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HIGH LATITUDE MINOR ION ENHANCEMENTS: A CLUE FOR STUDIES OF MAGNETOSPHERE-ATMOSPHERE COUPLING

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HIGH LATITUDE MINOR ION ENHANCEMENTS: A CLUE FOR STUDIES OF MAGNETOSPHERE-ATMOSPHERE COUPLING

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ABSTRACT

Unexpectedly abrupt and pronounced distributions of the thermal molecular ions NO^+, O_2^+, and N_2^+ are observed at mid and high latitudes by the OGO-6 ion mass spectrometer. Normally considered trace constituents of the topside ionosphere, following magnetic storms these minor ions may reach concentration levels exceeding 10^3 ions/cm^3 at altitudes as great as 1000 km., suggestive of scale heights well in excess of those inferred from low and mid-latitude measurements, under relatively undisturbed conditions. The high latitude ion enhancements are sometimes observed to be narrowly defined in time and space, with molecular ion concentrations changing by as much as an order of magnitude between successive orbits. Assuming that these localized ion enhancements are associated with energetic perturbation of the lower ionosphere, it would follow that energy coupled to the lower altitudes may at times also be narrowly distributed in time and space within a given hemisphere. This view seems consistent with the observation that local magnetic substorm activity is closely associated in time

and space with the anomalous ion enhancements. These results suggest that the search for a link between solar-magnetic processes and perturbation of the lower atmosphere may well benefit from phenomenological investigations, in support of statistical methods attempted previously.

INTRODUCTION

During the exploratory phase of space research there has been a growing interest in the importance of the solar wind-magnetosphere system as an energy reservoir possibly sufficient to modify the configuration of both the upper and lower atmosphere, otherwise dominated by direct solar ultra violet input. Indicative of the emerging view of the significance of the magnetospheric energy input is the recent study of Ching and Chiu (1973) which concludes that the Joule dissipation rate of ionospheric electric fields at high latitudes is similar in magnitude and altitudinal profile to the global solar EUV absorption rate, confirming the earlier proposition by Cole (1971) that magnetosphericly induced Joule heating may, during magnetically active periods, constitute a heat source competitive with the direct EUV absorption.

In addition to electric and magnetic field effects, the importance of precipitating particles as an energy source has been the subject of even more numerous studies. The ion-cyclotron instability mode has been proposed as an important factor regulating precipitation, and the work of Brice (1971) suggests that these instabilities may result in localized precipitation patterns and associated energy changes.

This changing view of the relative importance of direct and

and indirect solar energy input to the upper atmosphere has been accompanied by a closely related interest in the degree of association between solar-magnetospheric processes and unexpected, unexplained perturbations observed in the mesosphere and troposphere. An example of the renewed interest in this area is the current investigation of the correlation between the winter pattern of 300 mb low pressure troughs across North America and the phasing of the sector structure of the solar magnetic field (Wilcox et al., 1973), which supports the work of Roberts and Olson (1973) who earlier identified a correlation between the trough intensity and the planetary magnetic index, Kp This study, like some related efforts to explain provocative ionospheric and thermospheric anomalies has tended to depend upon a statistical rather than a phenomenological study, due to a lack of controlled, in-situ observations of events and related conditions. The result of this limitation is that while general trends of correlation between atmospheric events and magnetic activity may be suggested, detailed agreement in specific cases has been difficult to identify. From this view, it may be inferred that rather unique sets of physical conditions may be required to either (1) permit the effective coupling of solar-geomagnetic energy into the lower atmosphere and/or (2) trigger a detectable atmospheric response to energy so deposited.

It is the purpose of this paper to examine upper ionosphere molecular ion composition data, which because of the unexpected, abrupt enhancements sometimes exhibited at high latitudes, may indirectly offer additional clues to understanding the processes by which the lower atmospheres becomes perturbed. Although we cannot demonstrate that these results from the thermosphere-exosphere region (400-1100 km) relate directly to conditions in the lowest layers of the atmosphere, the dynamic variations in the relatively heavy ions N_2^+, NO^+, and O_2^+ observed in the topside are surely indicative of importance disturbances in the 100-200 km source level, and may eventually be linked with conditions at still lower levels. We believe the evidence of irregularities makes a case for phenomenological studies, possibly on a substorm scale, in addition to statistical studies using globally averaged parameters. The main points we will emphasize are that (1) molecular ion irregularities are sometimes localized in a relatively narrow region of time/space, and (2) the abruptness of these events suggests that lower atmosphere energetic processes presumed responsible for the ion enhancements may also be narrowly distributed.

RESULTS

The data to be discussed have been obtained from the Bennett rf ion composition experiment on OGO-6 during 1969-1970. Over much of the near polar orbit (400-1100 km) the molecular ions N_2^+, NO^+ and O_2^+ are observed as secondary in content relative to the primary ions O^+, H^+, He^+ and N^+ (Taylor, 1973). At high latitudes, however, and particularly during magnetic storms, the concentration of each of the molecular ions increases significantly often in the form of pronounced enhancements or peaks which emerge abruptly even as the satellite height is increasing rapidly with latitude.

To illustrate the significance of the high latitude enhancements in the molecular ions, we first examine the strong altitudinal dependence exhibited by the molecular ion distributions at low and mid latitudes. In Figure 1, the distributions of NO^+, N_2+, and O_2^+ are shown for equinox, early morning local time, with altitude centered on the dipole equator. The inter-hemispheric symmetry observed between the distributions is indicative of the strong altitude-magnetic latitude relationship in ordering the distributions during quiet magnetic activity.

The observed rapid decrease in molecular ion concentrations with increasing altitude is reasonably consistent with the assumption that above 400 km the distributions of these ions are controlled largely by diffusive equilibrium. Examination of a series of such profiles, has shown that a density decrease of a factor of 3 usually occurs in about 20-30 km for these ions at mid and low latitudes, under undisturbed conditions. Such a rapid decrease with altitude above the chemical equilibrium level is reasonably consistent with altitude profiles obtained from sounding rockets (Brinton et al., 1969) (Hoffman et al., 1969). Note that approaching high latitudes, near 60-70°, the distributions continue to decrease rapidly with altitude, providing no evidence of unusual enhancements at this particular local time, longitude, and quiet magnetic activity. Note also that similar distributions are obtained for each of the molecular ions, as is rather typical of the data examined to date. For simplicity and clarity we will show only NO^+ in the illustrations which follow, with the understanding that the NO^+ distributions are representative of similar variations in the other 2 molecular ions.

