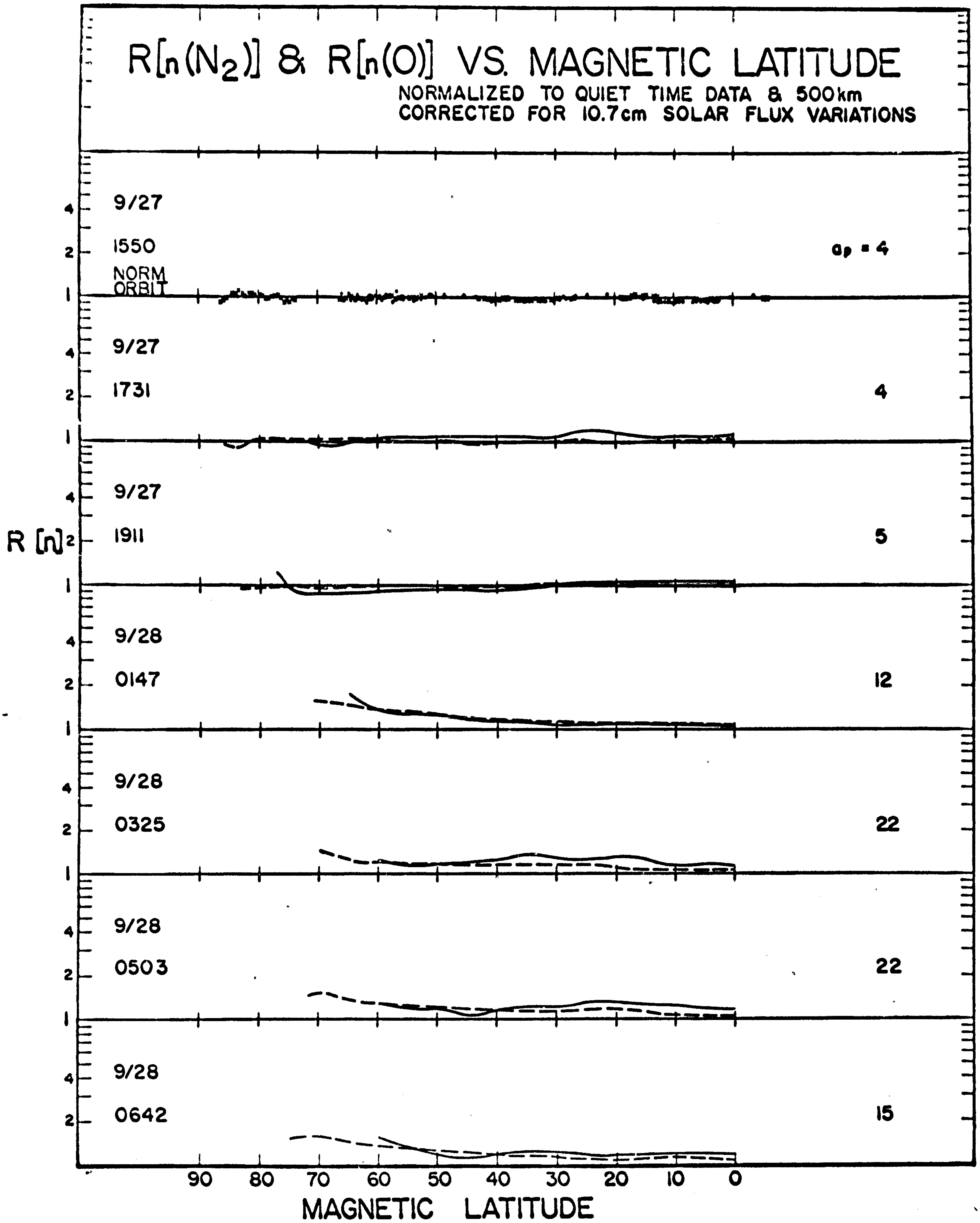

OGO-VI SOURCE DENSITY VS. TIME
SEPT. 27, 1969
10^10
10^9
10^8
10^7
10^6
SOURCE DENSITY (cm^-3)
O2
N2
O
He
GMT (SEC) 32000
34000
36000
MAG. LAT. +82
0
-84
ALTITUDE (km) 735
398
751

Figure 1



R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
9/27
1550
NORM
ORBIT
ap = 4
9/27
1731
4
9/27
1911
5
R [n]
9/28
0147
12
9/28
0325
22
9/28
0503
22
9/28
0642
15
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 2

