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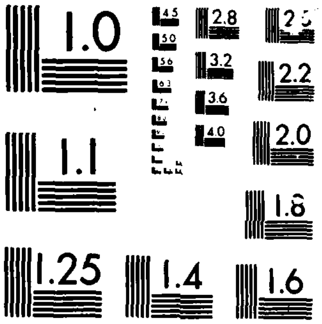

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A rocket and ground-based measurement program was conducted to investigate infrared airglow and atomic oxygen density as part of the international MAP/WINE campaign in northern Scandinavia. The mean OH Meinel rotational temperature was approximately 199^{c} K during a stratospheric warming event measured by a ground-based interferometer at ESRANGE in Sweden. This temperature is approximately 30 to 40 degrees cooler than measurements taken when no stratospheric events were taking place and confirms the coupling theory that stratospheric warming results in mesospheric cooling. The atomic oxygen profiles measured by a rocket-borne resonance lamp technique showed a peak con-

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J. Ulwick, K. Baker, A.J. Steed

Center for Space Engineering
Utah State University
Logan, UT 84322-4140

January 1986

FINAL REPORT
Contract No. F49620-83-C-0122
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Prepared for:
DIRECTORATE OF CHEMICAL AND ATMOSPHERIC SCIENCES
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SUMMARY

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A rocket and ground-based measurement program was conducted to investigate infrared airglow and atomic oxygen density as part of the international MAP/WINE campaign in northern Scandinavia. The mean OH Meinel rotational temperature was approximately 199° K during a stratospheric warming event measured by a ground-based interferometer at ESRANGE in Sweden. This temperature is approximately 30 to 40 degrees cooler than measurements taken when no stratospheric events were taking place and confirms the coupling theory that stratospheric warming results in mesospheric cooling. The atomic oxygen profiles measured by a rocket-borne resonance lamp technique showed a peak concentration of approximately 10^{11} cm^{-3} between 90 and 100 km. The rocket results obtained between 90 and 180 km altitude show densities consistently almost an order of magnitude less than predicted by standard models. However, the rocket results are consistent with other measurements taken under similar conditions: winter nights with no particle precipitation. The results from 85 to 110 km show considerably more structure than the models predict. The 1.6 micrometer rocket-borne infrared radiometer also provided excellent altitude profiles of OH emissions, showing a peak at 86 km with a maxiumum volume emission rate of about 10^5 photons/sec/cm^3. These data also show nonuniformity and structure within the layer.

The STATE campaign examined some of the same phenomena with sounding rockets and in-situ probes launched from the Poker Flat Research Range, Alaska. Specifically, the campaign was designed to help us understand the origin and character of variations in the atmospheric index of refraction which give rise to the so-called summer mesospheric echoes detected at high latitudes by VHF radar. Research identified at least two types of scattering sources and that short-wavelength turbulence above the mesopause is organized by a larger scale wave-like process. Lower intensity mesopause scattering is believed, based on STATE data, to be organized by sharp gradients in the electron density, possibly due to electron attachment to "cloud particles" at that height. Radar backscatter data and fluctuations measured with in-situ probes were in fundamental agreement.

1.0 RESEARCH OBJECTIVES

1.0.1 MAP/WINE

The major thrust of the Middle Atmosphere Project "Winter in Northern Europe" (MAP/WINE), coordinated jointly by scientists from France, West Germany, East Germany, the United States, Norway, the United Kingdom, Austria, Finland, Switzerland, the Soviet Union and Sweden, was the investigation of strong temporal and spatial variabilities in the middle atmosphere (stratosphere and mesosphere), particularly during winter at high latitudes.

The middle atmosphere is comprised mainly of the regions denoted as the stratosphere and mesosphere and is the region of the atmosphere about which we know the least. The complexity of its physical processes and its inaccessibility have been barriers to any thorough exploration of the region.

Two strong energy sources interact in the region: solar ultraviolet light and wave motions propagated through the troposphere into the stratosphere and mesosphere.

Specifically, MAP/WINE sought to provide a better understanding of:

- the interaction of planetary waves of tropospheric origin with the mean flow in the stratosphere and mesosphere,

- the temporal and spatial development of sudden stratospheric warmings including the pre-warming conditions and the trigger mechanisms for the warming,

- the temporal and spatial development of mesospheric cooling events in conjunction with stratospheric warmings,

- the vertical and horizontal transport of minor constituents like trace gases, excited species and charged particles,

- the effects on the chemistry of neutral and charged species of the large temperature changes occurring during stratospheric warmings and mesospheric coolings,

- sources of turbulent energy in the mesosphere and turbopause region,

- the temporal and spatial development of turbulent layers, and

- the contributions of dynamical processes to the heating and cooling of the mesospheric and turbopause regions.

The MAP/WINE project centered on the study of the middle atmosphere over the full winter season of 1983/84. An international team of scientists performed a study of the structure, motions and composition of the middle atmosphere between about 50° and 70° northern latitudes. MST radars, LIDAR sounders, EISCAT radar and optical and radio monitoring experiments (interferometers, photometers, etc.) measured small-scale and mesoscale processes at selected sites on an almost continual basis. Meteorological satellite data provided important information on global scale processes. Special high-altitude radiodondes, meteorological rockets, meteorwind radars and sounding rockets provided the additional and vital data not routinely available from WMO observations or remote sensing satellite experiments.

Utah State University's contribution to the program addresses most of the objectives directly by providing rocket measurements of structure in two prime minor species, atomic oxygen and hydroxyl, and a related emission from an excited species of oxygen, $O_2{}^1\Delta_g$. In addition, ground measurements of OH emissions were made over several months to study mesospheric temperature variations and to support the rocket measurements. USU became involved in the experiment at the invitation of West Germany's University of Wuppertal.

The OH emission is the strongest infrared emitter in the mesosphere and has been observed to have variations and wave-like structure . The cause of these structures has been suggested to be gravity waves, phenomena of particular interest to the MAP/WINE researchers. The concentration of $O_2{}^1\Delta_g$ is important to atmospheric chemical reactions involving the important minor constituents O, OH and O_3.

1.0.2 Contractual Statement of Work

The following is from Section B 0001 of the initial contract:

0001 RESEARCH

0001AA

During the period of this contract, Utah State University will participate in the international university Middle Atmosphere Program (MAP); specifically, the Winter in Northern Europe (MAP/WINE) field program. Utah State University will:

a. Provide the following two instruments for rocket-borne measurements of atomic oxygen density as well as OH and O_2 (ID) emissions:

   (1) Atomic Oxygen Detector
   (2) IR Radiometer

b. Perform instrument calibrations.

c. Participate in instrument integration into the rocket payload.

d. Conduct on-site flight operations during the experiment.

e. Complete a preliminary data evaluation and a report of measurement results apparent from the initial evaluation effort.

The contract was modified in June 1984 to include the following:

0001AA

f. Analyze data from the "STATE" field program to investigate the power spectrum in the frequency and spatial domains for turbulent region.

g. Analyze and study measurement of atomic oxygen and hydroxyl made during the MAP/WINE campaign.

h. Publish results from "STATE", "MAP/WINE", and "Energy Budget" campaign field programs.

2.0 STATUS OF RESEARCH

2.1 Introduction

Utah State University (USU) played a pivotal role in the MAP/WINE program, providing measurements of structure in the prime measurement species of atomic oxygen and hydroxyl, and a related species of oxygen.

The USU resonance lamp system to measure atomic oxygen concentrations and a dual channel infrared radiometer for measuring OH emissions around 1.6 μm in wavelength and $O_2{}^1\Delta_g$ at 1.27 μm was flown aboard the MI Skylark rocket payload from the ESRANGE base in Norway while middle atmospheric conditions were extremely inactive. USU also supported MAP/WINE ground measurements made with a variety of radar and ground-based spectrometers. In particular, a portable USU-built ground station utilizing an infrared interferometer spectrometer provided continuous nighttime monitoring of of OH spectra. Much of the USU effort was specifically directed toward understanding the effects of the nonuniformity of the atmosphere on infrared background radiation (small and large scale structures against smoothly-varying atmospheric densities) which is important for the design of future USAF staring infrared surveillance systems. A more complete description of the status of research in the MAP/WINE program is presented in section 2.2.

Also among the major objectives of this contract were efforts to analyze and publish the results from the Energy Budget campaign, the STATE campaign and the MAP/WINE campaign. The results from the Energy Budget campaign have been completed and published and are listed in section 3.1. The results from the STATE campaign have been partially published and are described in Section 3.2. Planned publications associated with MAP/WINE are listed in section 3.3. Complete data analysis and associated publications will be completed under a new contract.

2.2 MAP/WINE

The field program for MAP/WINE was very successful. Papers have been and will be presented at scientific meetings as shown in the next section (abstracts are included in Appendix A). However, the completed analysis and publication will be accomplished as specified under our present contract.

2.2.1 Rocketborne Measurements

The infrared radiometer aboard the MI-1 rocket payload was a dual channel instrument to measure O_2 singlet delta emission at 1.27 μm and the lower vibrational level of the OH first overtone in the vicinity of 1.6 μm. The instrument was mounted to view at an elevation angle of 45 degrees when the rocket axis was controlled to be vertical. As the rocket rolled around the longitudinal axis and the rocket moved vertically through the emitting layer the instrument scan could be described as a helix. The angular variations will be directly related to the nonuniform spatial distribution of the excited OH radicals and the falloff with altitude will give the emission rate altitude profile.