As the longitude and magnetic local time of the orbit shifts from day to day, the prominence of the low altitude molecular ion distribution changes significantly, particularly near the terminator where abrupt day-night variations in ion content are observed. In Figure 2, the significance of magnetic local time variation relative to the NO^+ distribution is examined by comparing measurements obtained near local dawn, in orbits separated by only 3 days in UT and less than 30 minutes in magnetic local time. Note the absence on March 26 of the broad NO^+ peak formerly observed at perigee on March 23 when the satellite was nearer "magnetic dayside" conditions. The low altitude portion of the March 26 NO^+ profile thus reflects nightside conditions, with a much depleted low altitude distribution of molecular ions. At this location, the presence of the narrow spikes of NO^+ enhancement seen near 70-80° on March 26 becomes quite obvious. Note that NO^+ increases sharply from the instrument background level to 40-50 ions/cm^3, even as the satellite height is increasing between 500-600 km. As shown, while the low latitude production of NO^+ falls off abruptly as the nightside is penetrated, a high latitude source is retained. Although these data were selected to emphasize the variable relative importance of the low and high latitude ion contributions, it is emphasized that the molecular enhancements are not restricted to the nightside. Such peaks are observed over a wide range of local times, being quite prominent on the dayside.

Although the high latitude NO^+ enhancements in Figure 2 are relatively modest, we note that the magnetic activity was moderately quiet with $Kp = 2_o$ in the 6 hours preceding the measurements. At higher levels of Kp, significantly larger NO^+ peaks are frequently observed. An example of the magnitude and structure of the storm-time enhancements is shown in Figure 3, for a disturbed period when the prior 6 hour Kp level reached 4_o. Note the abruptness of the enhancements, which exhibit peaks as narrow as 2-3° in width, with concentrations approaching 10^3 ions/cm^3 near 1000 km altitude.

A most important characteristic of the high latitude molecular ion enhancements is the frequent lack of persistence from orbit to orbit, indicating that the source of the enhancements is at times relatively isolated in either time or position. Examples of the isolated type of molecular ion peak are shown in Figures 4 and 5 for orbits located near local dawn. These examples were chosen to illustrate the case for the high latitude peak emerging at high altitude, thus emphasizing the magnitude of the mechanism responsible for this unexpected increase in heavy ion concentration in the topside region. In this way we have also attempted to avoid the confusion produced by the overlap between the lower altitude variations and the dynamic enhancement under study.

The difficulty in separating these effects in a given orbit is seen in Figure 4, where the southern hemisphere perigee distribution of NO^+ appears as the combined result of decreasing altitude and the onset of high latitude enhancement. Near apogee in the northern hemisphere, however, the low altitude component is not present, and the presence or absence of a high latitude peak becomes obvious. As shown, an unexpected, significant peak in NO^+ is observed on the second of series of 3 consecutive passes, which are separated by about 100 minutes in UT and 24 longitude. In sharp contrast to pass 2, the NO^+ concentration for passes 1 and 3 drops to the measurement background level, revealing at least an order of magnitude increase in NO^+ concentration for pass 2, within the time and space resolution afforded by the observations.

A similar example of an abrupt, isolated enhancement in NO^+ is given in Figure 5, again near local dawn with apogee in the northern hemisphere. Note that while a persistent enhancement in NO^+ is measured in the south, at considerably lower altitude, the northern hemisphere increase of more than an order of magnitude in NO^+ is restricted to pass 2. In this case the longitudinal extent of the peak is necessarily less well defined than Figure 4, since the 3rd pass in the sequence of 4 was lost in data processing.

As indicated earlier, the enhancements in Figures 4 and 5 were observed during disturbed conditions, when Kp = 4-5. A reasonable implication from this is that these enhancements may be linked with substorm activity, and that the dimensions of the substorm may be associated with the relative abruptness of the presence or absence of the molecular ion increase. A check of magnetograms from ground observatories in the longitude range of the observations of both Figures 4 and 5 has verified that discrete substorm activity was indeed present near the time and location of the molecular peak observations, with a well defined onset of bay activity several hours prior to the observation of the peak. In Figures 6 and 7, magnetograms are shown, corresponding to the times and locations of the data Figures 4 and 5, respectively. Note in each case the onset of magnetic bay activity occuring 1-2 hours prior to the observation of the isolated NO^+ enhancement in the northern hemisphere.

DISCUSSION

The molecular ion enhancements provide evidence that, for certain conditions, the high latitude ionosphere undergoes significant changes which may be narrowly restricted in time and space. It is evident that even under relatively quiet conditions there may be a substantial high latitude upsurge of molecular ions, as shown in Figure 2. Due to the location (near 70°Λ) and relatively narrow latitudinal extent of these ion peaks, it is tempting to associate them with the magnetospheric cusp, since this mechanism could possibly supply the needed energy to perturb the lower ionosphere region (100-200 km) where molecular ion production and chemistry are most important. It is interesting to note that the latitudinal extent frequently observed for the NO^+ peaks is rather similar to the latitudinal zone of 2 -5°Λ identified for the penetration of magneto-sheath plasma at the cusp or neutral point by Heikkila and Winningham (1971). While direct precipitating particle data has not yet been possible, the extensive correlation already established between soft electron precipitation and auroral disturbances (e.g. Hoffman and Laaspere, 1972) supports the premise that the ion anomalies may be associated with particle events.