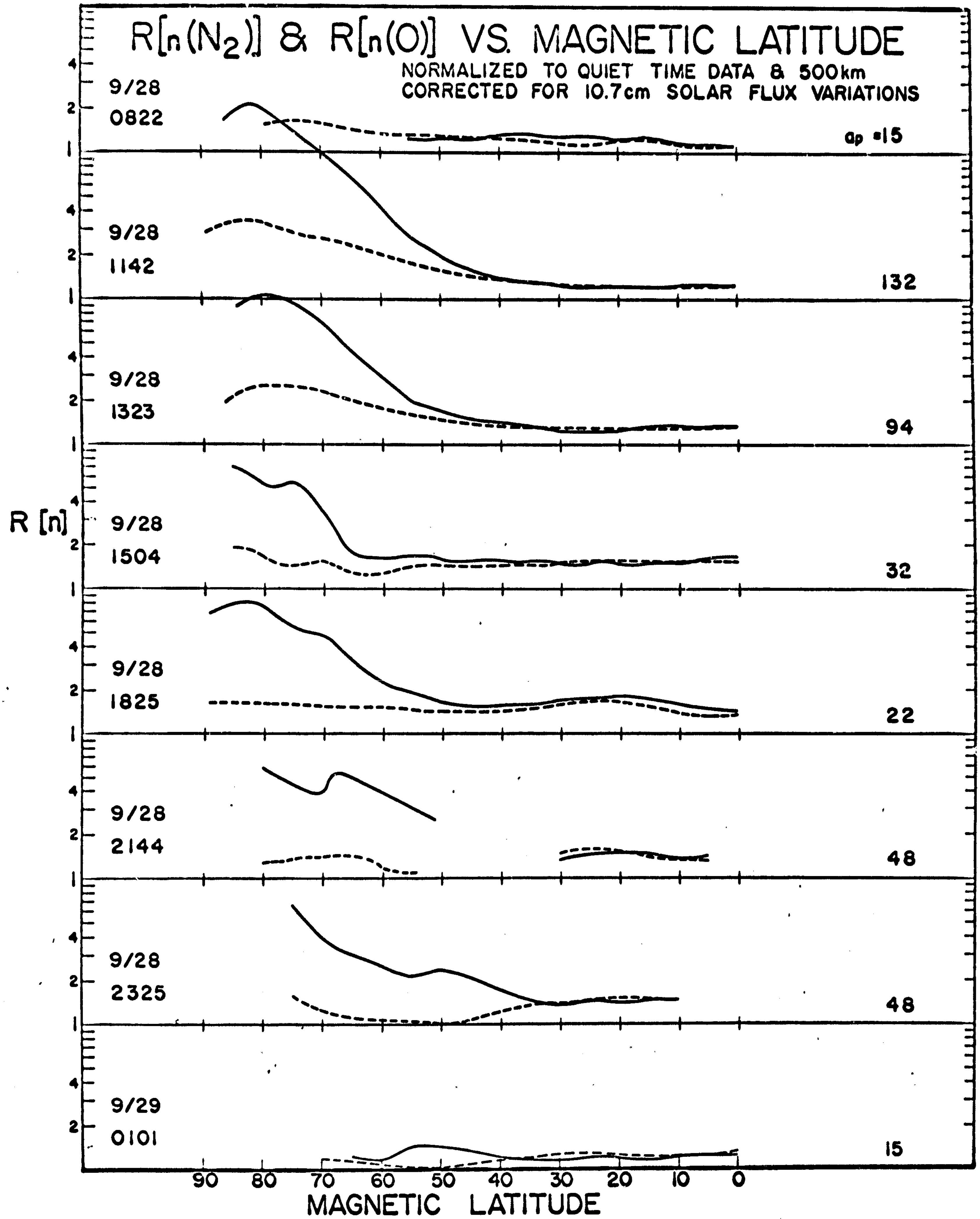

R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
R [n]
9/28
0822
ap =15
9/28
1142
132
9/28
1323
94
9/28
1504
32
9/28
1825
22
9/28
2144
48
9/28
2325
48
9/29
0101
15
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 3

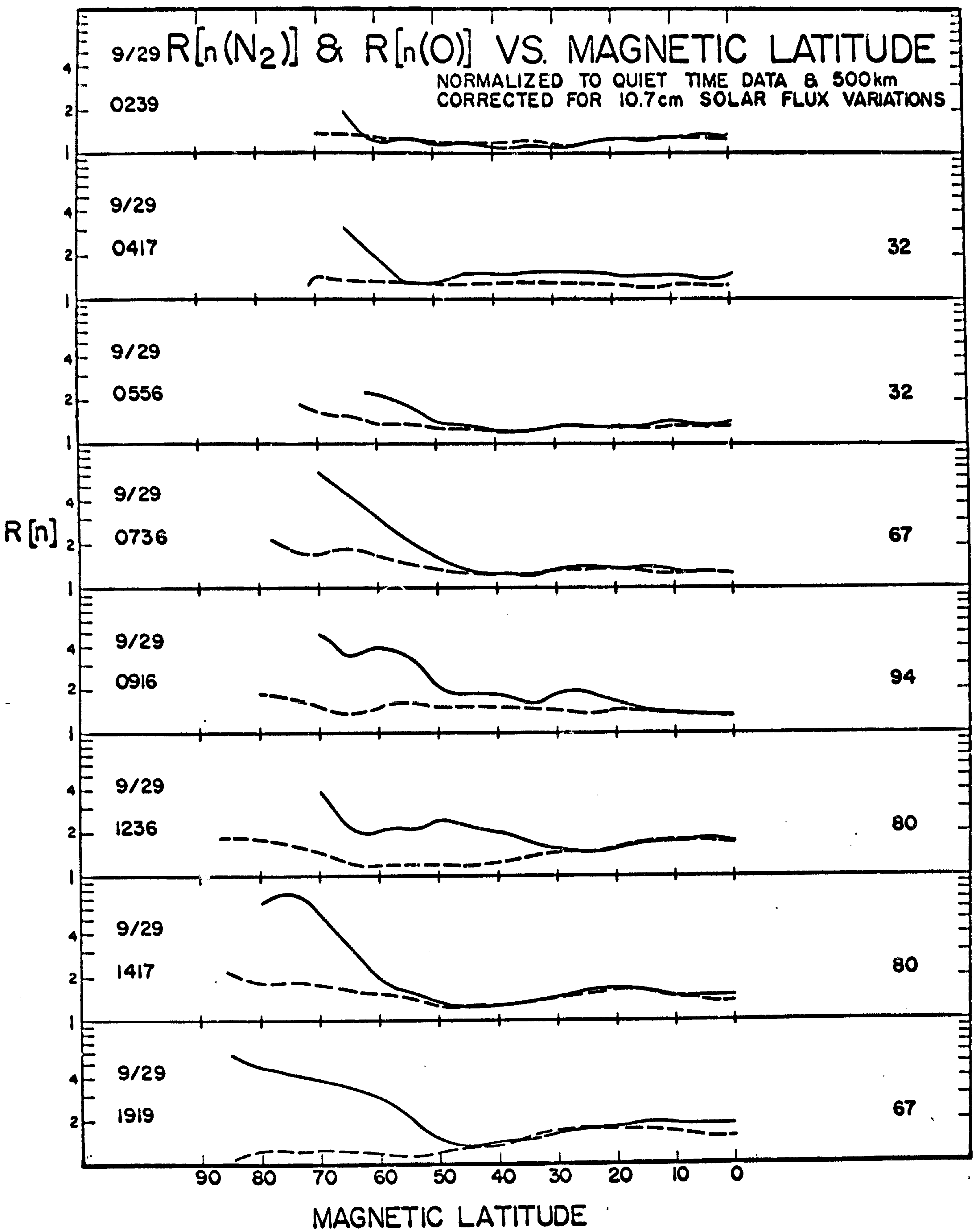

9/29 R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
R[n]
9/29 0239
9/29 0417
32
9/29 0556
32
9/29 0736
67
9/29 0916
94
9/29 1236
80
9/29 1417
80
9/29 1919
67
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 4