The flight carrying USU's instruments provided a valuable opportunity to compare results of measurements of atomic oxygen from the USU resonance lamp with those derived from experiments conducted on another rocket flown one hour earlier by the University of Stockholm, Sweden. A joint paper on these results is in preparation.

Also, USU is using its own atomic oxygen and OH emission measurements in addition to ozone measurements from the University of Wuppertal taken during the MAP/WINE campaign to model hydroxyl airglow infrared emissions in the mesosphere. Reciprocally, measurements taken by the Center for Space Engineering are being used by other MAP/WINE experimenters. For example, CSE's atomic oxygen measurements have proven useful in understanding nitric oxide IR emissions being studied by the University of Wuppertal. Collaborators from several different countries will publish MAP/WINE results in a single volume of The Journal of Atmospheric and Terrestrial Physics (JATP). Although cooperative research efforts require a relatively long waiting period prior to publication, this integrated approach can successfully advance understanding of upper atmospheric physics and chemistry. The Energy Budget Campaign (Feb. 1985, JATP) provides a prominent example of the advances possible in such a cooperative effort.

Ground measurements utilized a wide-angle Michelson interferometer spectrometer to obtain spectra in the λ0.8 μm to 1.7 μm range which includes airglow bands of hydroxyl and molecular oxygen, auroral bands of both neutral and ionized molecular nitrogen and auroral atomic nitrogen and oxygen lines.

The interferometer was operated with a resolving power of 5000 at 1.0 μm and a temporal resolution of 40 seconds. An NESR of 4.10^{-14} watts-$cm^{-2}sr^{-1}/cm^{-1}$ at 1.4 μm was achieved through the use of large-aperture optics, oblique ray compensation, an electromagnetic drive, a gas bearing and a liquid-nitrogen-cooled germanium detector. In addition, coaligned photometer/radiometers were operated at λ3914Å, 1.27 μm and 1.7 μm to provide continuous absolute measurements of emission bands of N_2, N_2^+, O_2 and OH. Rotational temperatures were computed from the observed OH band structure.

2.2.3 Publication of Results

The results synopsized in this report will be published in one USU-authored paper and at least two other articles co-authored by USU researchers. Before publication, researchers will carefully examine and study the significant measurements made by USU during MAP/WINE. This means critically evaluating atomic and OH rocket measurements and ground-based OH measurements and comparing them with past measurements made by USU and others in order to obtain the most complete and accurate results possible. Two papers [Ulwick et al., 1985; Baker et al.,1983] were presented at meetings of the American Geophysical Union based on these studies. Abstracts appear in Appendix A.

In sections 2.3, 2.4 and 2.5 we present the results of each of the MAP/WINE studies in some detail, since full publication will be delayed. Further, in section 2.6, we present a summary of the latest findings of the STATE experiment which are being prepared for publication.

2.3 Atomic Oxygen Detection

Accurate measurement of the concentration of atomic oxygen [O] in the mesosphere and lower thermosphere is critically important in understanding the reactive cycles in that region. Pertaining to the MAP/WINE effort, atomic oxygen concentration is important in the mechanisms leading to the formation and quenching of excited OH. The peak concentration of O normally occurs at altitudes between 90 and 100 km. Ozone at 85 km is formed primarily by the oxidation of O_2 by O. In addition, according to the Bates and Nicolet (1950) theory, vibrationally-excited OH is produced by the exothermic nature of the chemical reaction:

$$H + O_3 \xrightarrow{K_1} OH^{\ddagger} + O_2 \text{ (+3.3 ev = 78 K cal/mole)}$$

Also, the oxidation of H_2O can lead to the formation of vibrationally-excited OH:

$$O + H_2O \xrightarrow{K_z} OH^{\ddagger} + O_2 \text{ (+2.3 ev = 54 cal/mole)}$$

Three approaches are used to measure O using rocket-borne techniques, including resonance fluorescence [Dickinson et al., 1980], height profiles of optical emissions [Sharp, 1971], and mass spectometry [Scholz and Offermann, 1974]. Each of the techniques has limitations and the published data vary [Offerman et al., 1981] by more than a factor of 10 at 120 km and a factor of 40 for the peak at about 95 km. The data also reveal variations which can be attributed to season, latitude, and dynamics.

For the MAP/WINE campaign, USU employed the resonance fluorescence technique for measuring concentrations of atomic oxygen. The results were compared with rocket results obtained an hour earlier by a resonance absorption sensor on the SOAP payload. In addition, previous measurements taken by USU and others under similar conditions, i.e., nighttime winter months and quiet backgrounds are used for comparison references.

Figure 1 shows the USU atomic oxygen profiles for rocket ascent and descent for MAP/WINE rocket M1. The rocket was launched at 0400 UT into very quiet background conditions, i.e. no particle precipitation. In fact, the $O_2(^1\Delta g)$ emission and the hydroxyl emissions as measured from the ground were very low compared to normal. The peak concentration puts this measurement of about 10^{11} atoms per cm^3 between 90-100 km in the "low atomic oxygen" concentration group of measured results compared to the "high" group a factor of 5 to 10 greater. The ascent and descent results agree closely between 80 and 100 km even in the structure of two peaks near 90 and 100 km. The difference in ascent and descent results above 105 km (near a factor of two at 120 km) is probably attributable to horizontal spatial differences in the concentration. Simultaneous or nearly-simultaneous measurements made by other investigators will be examined to see if the inflection in the data at 130 km on the rocket ascent is associated with a physical phenomenon such as a wind shear at that altitude.

Reports by other investigators identify structure in the 90 to 100 km region. This is the first time such structure has been observed with such repeatability on rocket ascent and descent. Spatially, the two measurements are over 75 km apart which would argue against local turbulent effects as proposed by Keneshea et al. [1978].

In Figure 2, USU measurements are compared with those obtained during MAP/WINE from a resonance absorption experiment [Dickinson, P.G.H, private communication] measuring atomic oxygen conducted jointly by the Rutherford Appleton Laboratory, England and the Meteorological Institute, Stockholm University (MISU), Sweden, on a rocket called SOAP 2. This rocket was launched at 0300 hours, about one hour before the M1 rocket. The SOAP results generally reveal lesser densities of atomic oxygen than the USU results by a factor of about 2 to 3. Their results agree well in ascent and descent.

Dickinson stated in a private communication that his absolute values for [O] were based on descent data from his twin path absorption experiment. According to Dickinson, the data appear to have been perturbed by precession, and, on the ascent, by strong shock-wave effects. As a result of these difficul-

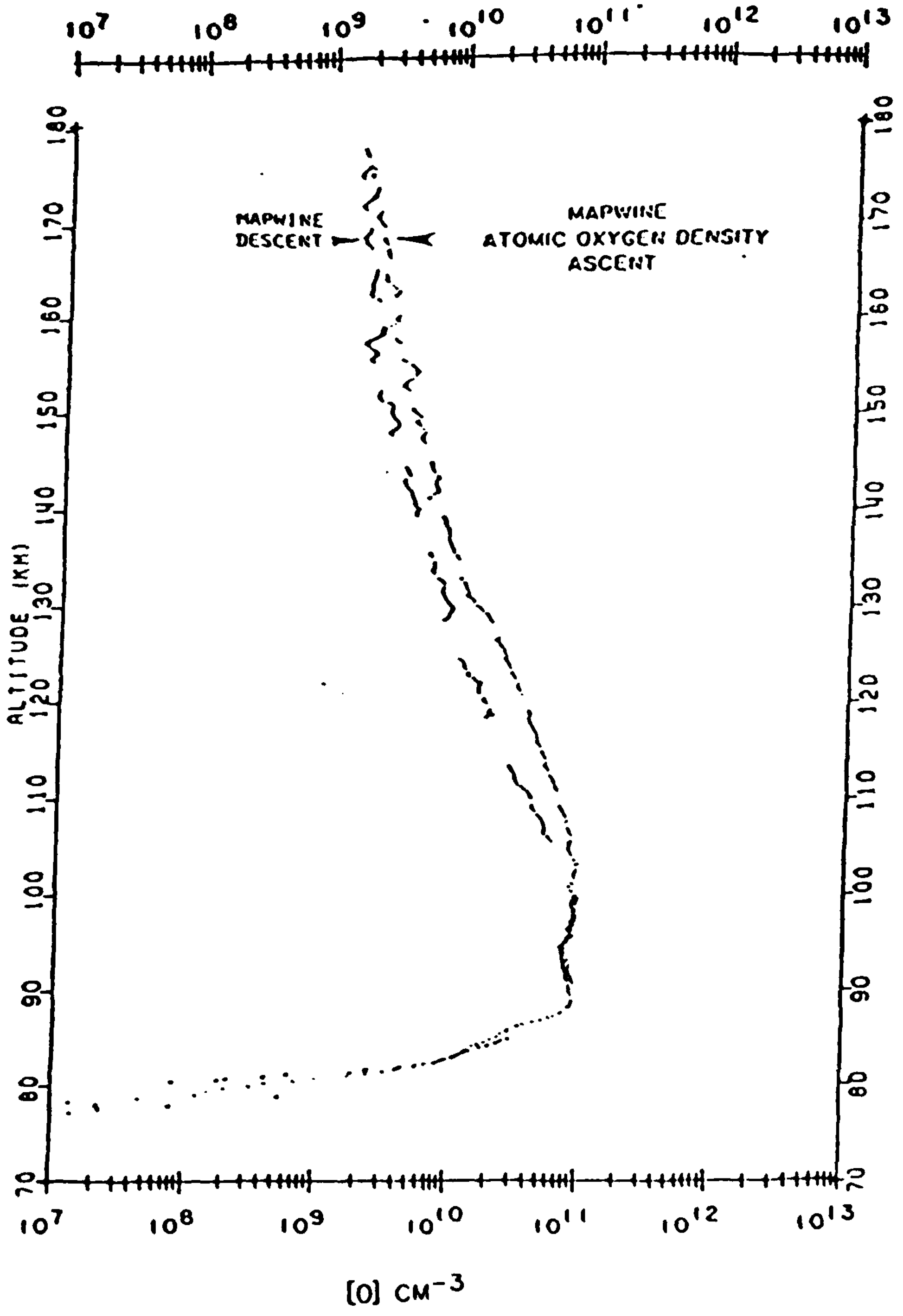

FIGURE 1

Rocket ascent and descent profiles of atomic oxygen concentration from USU resonance fluorescence measurements