The detailed temporal and spatial relationship between energy input, either in the form of particle precipitation or Joule heating, and resultant magnetic and atmospheric disturbances is not well known. From these measurements alone it cannot be concluded that the high altitude ionospheric disturbance results from a specific type and location of energy input to the lower atmosphere. These uncertainties notwithstanding, it is significant to note that pronounced enhancements have also been detected in the high latitude distributions of neutral N_2 (Reber and Hedin, 1972) in patterns which suggest magnetically controlled heating of the lower thermosphere at high latitudes. The high altitude data chosen for the present study particularly to minimize altitude effects has precluded correlation of the molecular ion peaks with possibly associated neutral N_2 peaks. However, direct ion-neutral comparisons at lower altitudes and latitudes do indeed show that storm time enhancements in NO^+ are accompanied by similar enhancements in N_2 (Taylor, 1973b).

Perhaps the most interesting feature of the present results which may be relevant to studies of the perturbation of the lower atmosphere is the evidence that whatever the mechanism, the associated ionospheric (and possibly the atmospheric) disturbance may be discontinuous and/or relatively localized in time and space. Considering precipitating particles as a possible energy source, the localized nature of the observed disturbance appears reasonable. First, numerous particle measurements have shown that the influx of cusp particles is not necessarily stable in intensity or location (e.g. Gurnett and Frank, 1973). Second, as shown in the auroral study by Stenbaek-Nielson et al., (1973) longitudinal variations in magnetic field intensity may explain related longitudinal differences in auroral intensity, by virtue of the dependence of energetic particle mirroring altitudes upon magnetic field intensity.

In view of these factors, it might be expected that atmospheric or ionospheric perturbations linked with particle events might exhibit a pulselike or longitudinally variable character. This possibility could present a significant problem for statistical studies of such phenomenon since the required resolution in time and space may well be unavailable in existing data sets.

While the present study does not permit direct insight into mechanisms responsible for perturbing lower atmospheric processes per se, we believe that the observed variability provides a relevant clue. Specifically, these results suggest that the search for understanding magnetosphere-atmosphere coupling may require phenomenological investigations in support of statistical studies which have not yet provided the necessary answers. For example, it seems clear that lower atmospheric irregularities like those of the upper ionosphere will not always occur a global scale, so that correlative studies attempting to determine a link with planetary indicators, such as Kp, may prove inconsistent.

With this view in mind we hope to encourage the phenomenological study of outstanding ionospheric and atmospheric anomalies. It is hoped that future studies will emphasize correlative results which may provide a more quantitative description of the energetic and dynamic processes responsible for coupling the solar wind-magnetosphere system not only to the ionosphere, but to the lower atmosphere as well.

REFERENCES

BRICE N.	1971	J. Geophys. Res., 76, 4698.
BRINTON H. C., PHARO M. W., III MAYR H. G. and TAYLOR H. A., JR.	1969	J. Geophys. Res., 74, 2941.
CHING B. K. and CHIU Y. T.	1973	Planet. Sp. Sci., 21, 1633.
COLE K. D.	1971	Planet. Sp. Sci., 19, 59.
GURNETT D. A. and FRANK L. A.	1973	J. Geophys. Res., 78, 145.
HEIKKILA W. T. and WINNINGHAM J. D.	1971	J. Geophys. Res., 76, 883.
HOFFMAN J. H., JOHNSON C. Y. HOLMES J. C. and YOUNG J. M.	1969	J. Geophys. Res., 74, 6281.
HOFFMAN R. A. and LAASPERE T.	1972	J. Geophys. Res., 71, 640.
REBER C. A. and HEDIN A. E.	1972	Trans. Am. Geo. Un., 53, 465.
ROBERTS W. O. and OLSON R. H.	1973	J. Atmos. Sci., 30, 135.
STENBAEK-NIELSEN H. C. WESCOTT E. M., DAVIS T. N. and PETERSON R. W.	1973	J. Geophys. Res., 78, 659.
TAYLOR H. A., JR.	1973	J. Geophys. Res., 78, 315.
TAYLOR H. A., JR.	1973b	Trans. Am Geo. Un., 54, 38.
WILCOX J. M., SCHERRER P. H., SVALGAARD L., ROBERTS W. O. and OLSON R. H.	1973	Science, 180, 185.

FIGURES

FIGURE 1: Quiet time distributions of molecular ions observed near dawn local time, near equinox. Kp_{-6} refers to the maximum value of Kp during the 6 hour interval preceding the measurement.

FIGURE 2: A comparison of NO^+ distributions observed near the dawn terminator. Passes are selected for nearly identical altitude, longitude and Kp conditions. At the latitudes of the 3 arrows, the corresponding magnetic local times are shown for each pass.

FIGURE 3: An example of the pronounced, irregular enhancement in NO^+ observed at high latitude and high altitude.

FIGURE 4: A series of 3 consecutive OGO-6 passes revealing an abrupt appearance of a high latitude enhancement in NO^+ on pass No. 2, above the noise level observed in the same location on passes 1 and 3. The broad southern hemisphere NO^+ distribution is attributed to a combination of altitude and latitude effects. (Longitudes shown in the right hand panels are geographic, for comparison with magnetic observatory locations in Figure 6.)

FIGURE 5: A series of 3 OGO-6 passes of which 1 and 2 are consecutive,

and with one orbit missing between 2 and 3, due to a data gap. Note on pass 2 that the northern hemisphere peak in NO^+ is at an altitude 200 km higher than that for the recurrent peak observed in the south.

FIGURE 6: Magnetogram records from stations in the longitude range of the northern hemisphere NO^+ peak study of Figure 4. The magnetic bay activity observed near 0300 UT occurs about 1.5 hours prior to the observation of the abrupt molecular ion enhancement on pass 2.

FIGURE 7: Magnetogram records from stations in the longitude range of the northern hemisphere NO^+ peak of Figure 5. The magnetic bay activity observed near 1030 UT occurs about 1 hour prior to the detection of the molecular ion enhancement on pass 2.