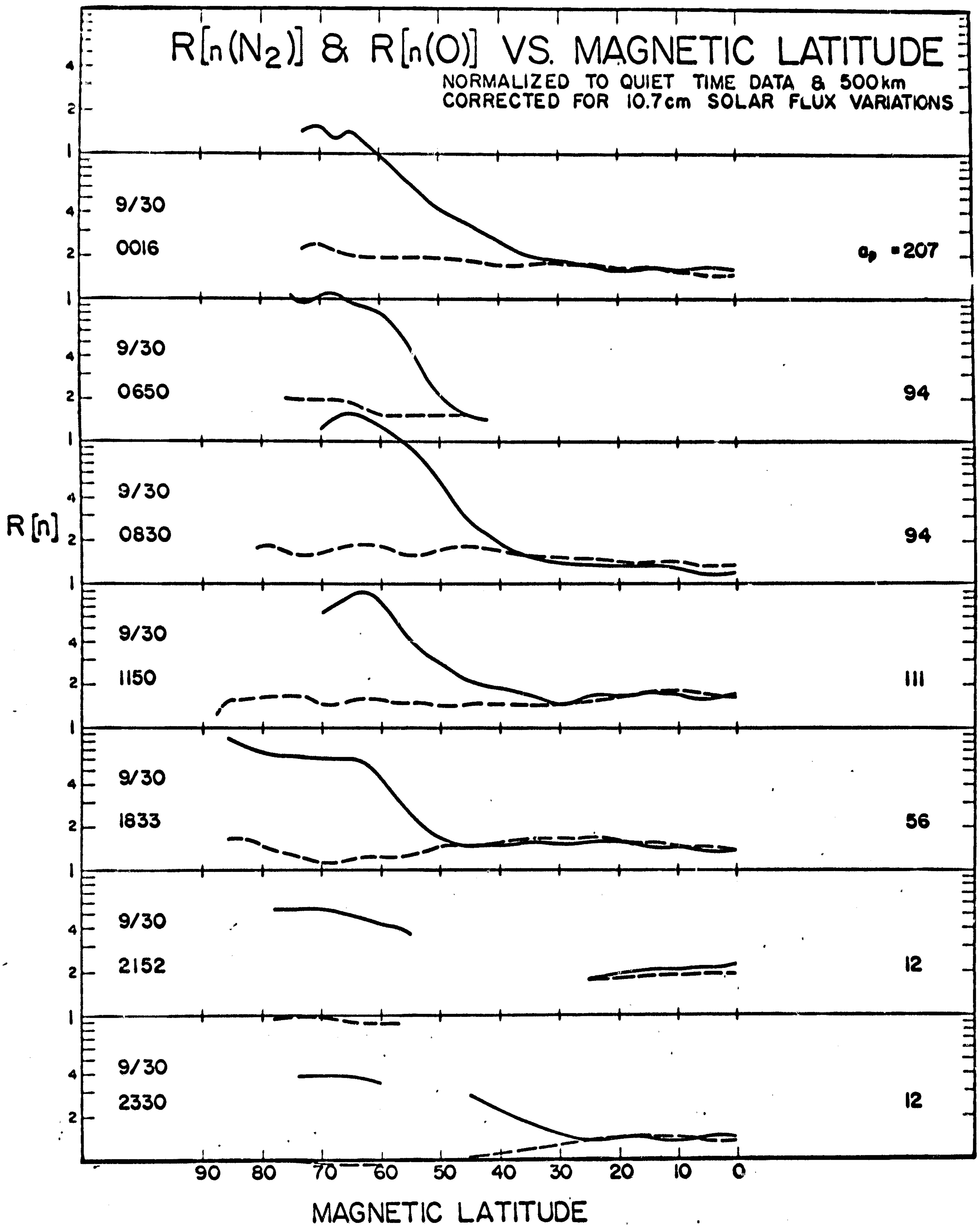

R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
9/30
0016
ap = 207
9/30
0650
94
9/30
0830
94
9/30
1150
111
9/30
1833
56
9/30
2152
12
9/30
2330
12
R[n]
90
80
70
60
50
40
30
20
10
0
MAGNETIC LATITUDE

Figure 5

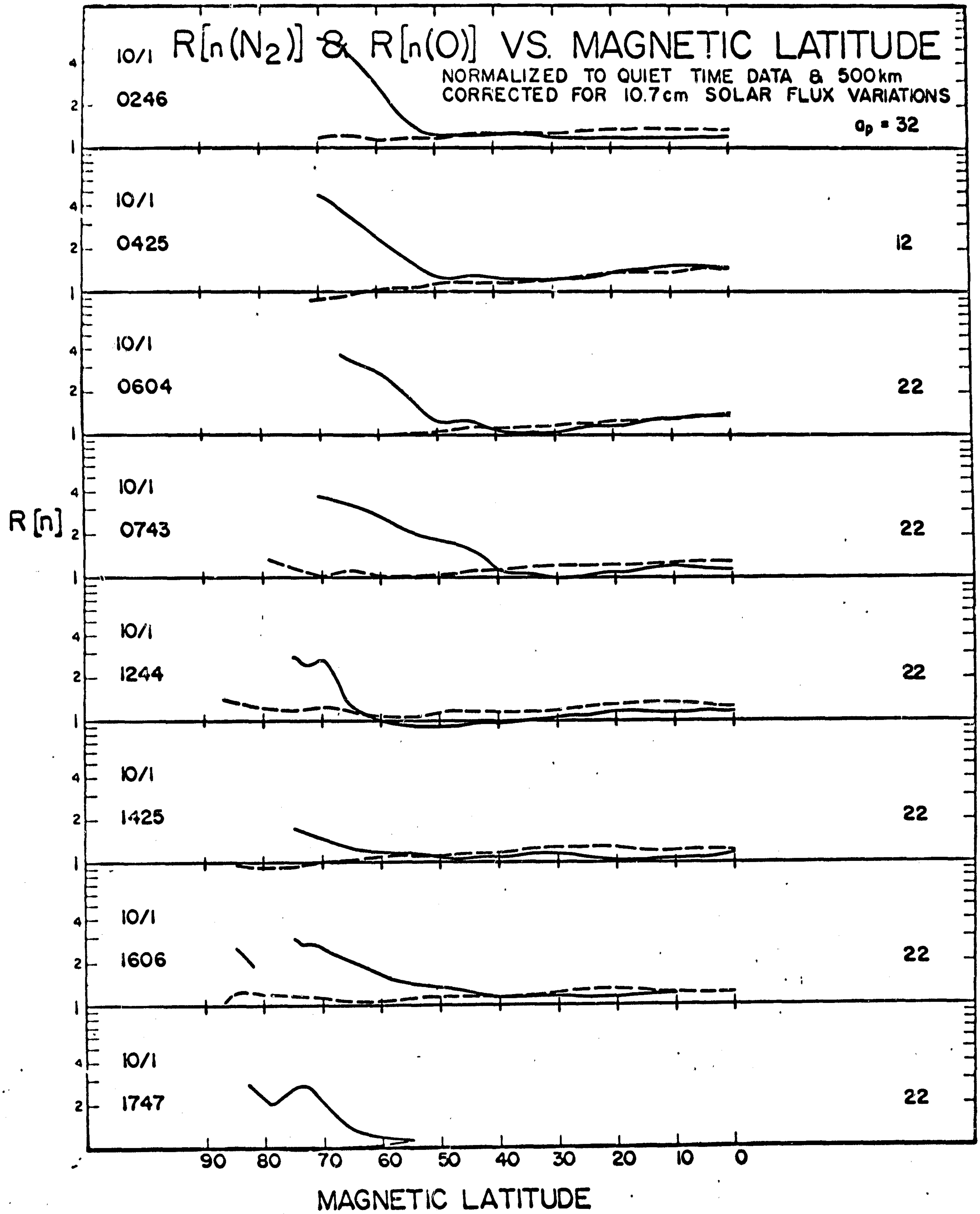

R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
ap = 32
R[n]
10/1 0246
10/1 0425
12
10/1 0604
22
10/1 0743
22
10/1 1244
22
10/1 1425
22
10/1 1606
22
10/1 1747
22
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 6