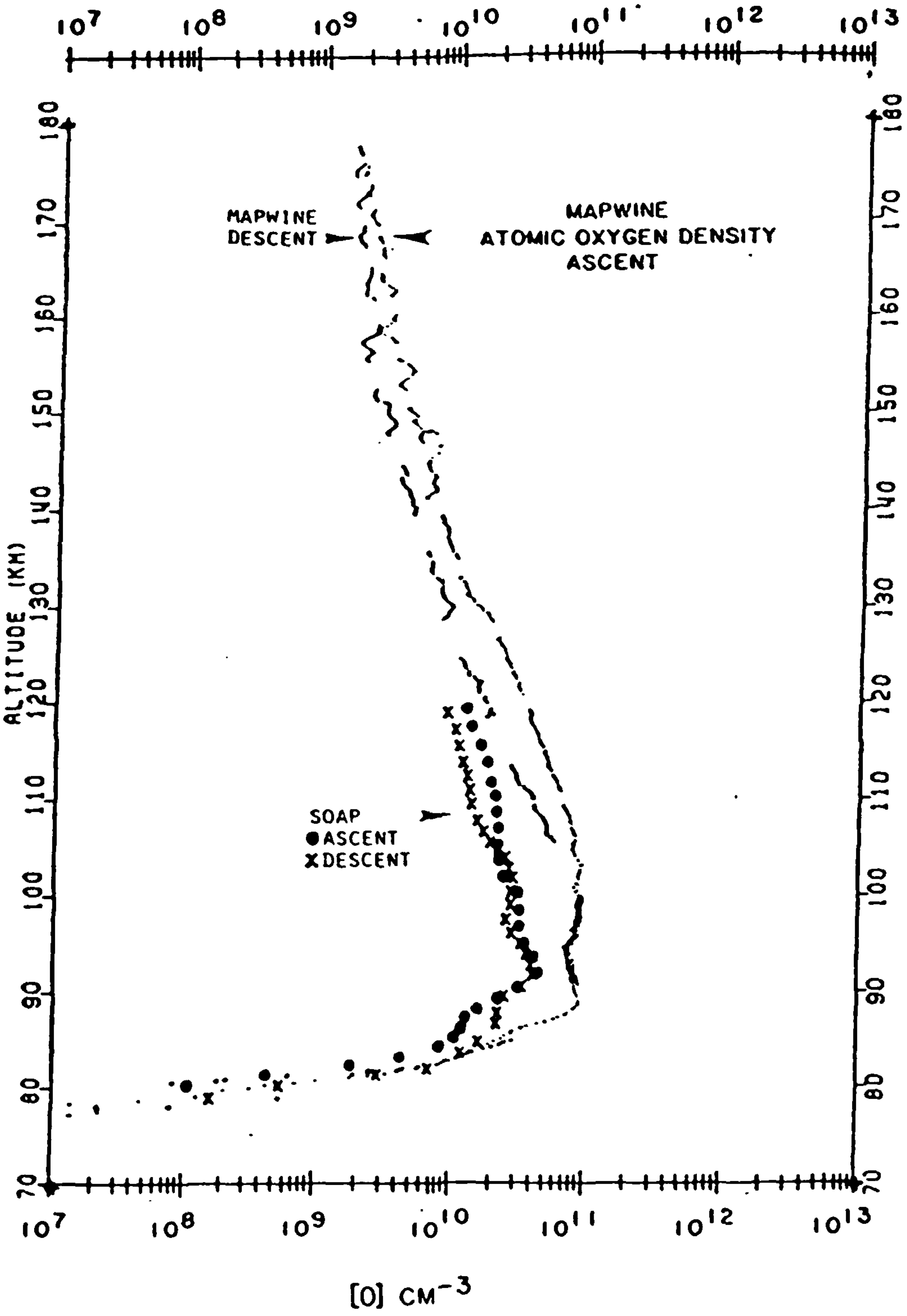

FIGURE 2

USU (O) MAP/WINE results compared with (O) measurements obtained one hour earlier (0300 U.T.) from resonance absorption measurements by Dickinson.

ties, he concludes that it is possible that the non-statistical error could be sufficient to explain the difference between his measurements and an airglow measurement on the same rocket that would indicate a peak concentration of about 2 x 10^{11} cm^{-3}. The latter measurement more resembles the USU measurement but cannot be taken as definitive due to assumptions required to derive the result. It does however, support the USU data which indicate a density almost an order of magnitude less than the CIRA 72 model. In Figure 3 we have shifted the CIRA model by almost an order of magnitude to compare it with the USU results. Note that from 100 km to peak altitude the two sets of measurements are in close agreement but below 100 km the model densities are low and without the structure exhibited in the USU results.

In Figure 4 we compare the MAP/WINE results with two independent measurements utilizing the resonance fluorescence technique for the measurement of [O]. The measurement labeled USMR Dec. 1975 was made at night by USU researchers and has been reported by Howlett et al. [1980]. The USMR rocket was a six-inch diameter Astrobee D rocket that reached a maximum altitude of 125 km. Due to the Astrobee rocket's smaller diameter, its flow (shock) characteristics were entirely different than those of the 16" diameter Skylark MAP/WINE rocket. Note, however, the excellent agreement of the two measurements including the similarity of structures between 85 km and 100 km. Also in the figure are the results of a rocket flight conducted at White Sands, N.M. [Sharp, 1980]. Again there is extraordinary agreement between the two USU [O] profiles although the structure around 90 to 100 km is different. The agreement between the results is quite surprising considering the time lapse between 1975, 1978 and 1983 and the different latitudes of the two USMR rockets compared to the ESRANGE, Sweden MAP/WINE rocket, as well as the variability of [O] reported by other investigators [e.g., Offermann et al., 1981].

To compare MAP/WINE results with other auroral-zone measurements, in Figure 5 we compare the resonance fluorescence measurements taken at Poker Flat Rocket Range (PFRR) Alaska with the MAP/WINE results. The agreement along the steep gradient from about 78 to 85 km, the peak near 90 km

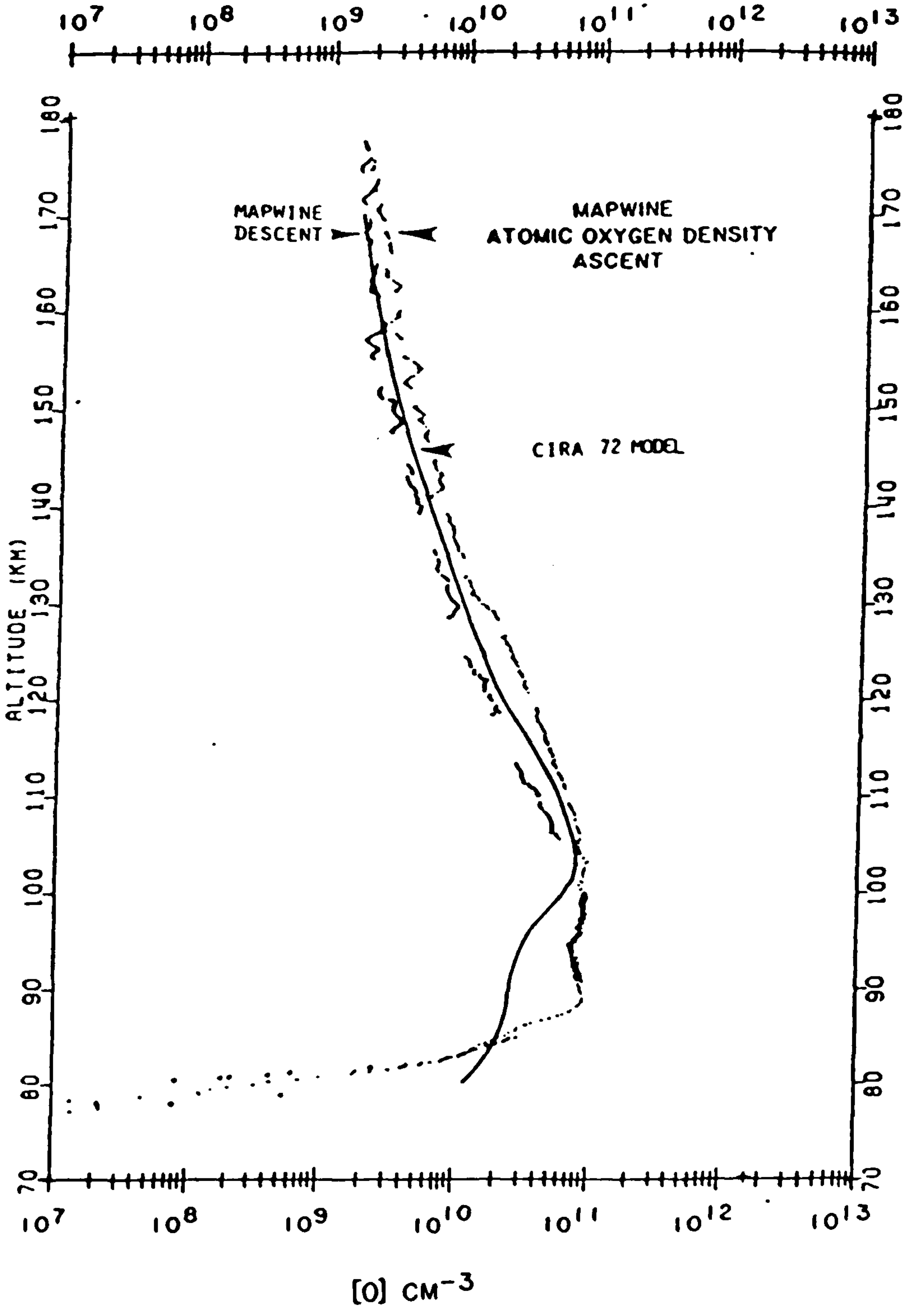

FIGURE 3

USU (O) MAP/WINE results compared with the CIRA 72 model.