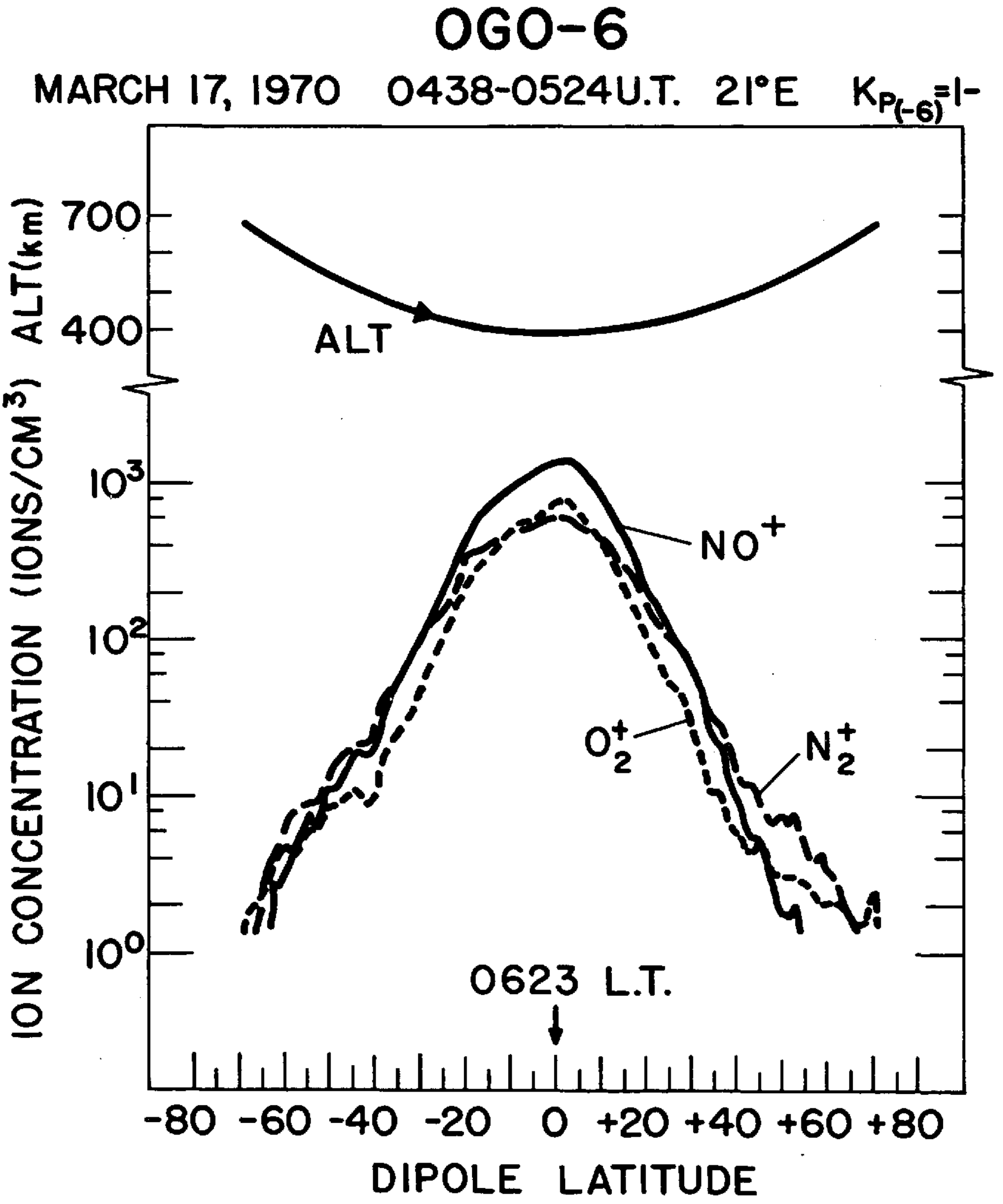
OGO-6
MARCH 17, 1970 0438-0524U.T. 21°E Kp(-6)=1-
ALT(km)
700
400
ALT
ION CONCENTRATION (IONS/CM³)
10³
10²
10¹
10⁰
NO⁺
O₂⁺
N₂⁺
0623 L.T.
-80 -60 -40 -20 0 +20 +40 +60 +80
DIPOLE LATITUDE