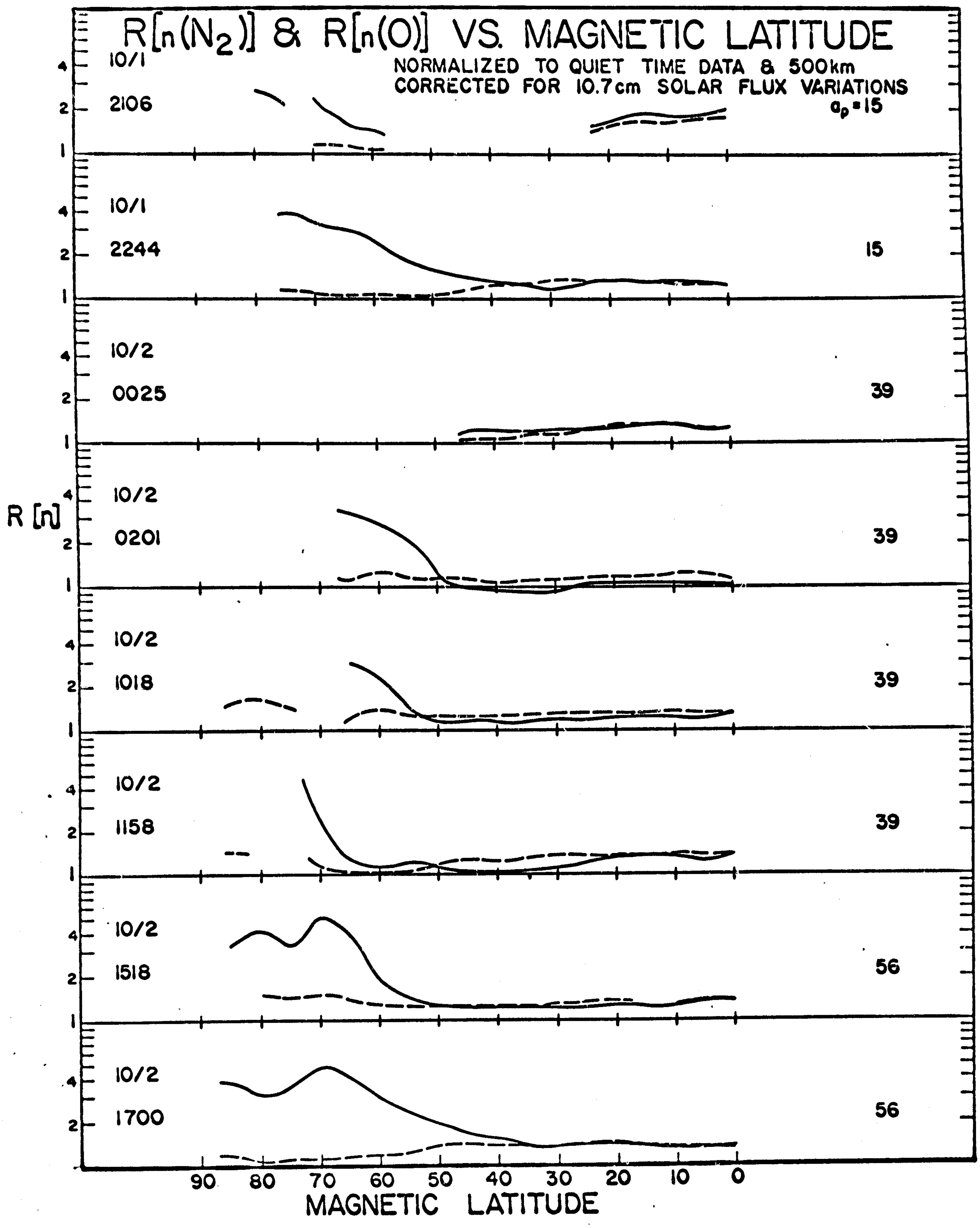

R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
10/1
2106
ap=15
10/1
2244
15
10/2
0025
39
10/2
0201
39
10/2
1018
39
10/2
1158
39
10/2
1518
56
10/2
1700
56
R [n]
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 7