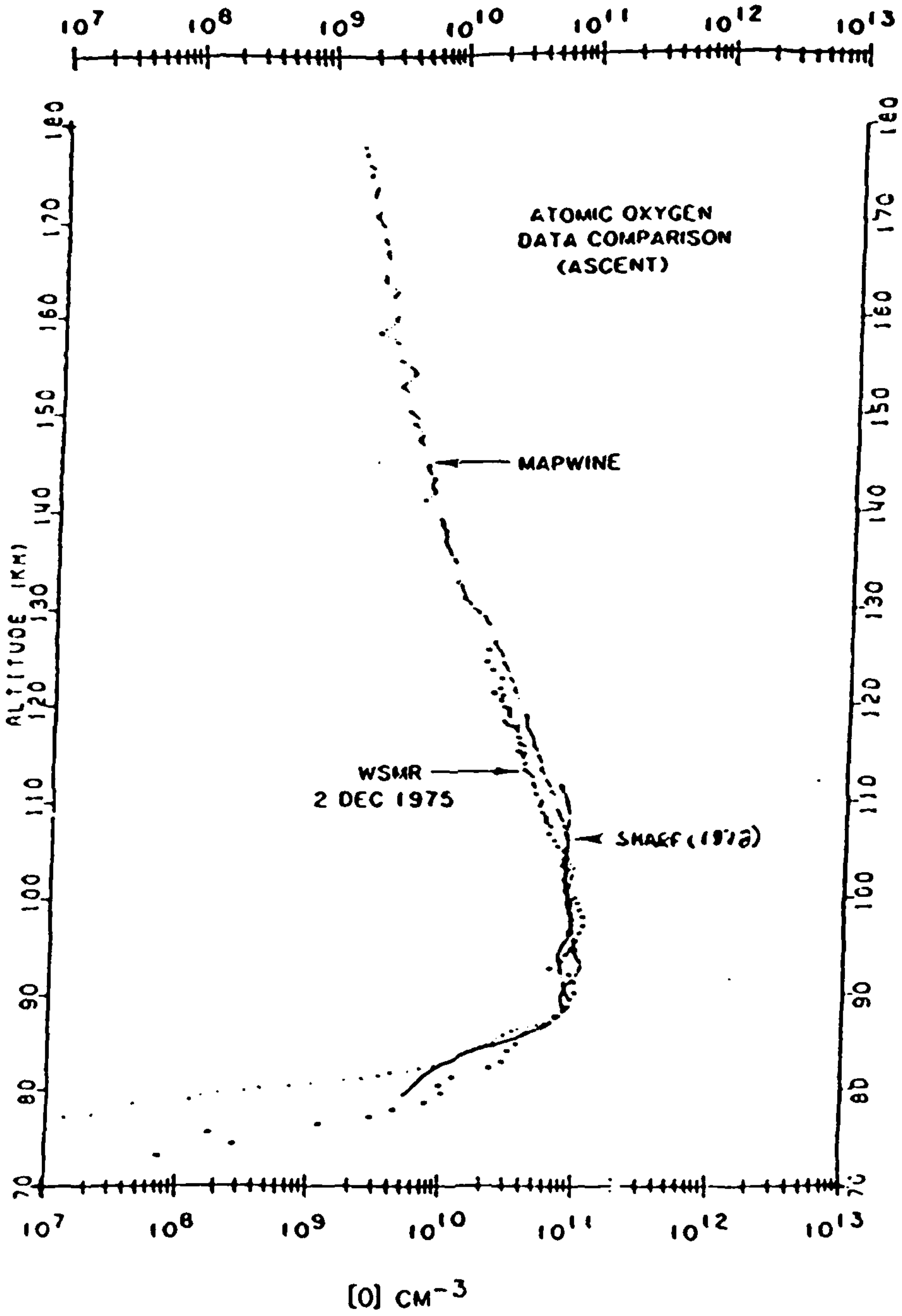

FIGURE 4

USU (O) MAP/WINE results compared with two sets of rocket measurements of (O) taken during wintertime nights (WSMR, 1975) reported by Howlett et al. and during twilight winter conditions by Sharp, 1978. All results were obtained using the resonance fluorescence technique.

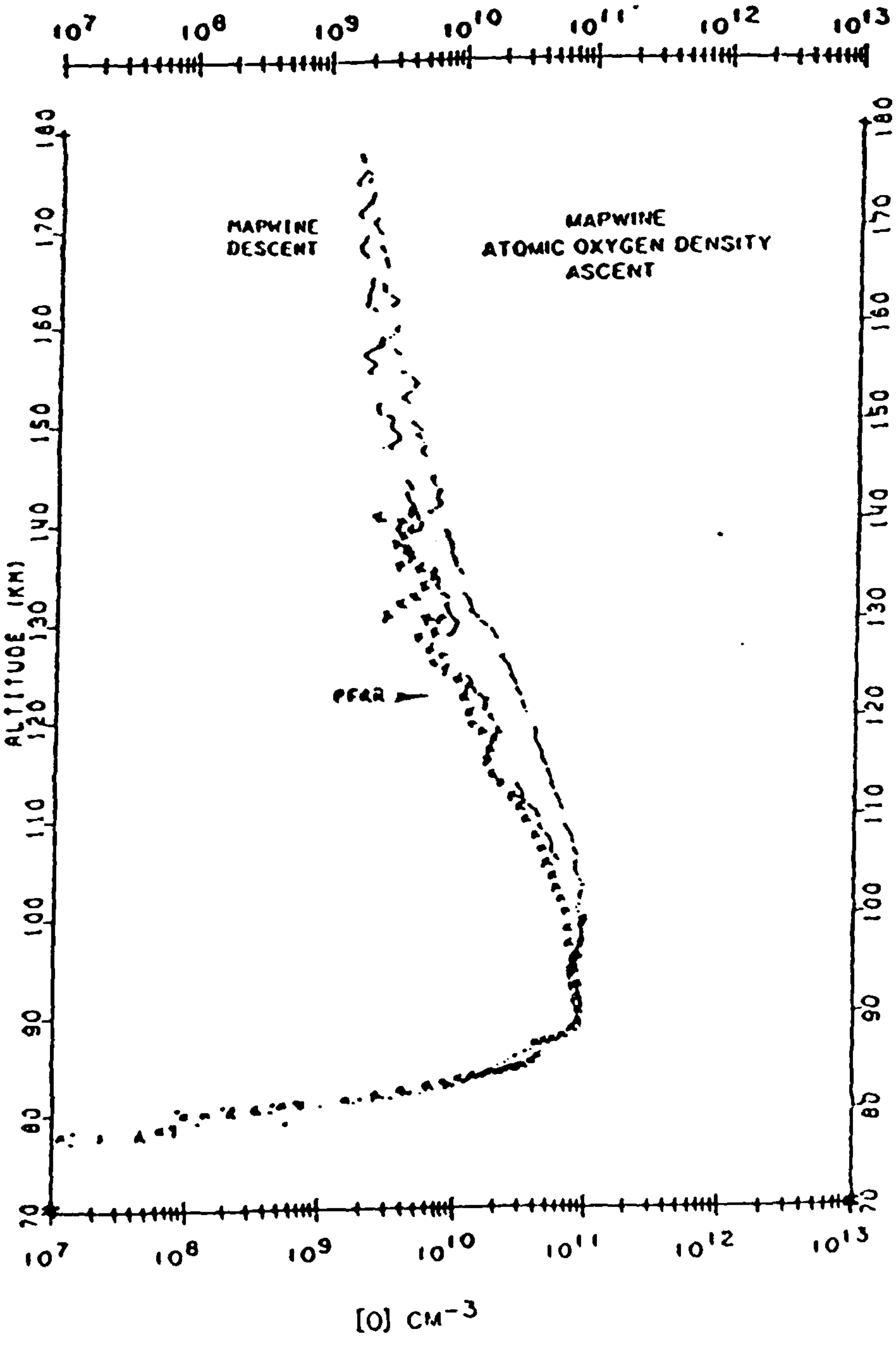

FIGURE 5

USU (O) MAP/WINE results compared with USU measurements made at Poker Flat Rocket Range, Alaska and the general agreement with the MAP/WINE descent values to 140 km is striking. The PFRR rocket was launched during an auroral event but other experiments on board (DC probe, photometer, electron deposition scintillator and ground-based measurements) showed that the energy deposition was almost entirely constrained to altitudes above 120 km. In other words, the spectrum of the auroral precipitating electrons was soft with very few energetic particles penetrating below about 110 km. We point this out since the MAP/WINE results were obtained during very quiet conditions with respect to particle precipitation.