Figure 1

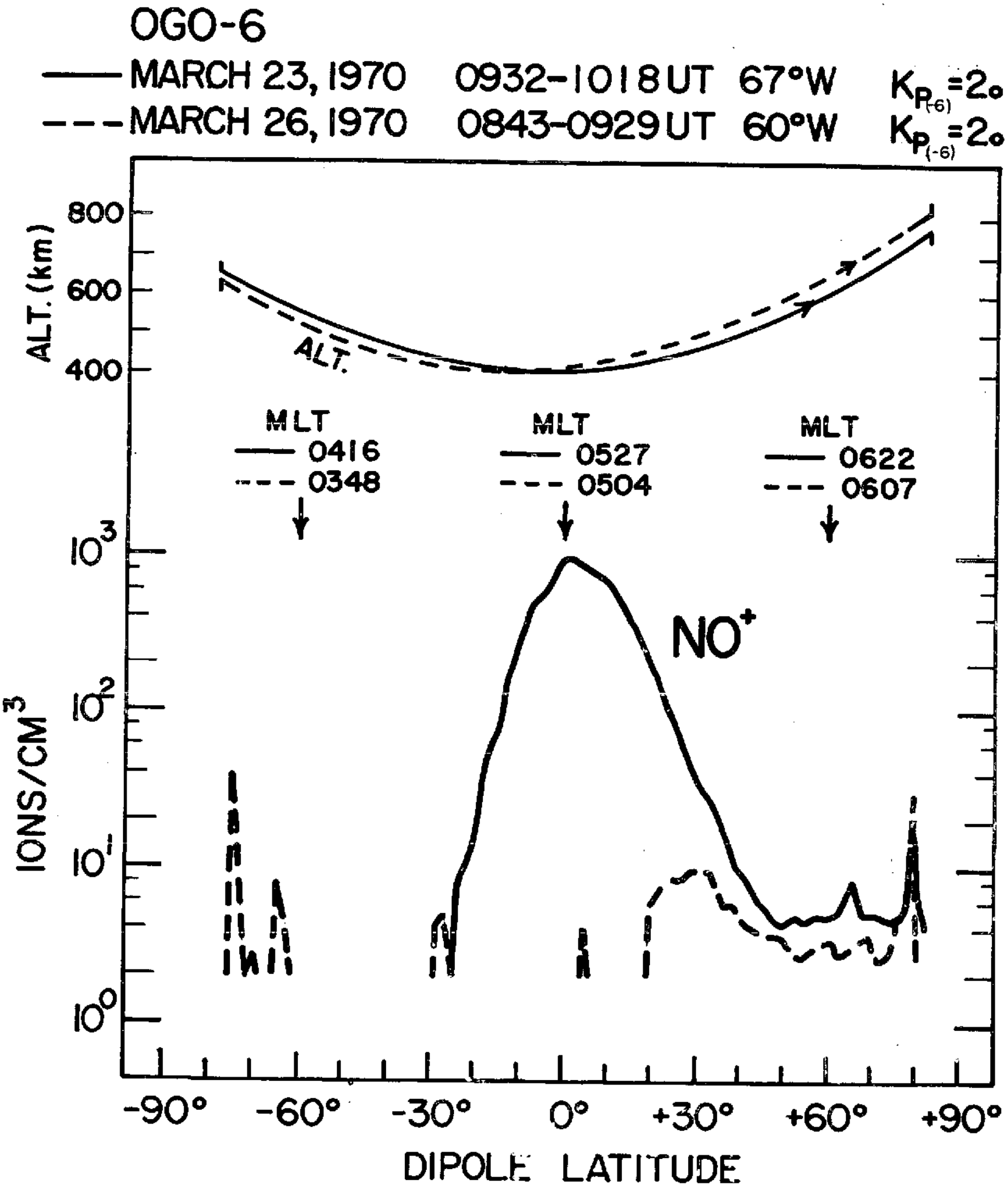
OGO-6
MARCH 23, 1970 0932-1018 UT 67°W $K_{P(-6)}=2_o$
MARCH 26, 1970 0843-0929 UT 60°W $K_{P(-6)}=2_o$
ALT. (km)
800
600
400
ALT.
MLT 0416 0348
MLT 0527 0504
MLT 0622 0607
10^3
10^2
10^1
10^0
IONS/CM^3
NO$^+$
-90°
-60°
-30°
0°
+30°
+60°
+90°
DIPOLE LATITUDE

Figure 2

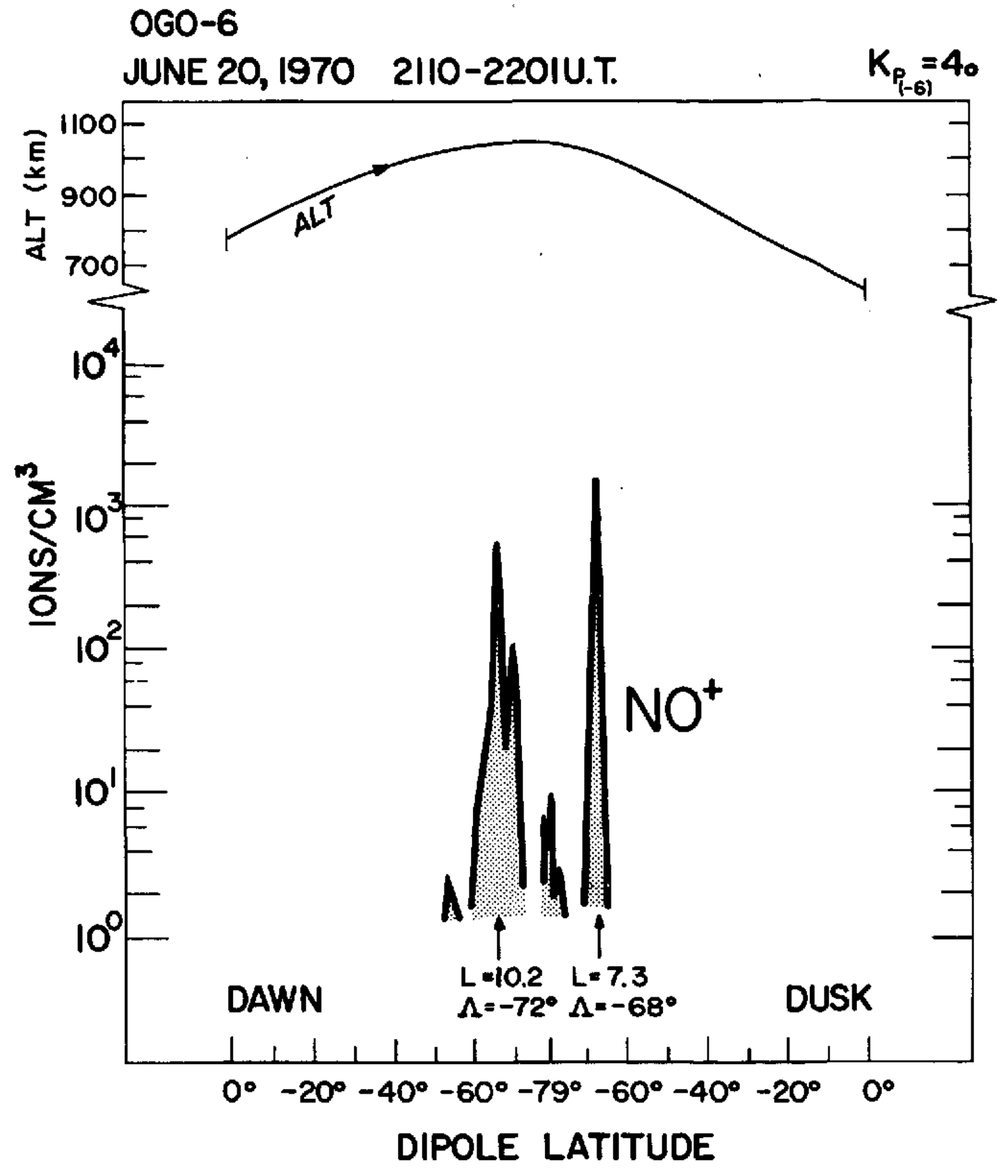
OGO-6
JUNE 20, 1970 2110-2201U.T.
$K_{p_{(-6)}} = 4_o$
ALT (km)
1100
900
700
ALT
IONS/CM^3
10^4
10^3
10^2
10^1
10^0
NO$^+$
L=10.2
Λ=-72°
L=7.3
Λ=-68°
DAWN
DUSK
0° -20° -40° -60° -79° -60° -40° -20° 0°
DIPOLE LATITUDE