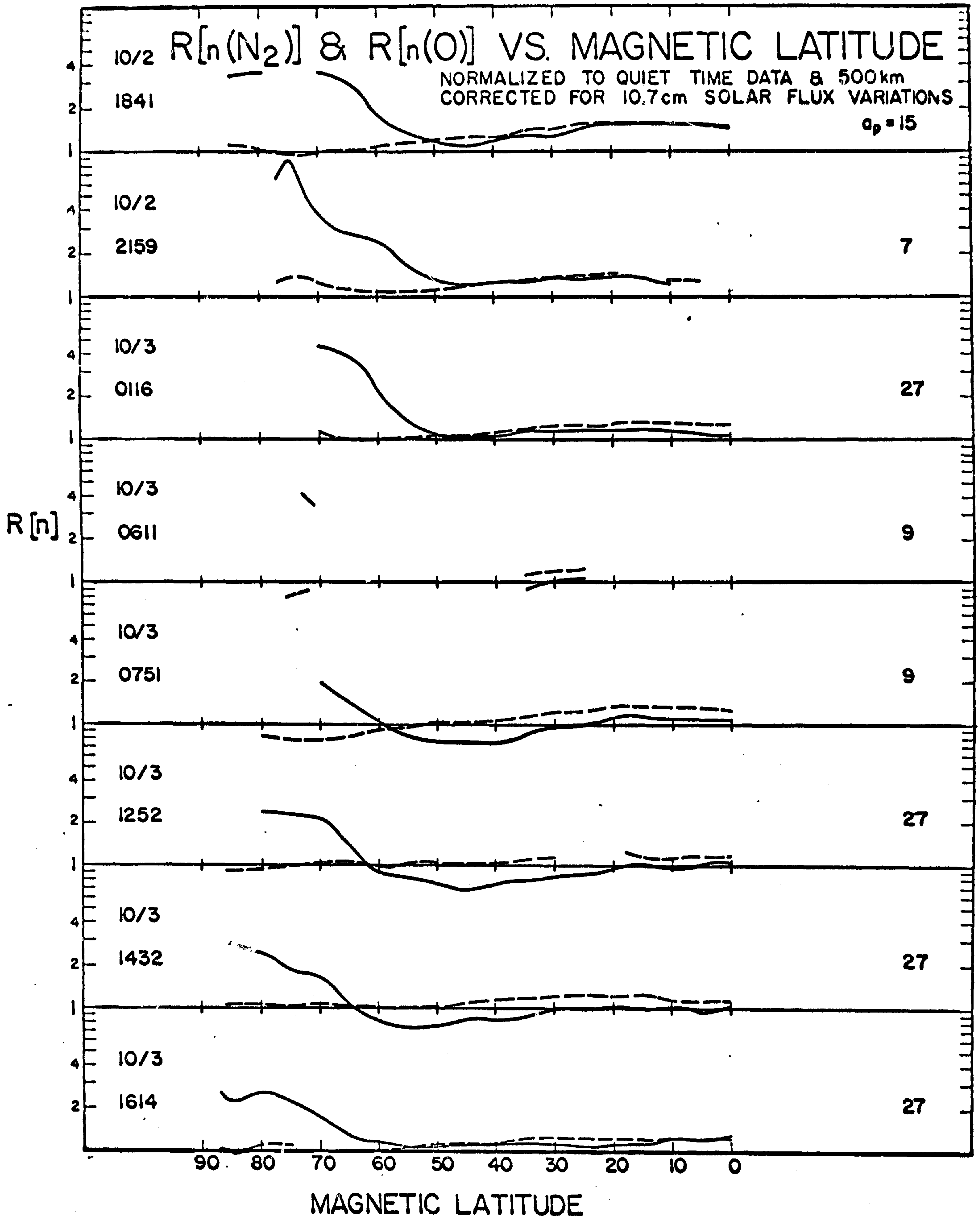
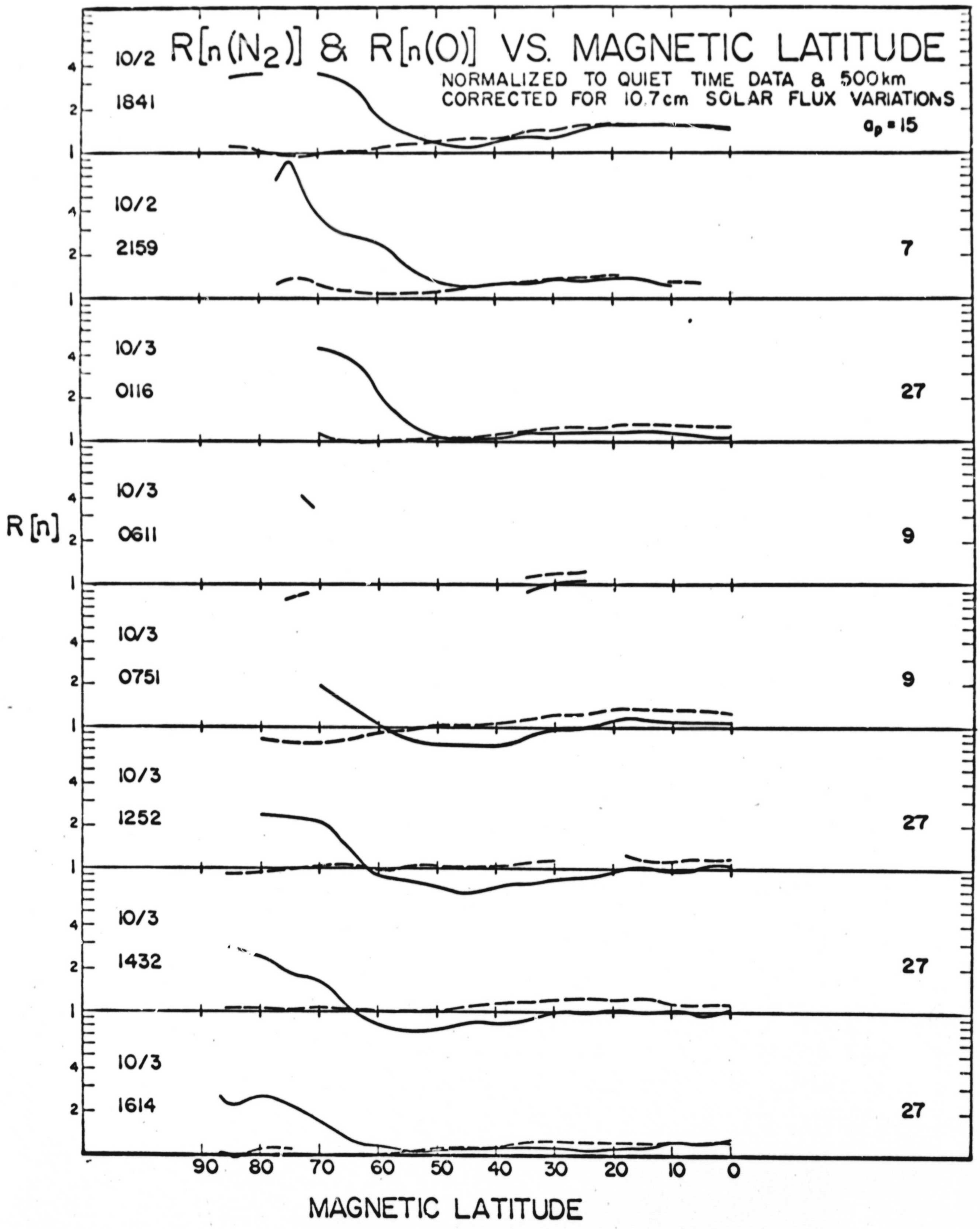
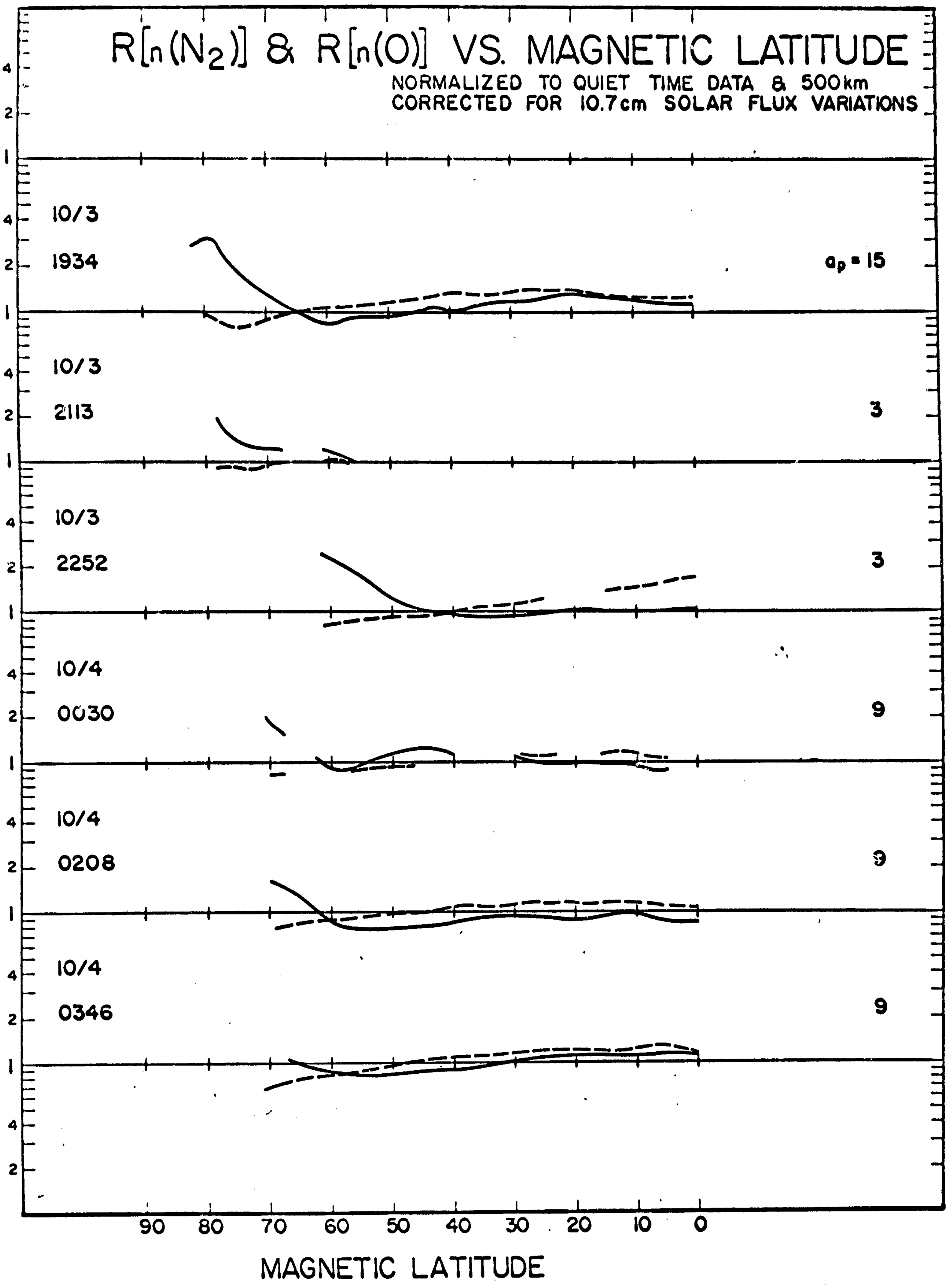