In Figure 6 we add two other auroral-zone measurements of [O] to Figure 5. The results are from two different rocket flights from the Churchill, Canada, rocket range. Each rocket carried several instruments dedicated to measuring atomic oxygen in the upper atmosphere and penetrated regions of auroral activity. The results published by Sharp et al. [1979], indicated a launch into somewhat more stable auroral conditions than those reported by Deans and Shepherd,[1978]. However, neither were launched into a particularly bright auroral display. The Deans and Shepherd atomic-oxygen profile was derived from the $O_2(b^1\Sigma g^+)$ nightglow emission rate, neutral-ion mass spectrometer data and the quenching of the $N_2(A^3\Sigma\mu^+$, V=1) level. Their mean value is higher than the USU-Sharp high values by a factor of about two or three throughout the altitude regime, but falls within the error bars of the measurements.

Results obtained by Sharp et al. [1979] agree quite closely with the MAP/WINE USU rocket ascent results. The shape of the altitude particle density profile of atomic oxygen was derived from the quenching of rocket-borne observations of 3220A band of the Vegard-Kaplan system by O. The profile was normalized to mass spectrometer satellite measurements above 160 km (nearly simultaneous satellite overpass). In general, there is good agreement in the results which would suggest that the published models are based on densities much greater than those empirically recorded. These results were presented at the American Geophysical Union 1985 December meeting and the abstract published in EOS [Ulwick et al., 1985].

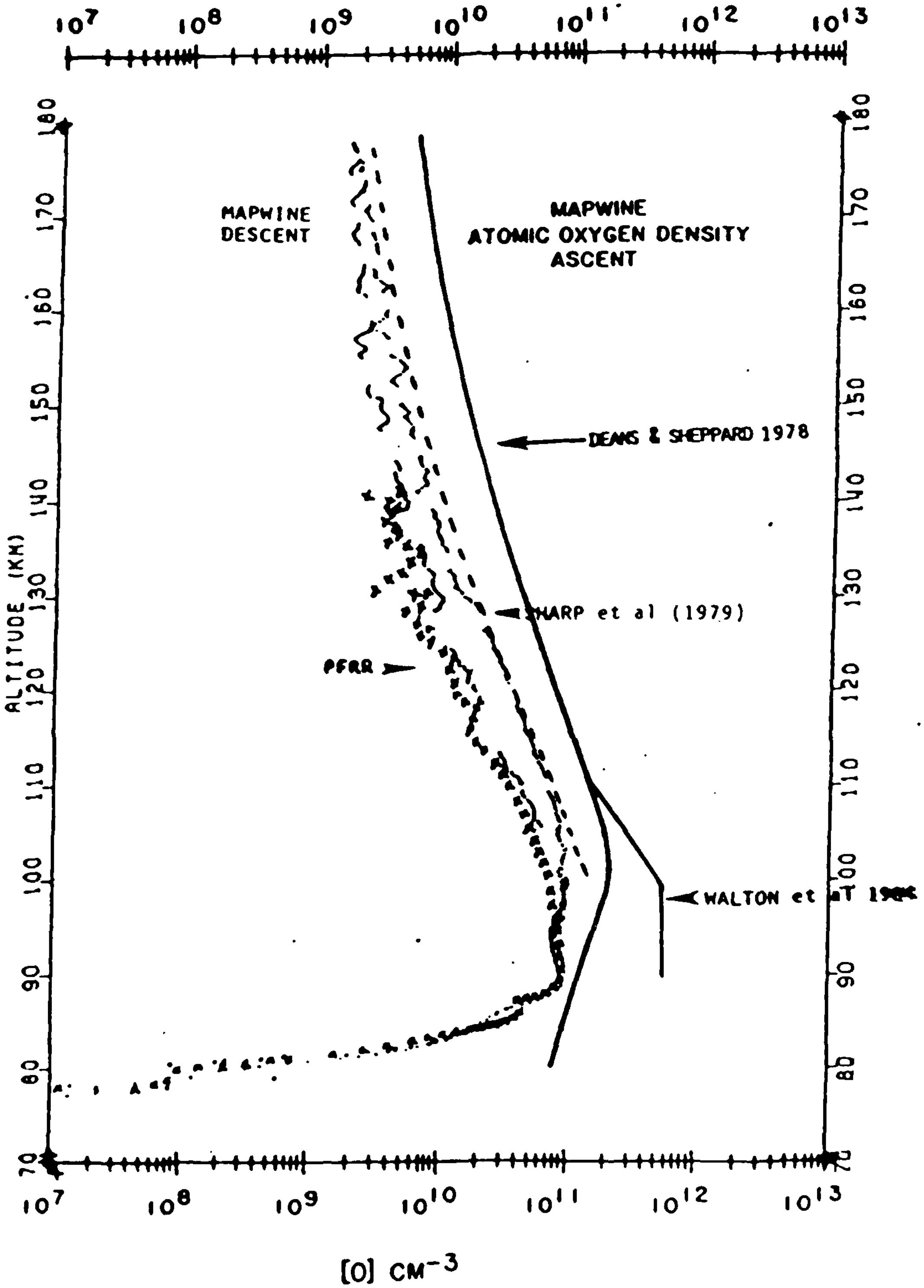

FIGURE 6

USU MAP/WINE results compared with measurements taken at Churchill, Canada by Sharp et al. [1979] and Dean and Sheppard et al. [1978].

2.4 OH Radiometer Data

The infrared radiometer aboard the MAP/WINE MI-1 rocket payload was a dual-channel instrument designed to measure O_2 singlet delta emissions at 1.27 µm and the lower vibrational level of the OH first overtone in the vicinity of 1.6 µm. The instrument was mounted to view at an elevation angle of 45^c from the vertically stabilized rocket axis. As the rocket rolled around the longitudinal axis and moved vertically through the emitting layer, the instrument scan could be described as a helix. The angular variations will be directly related to the non-uniform spatial distribution of the excited OH radicals and the fall-off with altitude will give the emission rate altitude profile.

Very little evidence of auroral activity or other atmospheric disturbances was recorded on the night of launch. Predictably, the airglow emissions were at very low levels. The O_2 (Δg) emission monitored by the USU ground station at ESRANGE were unusually weak in intensity. The rocket-borne radiometer showed the 1.27 µm emission to be below the measurement threshold. At that level, the emission was adequate only to verify the extremely low level of activity.

The OH radiometer channel did provide good results for both rocket ascent and descent. Figure 7 shows these plotted versus altitude for the rocket ascent and Figure 8 shows the same figures for rocket descent. The modulation with the rocket spin shows that the OH emitting regions were not uniformly distributed. In other words, horizontal spatial structure exists in the airglow layer. The modulation can be seen to be somewhat different as viewed on rocket ascent and descent. The rough mean level of the intensity is approximately constant from instrument exposure at 57 km up to about 82 km on ascent with similar results for the descent portion. Above 82 km the intensity drops off with altitude until it merges into the background noise level at about 95 km.

The spin-related (view direction) structure can be more readily seen in the 10-second samples of ascent data shown in Figure 9. The structure is complex in shape and is not strictly sinusoidal. The magnitude of the variations decreases with increasing altitude and disappears as the layer is being penetrated as would be expected when the instrument is immersed in the emitting region.