Figure 3

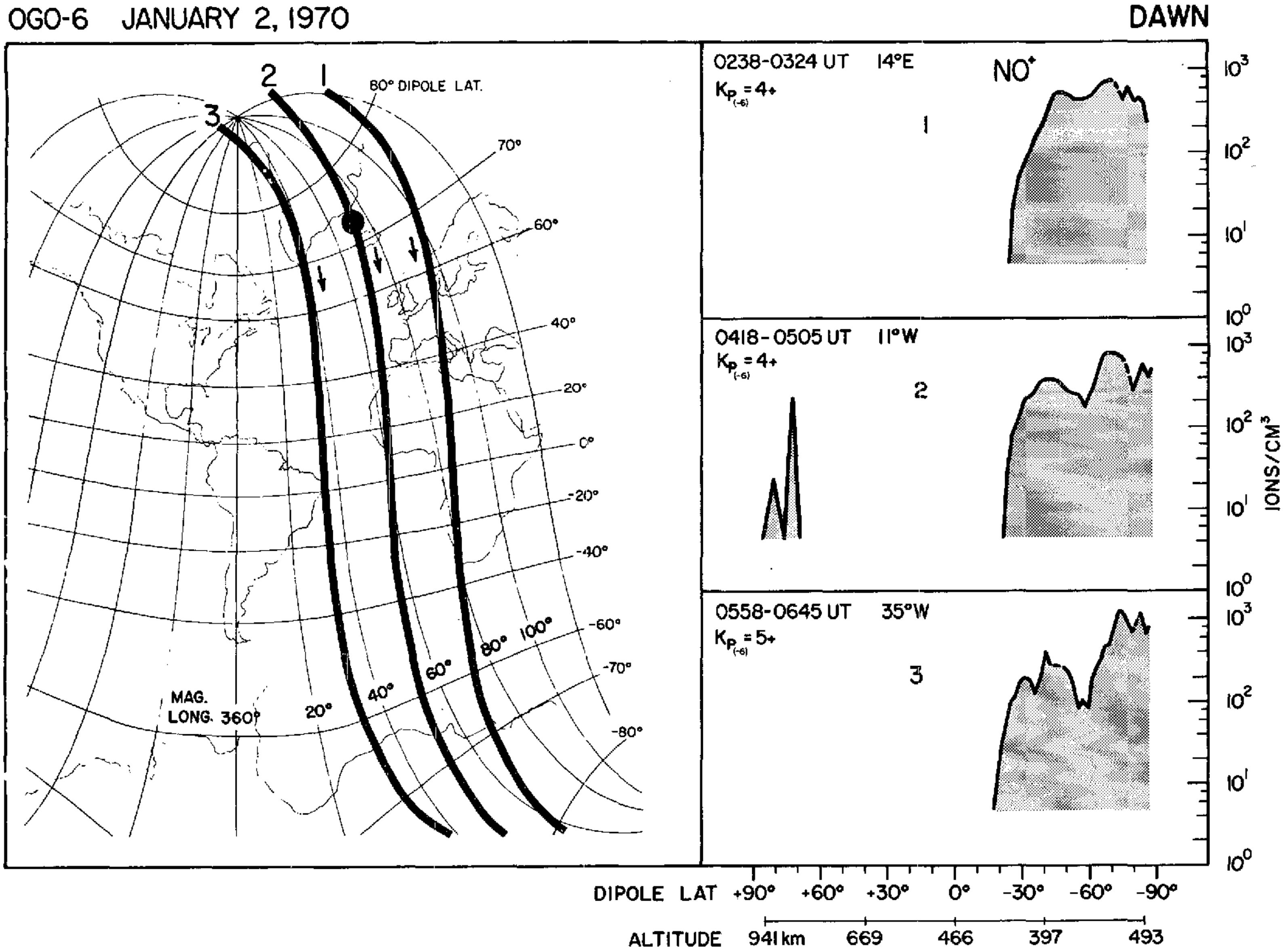
OGO-6 JANUARY 2, 1970
DAWN
80° DIPOLE LAT.
1
2
3
70°
60°
40°
20°
0°
-20°
-40°
-60°
-70°
-80°
MAG. LONG. 360°
20°
40°
60°
80°
100°
0238-0324 UT 14°E
$K_{P_{(-6)}} = 4+$
NO+
1
0418-0505 UT 11°W
$K_{P_{(-6)}} = 4+$
2
0558-0645 UT 35°W
$K_{P_{(-6)}} = 5+$
3
10^3
10^2
10^1
10^0
IONS/CM^3
DIPOLE LAT +90° +60° +30° 0° -30° -60° -90°
ALTITUDE 941 km 669 466 397 493