R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
ap = 15
10/2
1841
10/2
2159
7
10/3
0116
27
10/3
0611
9
10/3
0751
9
10/3
1252
27
10/3
1432
27
10/3
1614
27
R[n]
90
80
70
60
50
40
30
20
10
0
MAGNETIC LATITUDE

Figure 8



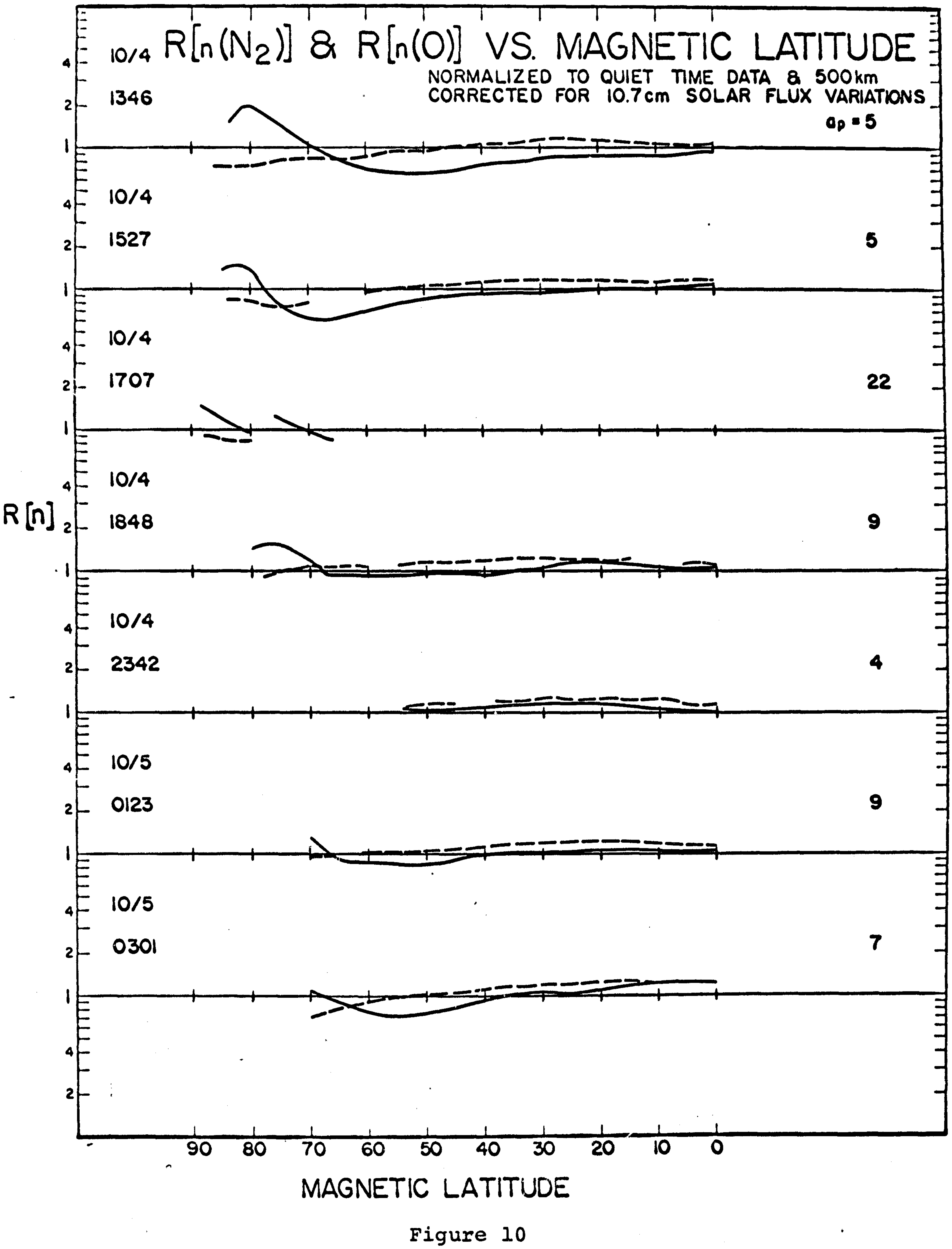
R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
ap = 15
10/2 1841
10/2 2159
7
10/3 0116
27
10/3 0611
9
10/3 0751
9
10/3 1252
27
10/3 1432
27
10/3 1614
27
R[n]
4
2
1
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 8