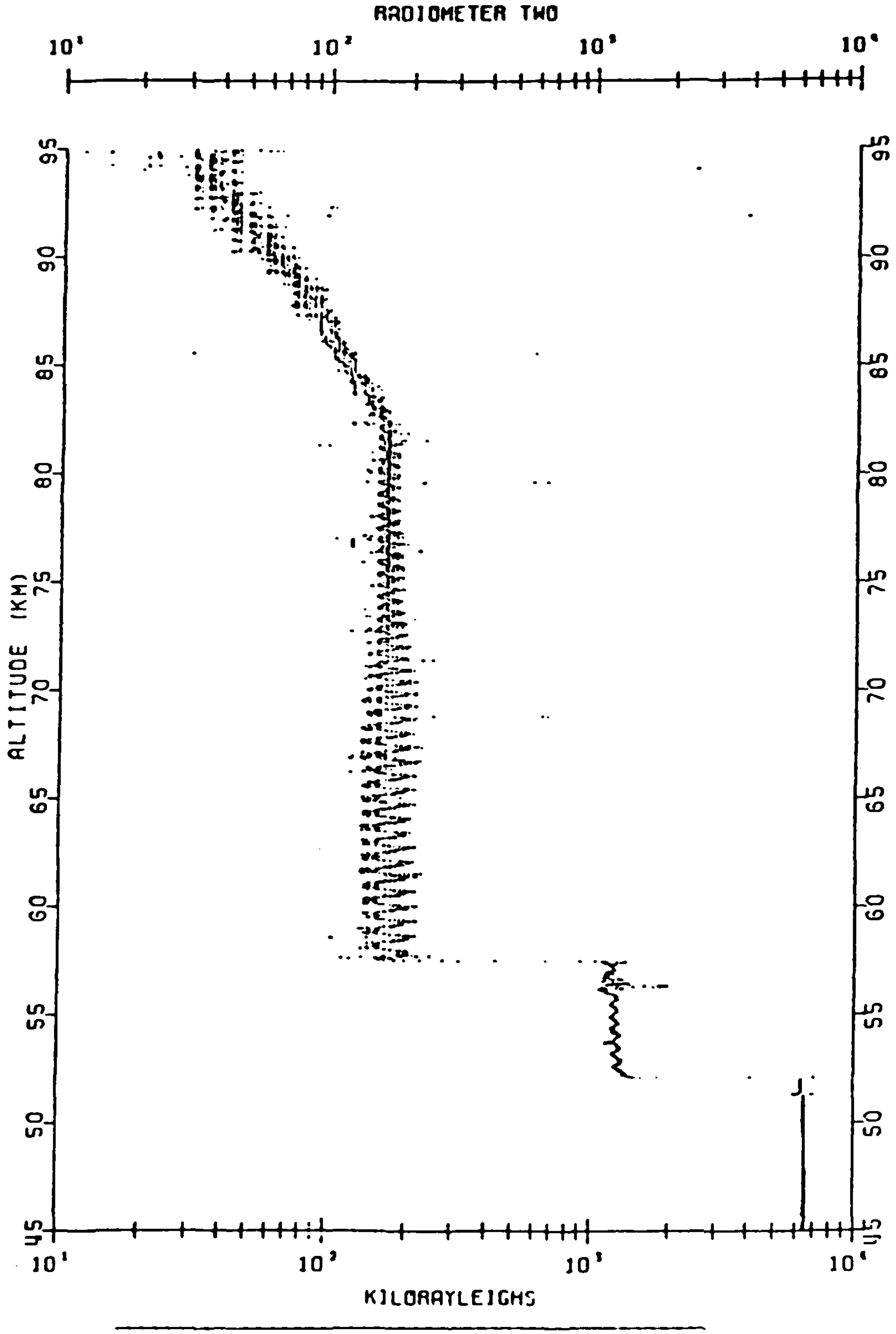

FIGURE 7

MAP/WINE OH Radiometer channel data plotted versus altitude for rocket ascent.

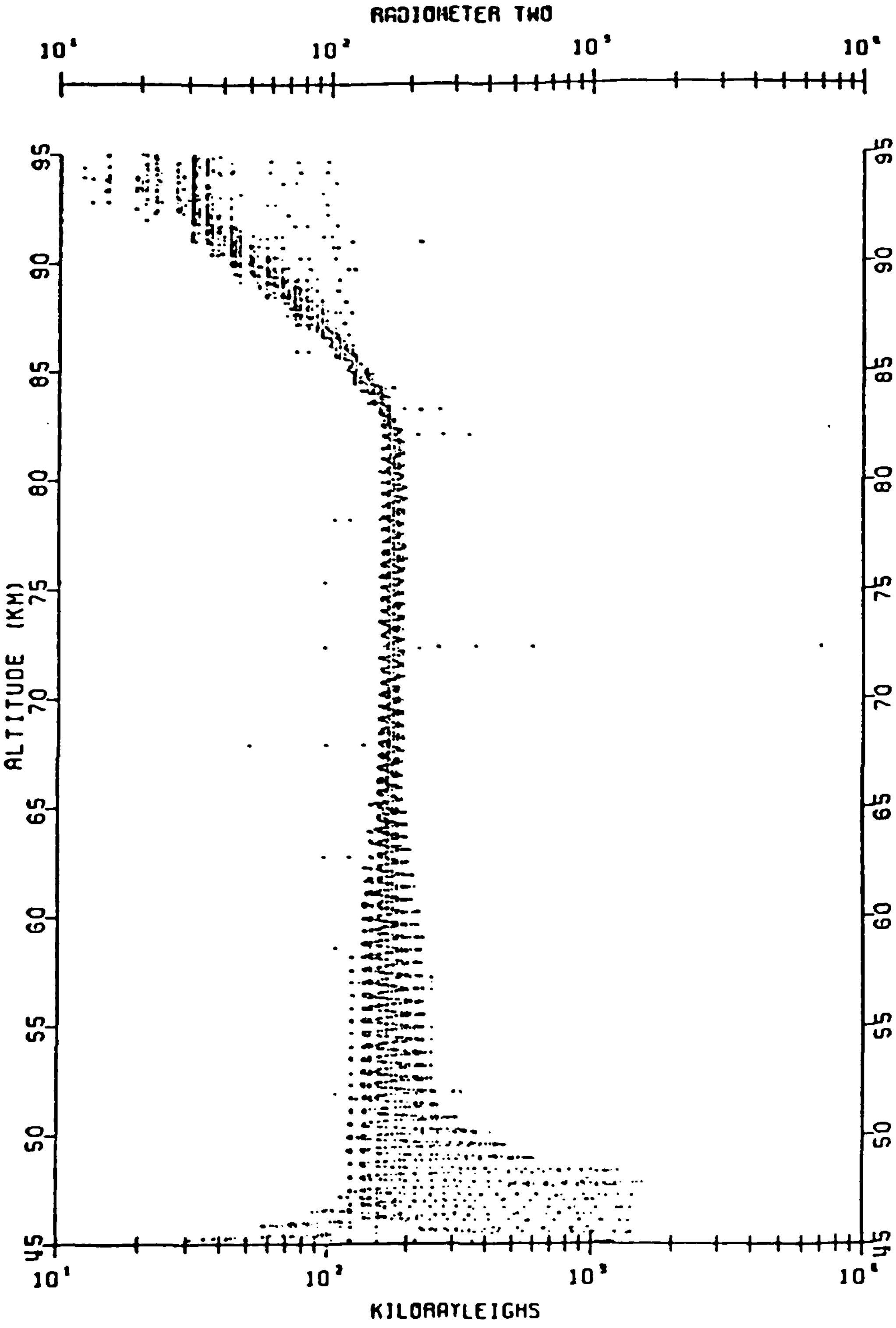

FIGURE 8

MAP/WINE OH Radiometer channel data plotted versus altitude, rocket descent

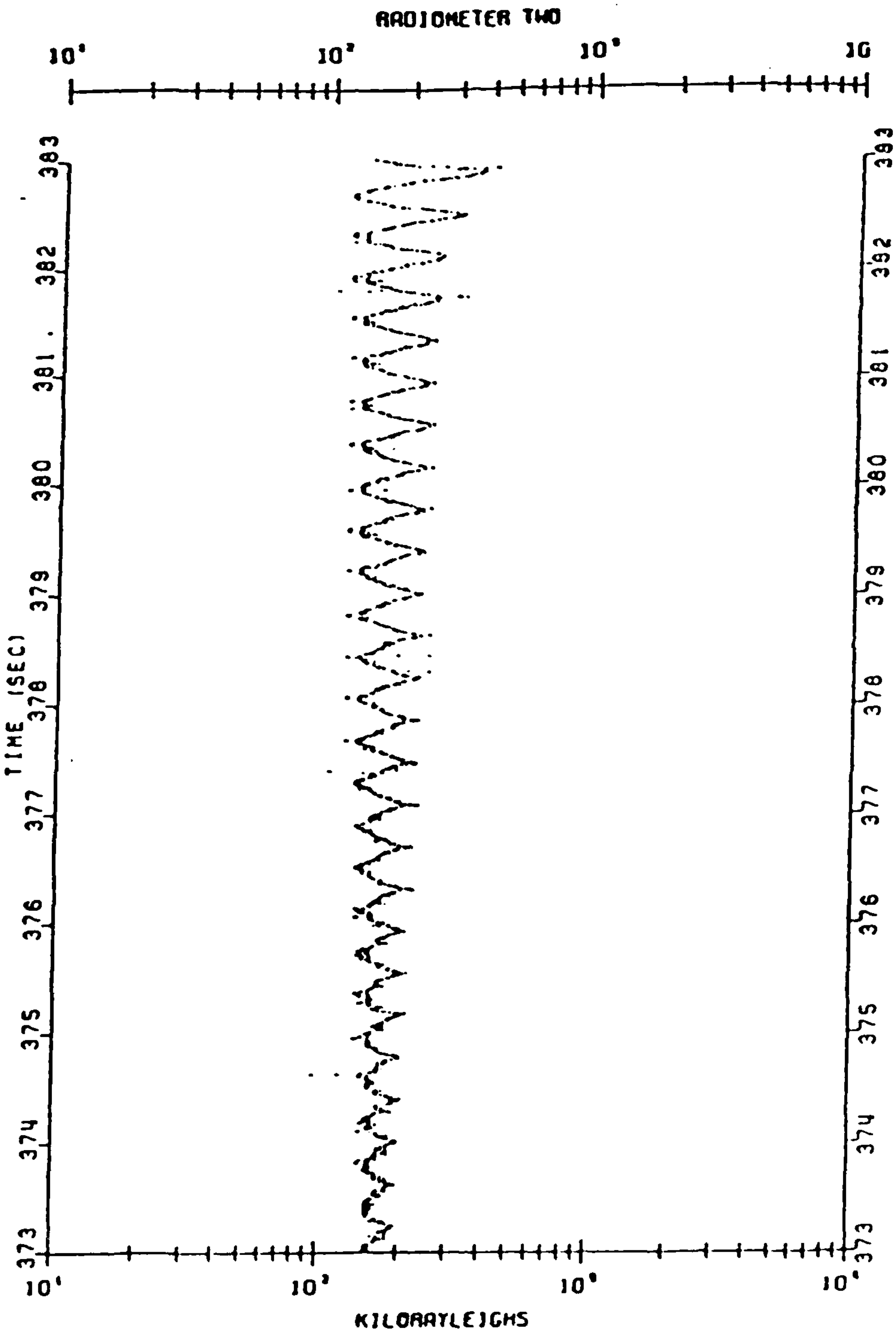

FIGURE 9

MAP/WINE OH Radiometer view direction data,
10-second samples.