Figure 4

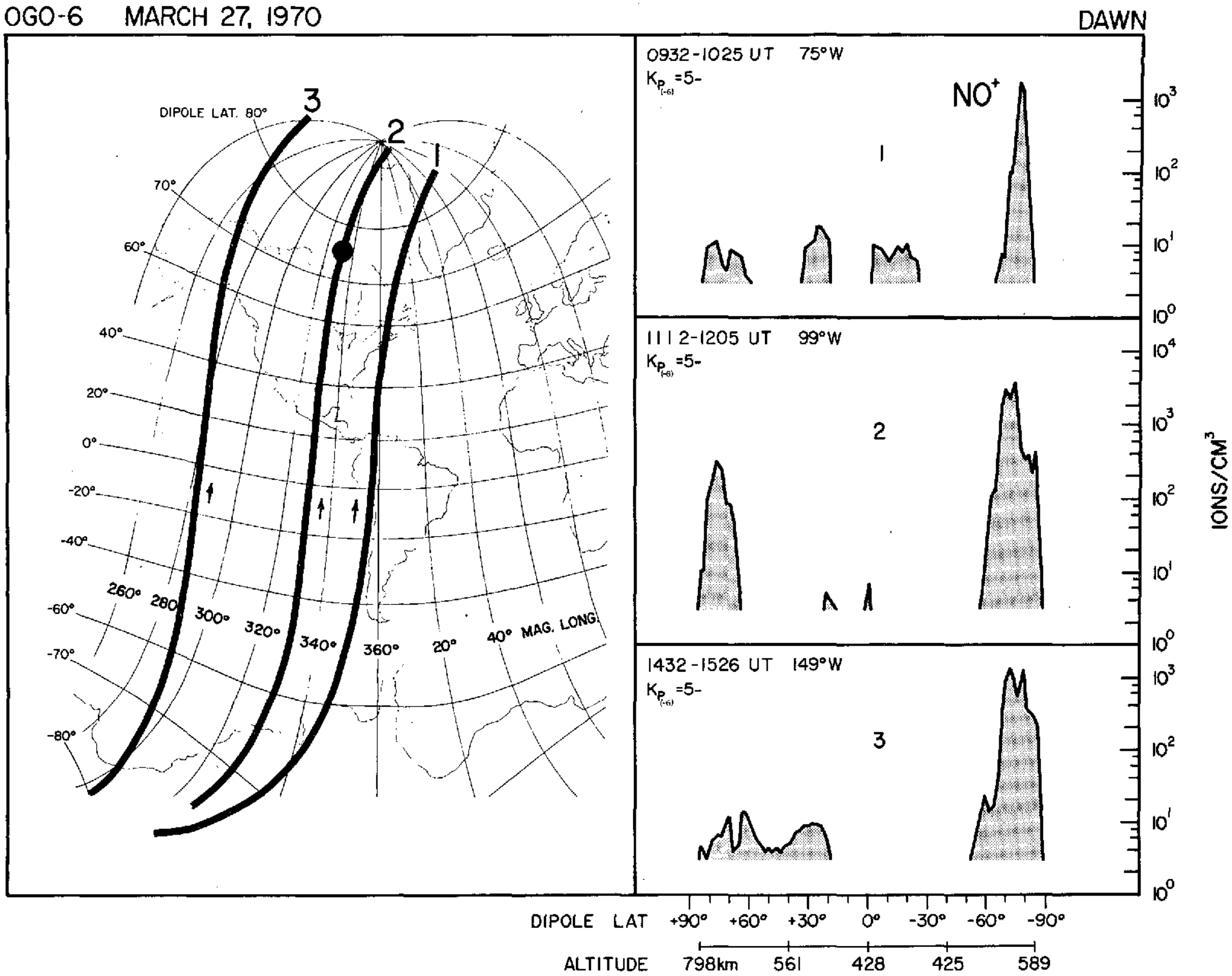
OGO-6 MARCH 27, 1970
DAWN
DIPOLE LAT. 80°
70°
60°
40°
20°
0°
-20°
-40°
-60°
-70°
-80°
260° 280° 300° 320° 340° 360° 20° 40° MAG. LONG.
1
2
3
0932-1025 UT 75°W
$K_{P_{(-6)}}$ =5-
NO$^+$
1111 2-1205 UT 99°W
$K_{P_{(-6)}}$ =5-
1432-1526 UT 149°W
$K_{P_{(-6)}}$ =5-
10^0
10^1
10^2
10^3
10^4
IONS/CM^3
DIPOLE LAT +90° +60° +30° 0° -30° -60° -90°
ALTITUDE 798km 561 428 425 589

Figure 5

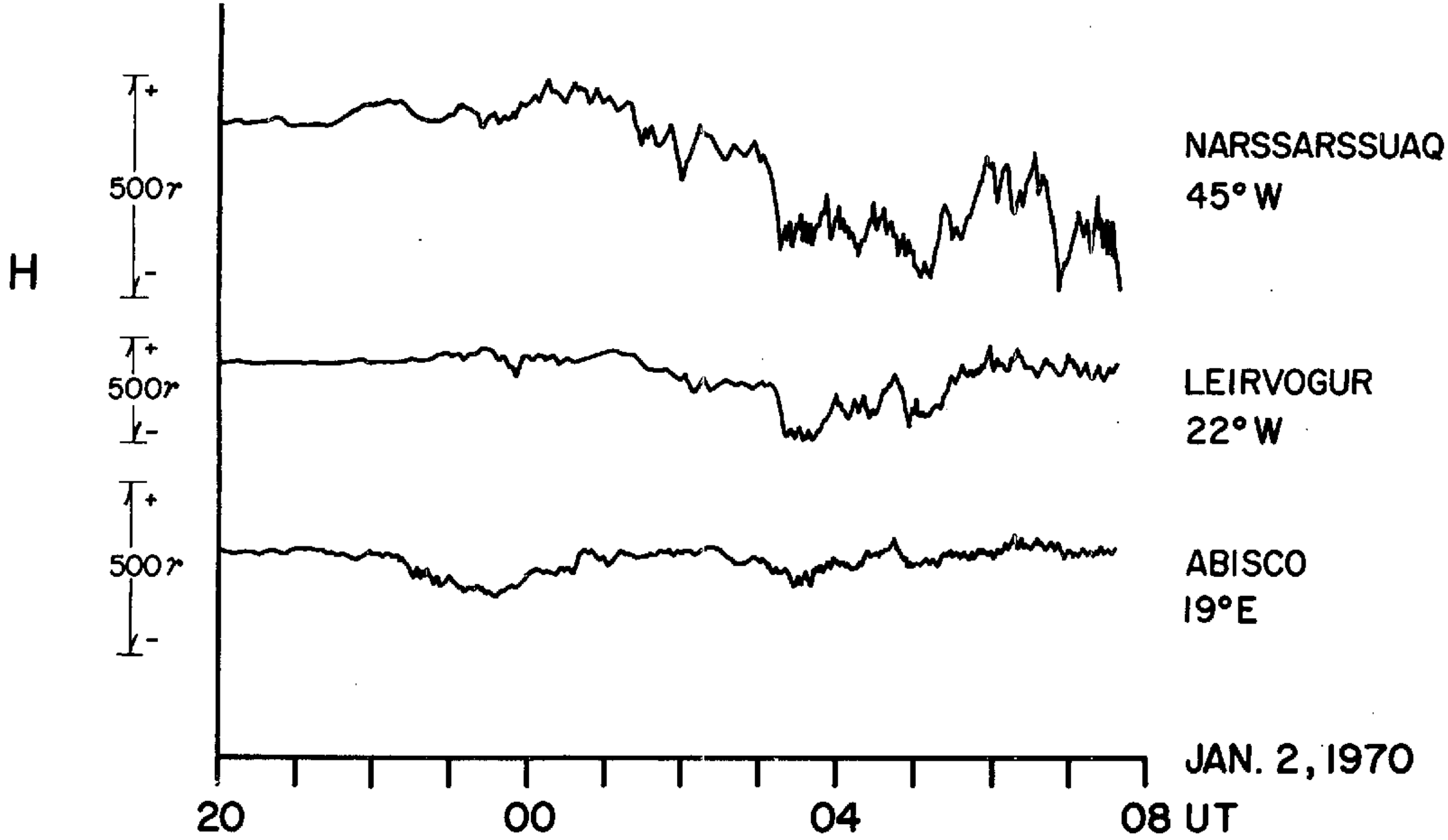
H
500γ
+
-
500γ
+
-
500γ
+
-
NARSSARSSUAQ
45° W
LEIRVOGUR
22° W
ABISCO
19°E
JAN. 2, 1970
20
00
04
08 UT