R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
R[n]
10/3
1934
a_p = 15
10/3
2113
3
10/3
2252
3
10/4
0030
9
10/4
0208
9
10/4
0346
9
90 80 70 60 50 40 30 20 10 0
MAGNETIC LATITUDE

Figure 9



R[n(N2)] & R[n(O)] VS. MAGNETIC LATITUDE
NORMALIZED TO QUIET TIME DATA & 500km
CORRECTED FOR 10.7cm SOLAR FLUX VARIATIONS
ap = 5
10/4
1346
10/4
1527
5
10/4
1707
22
10/4
1848
9
10/4
2342
4
10/5
0123
9
10/5
0301
7
R[n]
4
2
1
90
80
70
60
50
40
30
20
10
0
MAGNETIC LATITUDE

Figure 10

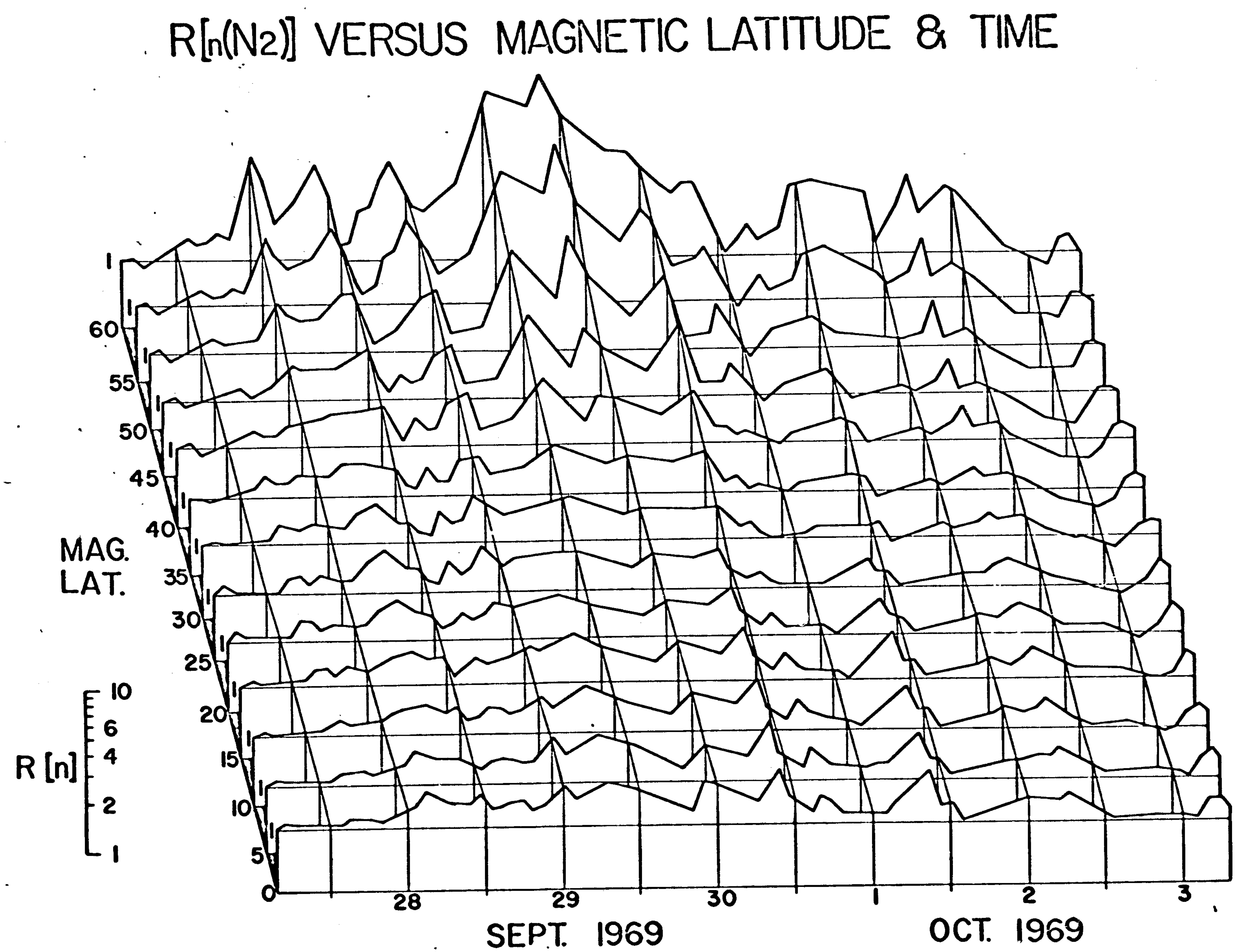

R[n(N2)] VERSUS MAGNETIC LATITUDE & TIME
MAG. LAT.
60
55
50
45
40
35
30
25
20
15
10
5
0
R [n]
10
6
4
2
1
28
29
30
1
2
3
SEPT. 1969
OCT. 1969