The drop-off of the intensity with altitude can be spatially differentiated (after smoothing) to give an altitude profile of the volume emission rate of the OH radicals. This was done by computer and the results for the rocket ascent data are shown in Figure 10. The emitting layer can be seen to have a maximum of about 10^5 photons/sec/cm^3 at an altitude of about 87 km.

The more complete analysis of the data in terms of the three-dimensional structure of the OH emitting regions and the resulting interpretation of OH excitation/emission processes must await the more detailed incorporation of the rocket aspect and the instrument view direction. Only recently did the aspect information become available and the further interpretation is now in process.

2.5 Ground-based OH‡ Measurements: Ground-based measurements were made by USU prior to, during, and after the rocket flight. The National Science Foundation funded this program. These measurements will be part of the OH‡ modeling study.

Figure 11 shows a spectrum taken by the interferometer near the rocket flight time. The OH M(3,1) rotational temperatures were calculated using these and other similar data taken during the night of February 9-10, 1984. The sample density was about 100 samples/hr and the mean temperature associated with the data set is 196.8° K.

Since the University of Wuppertal also made ground-based spectrometer measurements of OH‡ Meinel (M) temperatures at the Andoya Rocket Range, Norway (about 300 km to the northwest), during the campaign, interesting results are emerging in the comparison of the two data sets.

The USU set of OH M(3,1) mean nighttime absolute intensities is limited to 23 nights during the period of December 24, 1983, through February 8, 1984. Most of the nighttime averages reflect approximately 6-10 continuous hours of observing time, but a few are based on approximately 2-4 hours of observation, cut short due to poor viewing conditions.

The "Andoya temperatures" are compared with the "ESRANGE intensities" in Fig-

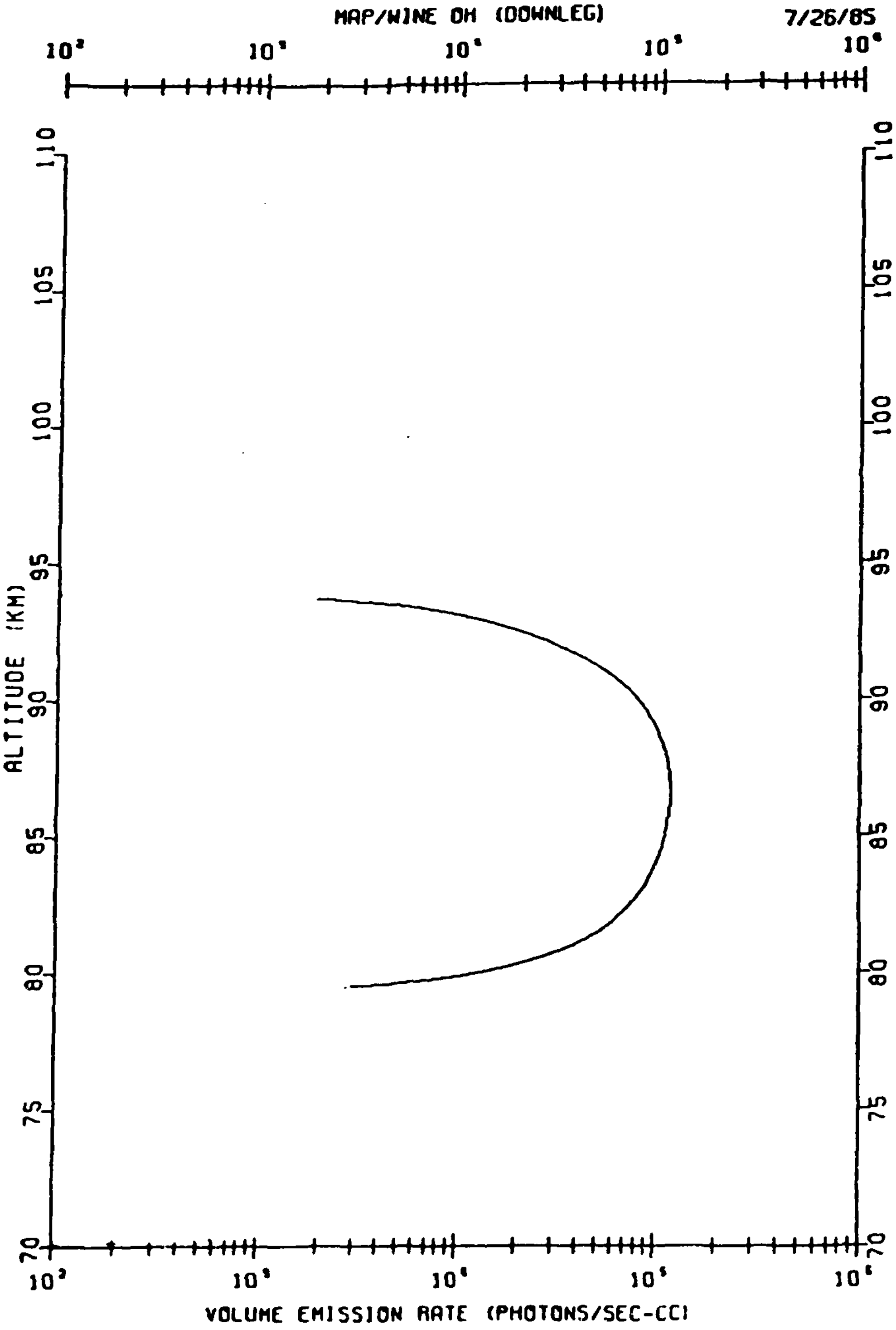

FIGURE 10

OH Radical Volume Emission Rate Profile, computer-smoothed.

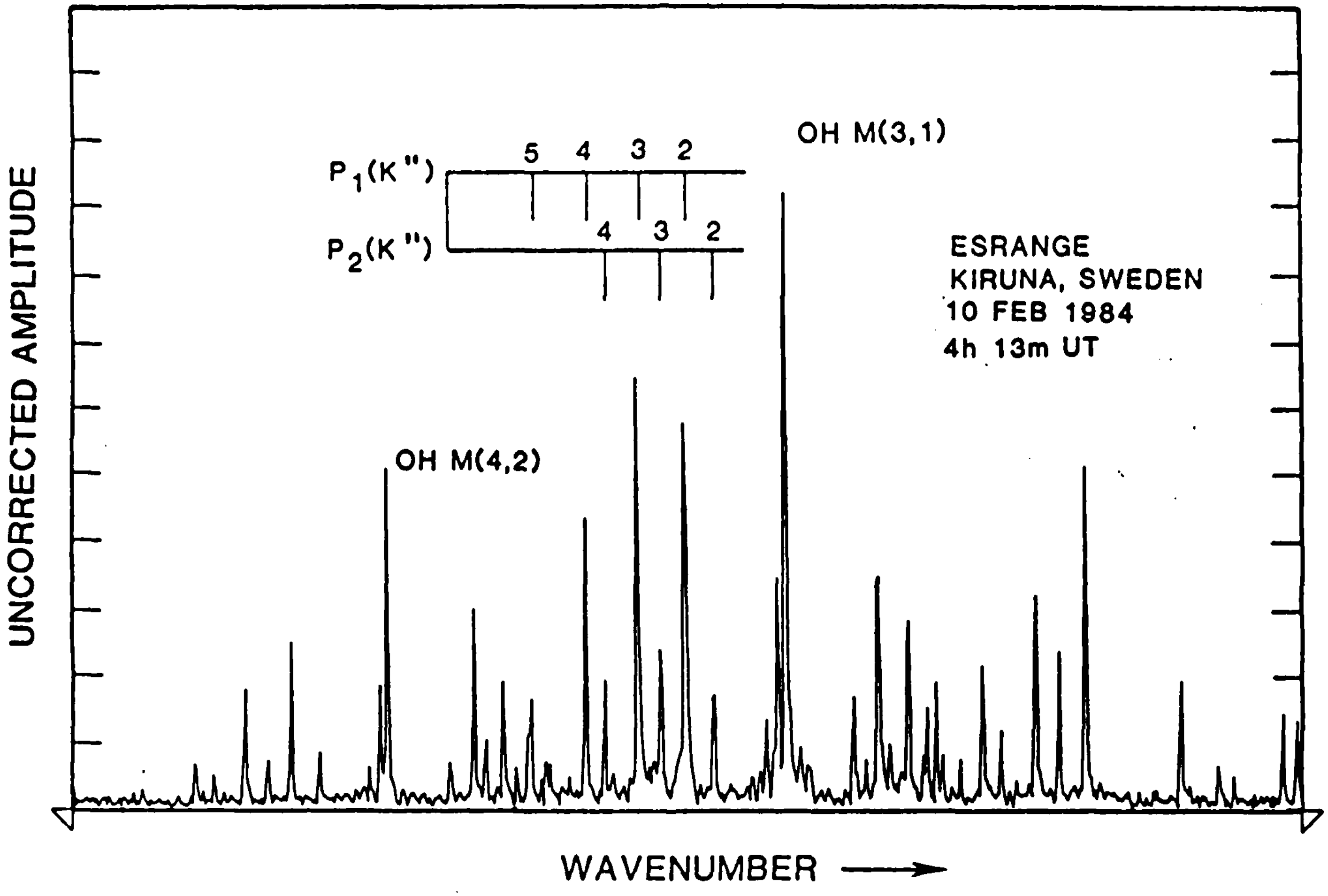

Figure 11. Spectrum taken by interferometer near flight time.

ure 12 where a relatively striking correlation is suggested. The enclosed "scatter diagram" (Figure 13) and related correlation analyses provide quantitative support for this correlation. If three somewhat uncertain points are omitted from the correlation analyses, then the Andoya temperatures correlate with the ESRANGE intensities at the level $r = 0.72$. We are presently checking the short-term correlation of our OH M(3,1) intensities and rotational temperatures. A comparison of long-term behavior will not be possible until more of the interferometer data have been fully processed. Note that the USU mean temperature for February 9-10, 1984, of 199°K is very near the German results. Further, this temperature is 30 to 40° lower than previous wintertime measurements. This result is consistent with the stratospheric warming event that took place during this observation period.