Figure 6

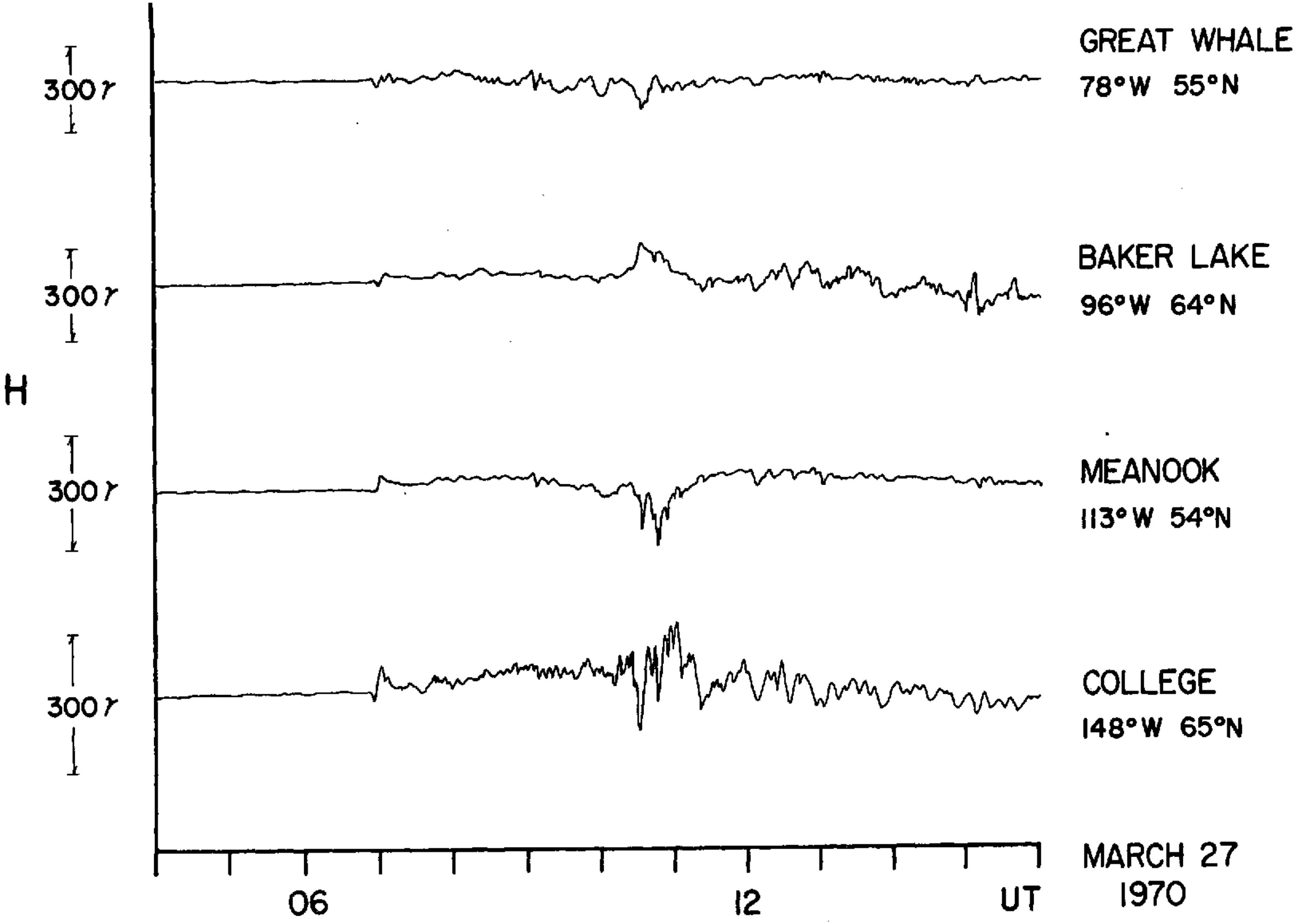
H
300 γ
300 γ
300 γ
300 γ
GREAT WHALE
78°W 55°N
BAKER LAKE
96°W 64°N
MEANOOK
113°W 54°N
COLLEGE
148°W 65°N
06
12
UT
MARCH 27
1970

Figure 7