Figure 11

R[n(O)] VERSUS MAGNETIC LATITUDE & TIME

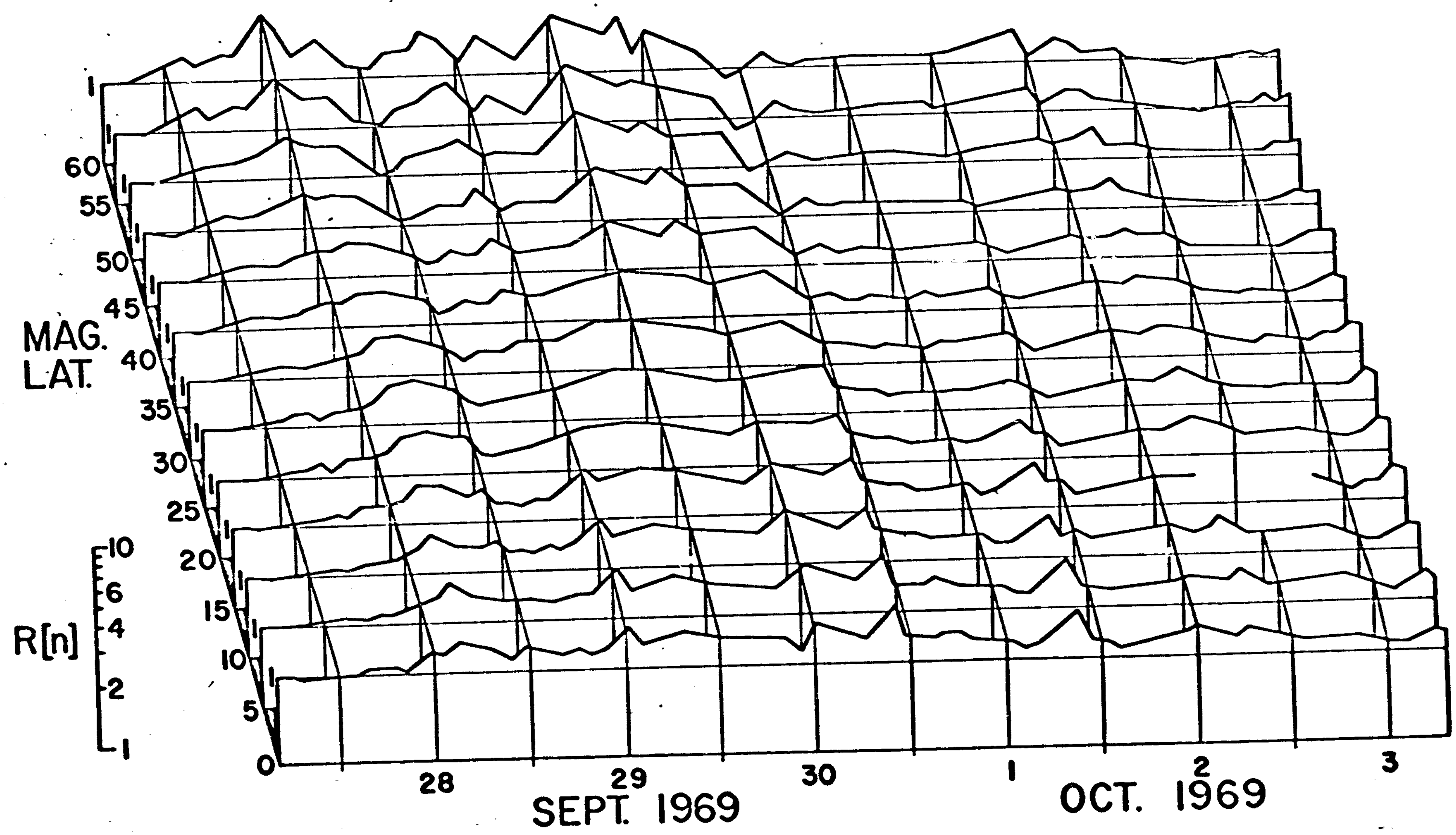


Figure 12

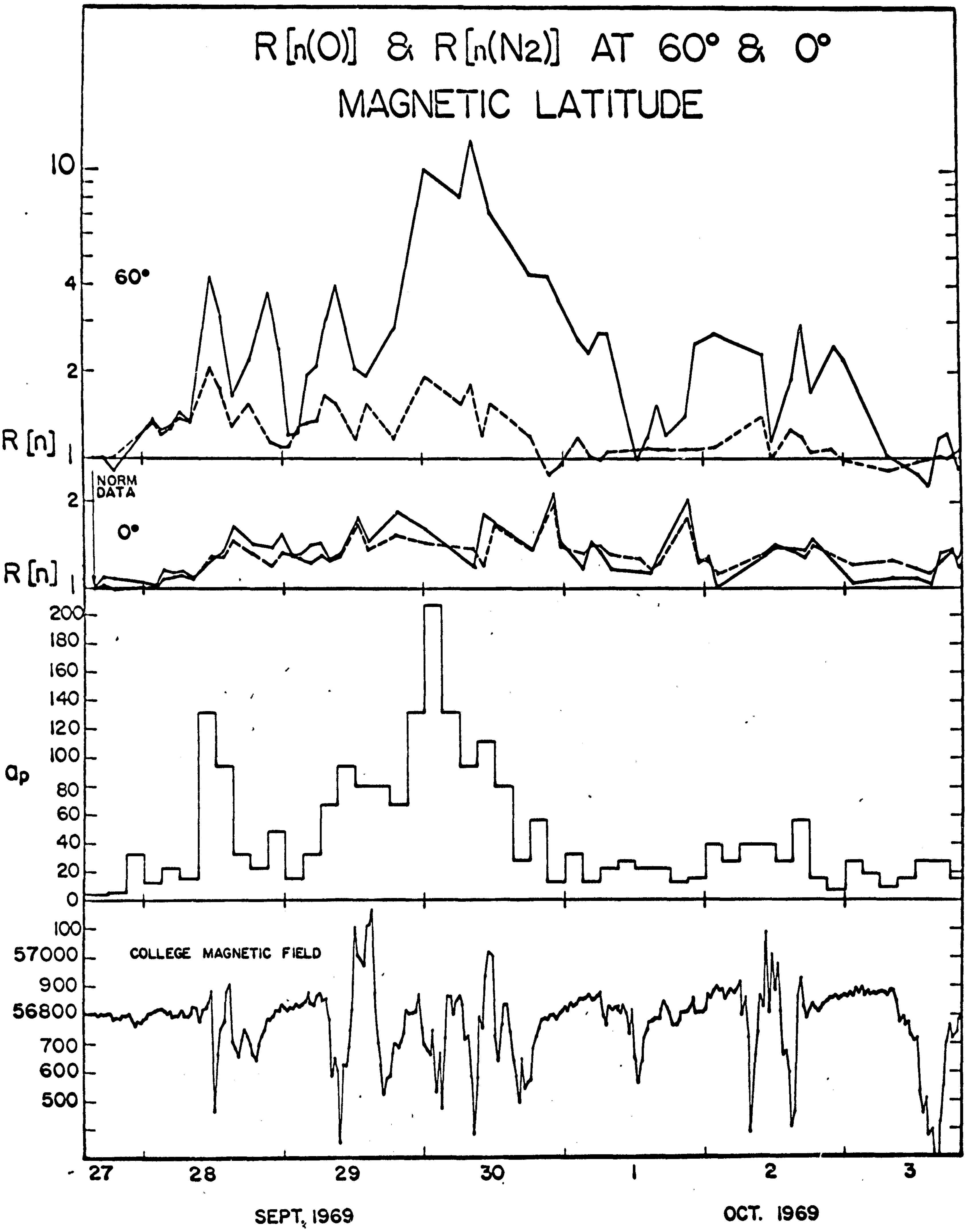

R[n(O)] & R[n(N2)] AT 60° & 0°
MAGNETIC LATITUDE
10
4
2
60°
R[n]
1
NORM DATA
2
0°
R[n]
1
200
180
160
140
120
100
80
60
40
20
0
ap
100
57000
900
56800
700
600
500
COLLEGE MAGNETIC FIELD
27
28
29
30
1
2
3
SEPT. 1969
OCT. 1969

Figure 13