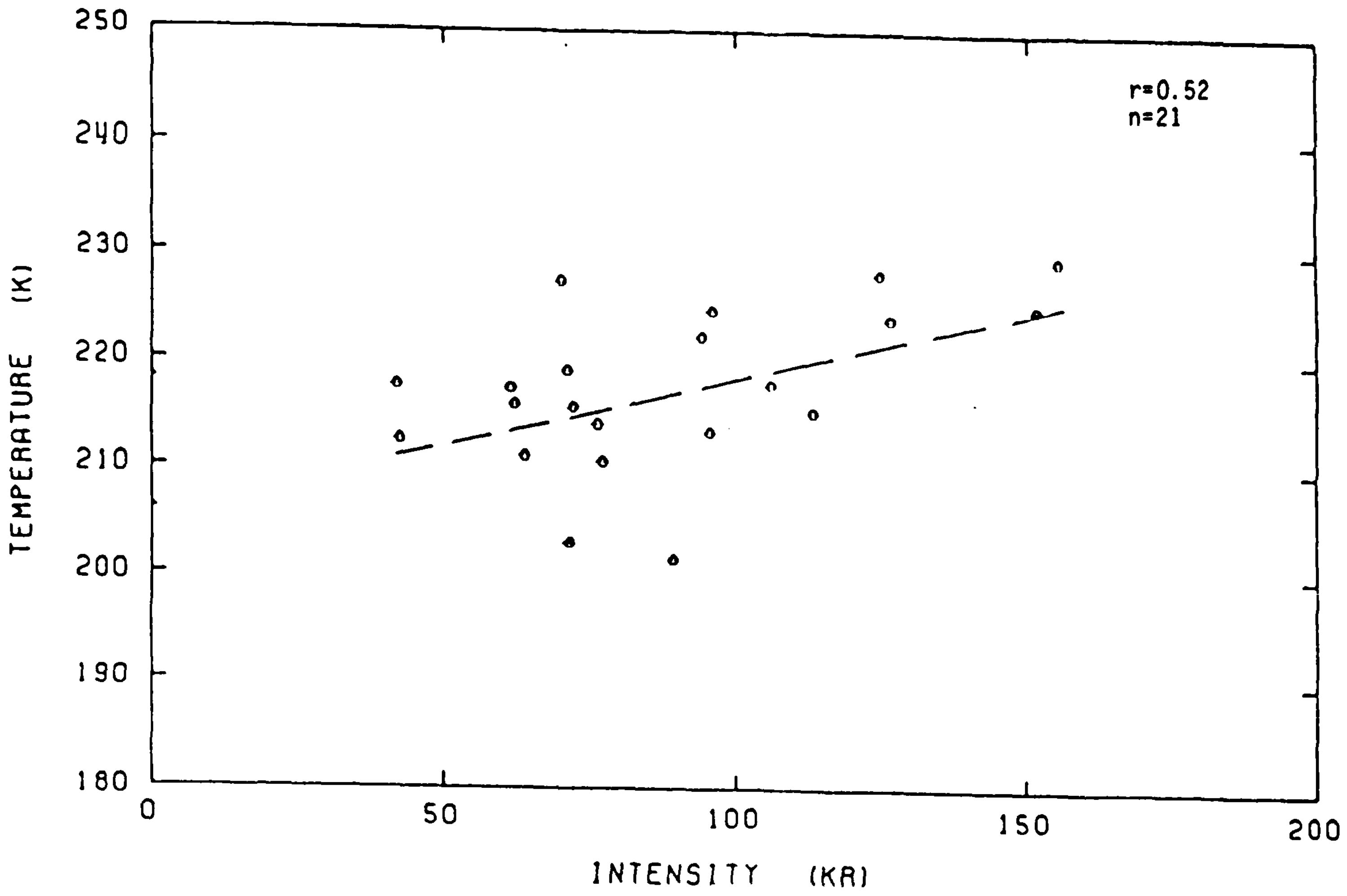

Figure 12. Andoya temperatures compared with ESRANGE intensities.

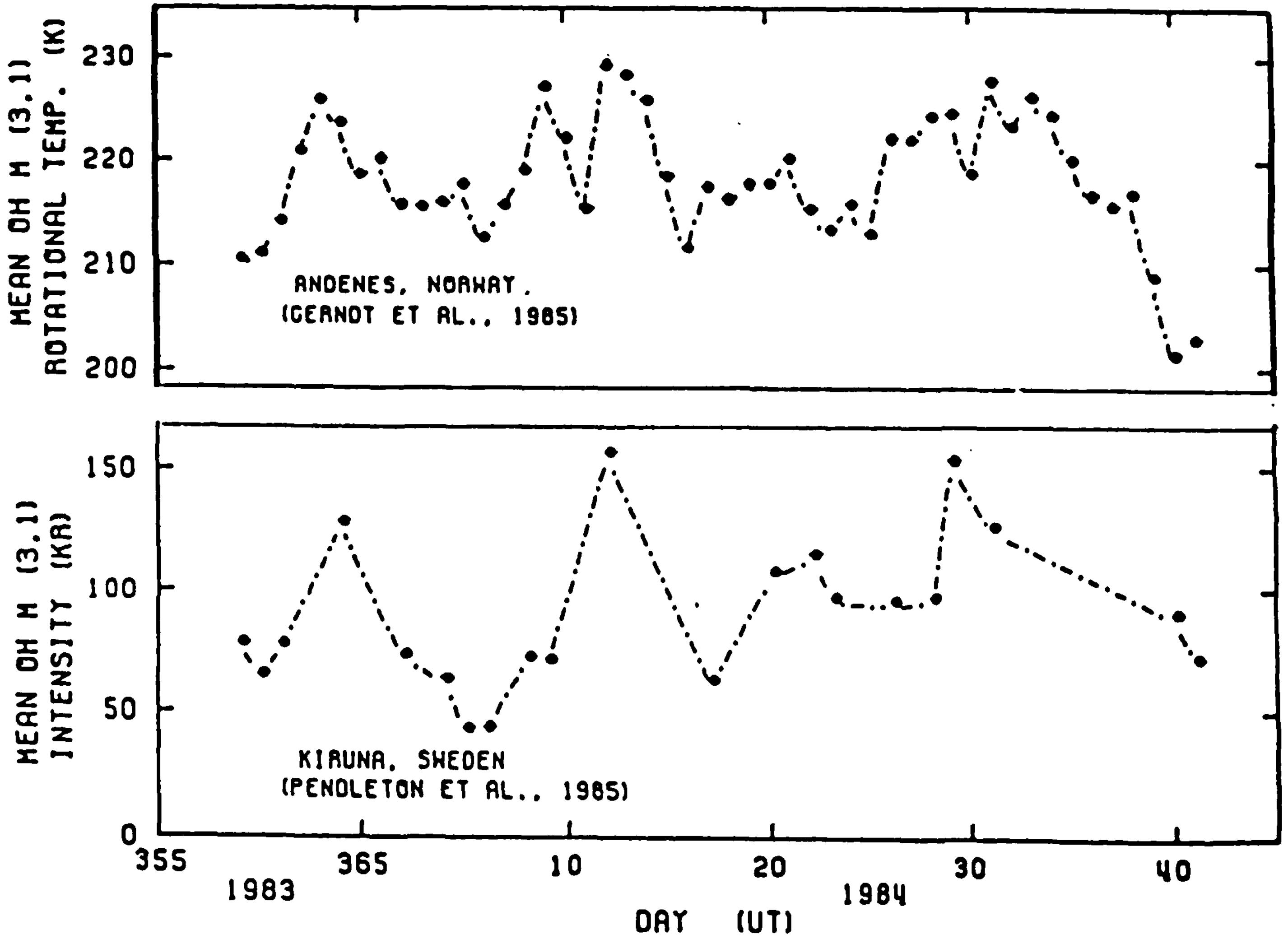

Figure 13. Scatter diagram illustrating relatively strong positive correlation of mean nightly OH M(3,1) ban intensities at Kiruna, Sweden, with mean nightly OH M(3,1) rotational temperatures at Andenes, Norway.

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2.6 STATE

The mesosphere is a very difficult region of the atmosphere to study. It is above balloon ceiling and well below heights where satellites can provide in-situ measurements. Rockets can provide occasional data but remote sensing is the only long term solution to these problems. Such probing is feasible from above (e.g., NASA's SME-Mesospheric Explorer Project) or from the ground via the MST radar technique (e.g., from Jicamarca, Peru, or from the Poker Flat Radar in Alaska). The STATE campaign was concerned with the latter technique and in particular with respect to the 50 MHz radar system operated in the Alaskan sector.

The STATE campaign was conducted from the Poker Flat Research Range, Alaska, and used sounding rockets and in-situ probes instrumented to accumulate data to help us understand the origin and character of the variations in atmospheric index of refraction which give rise to the so-called summer mesospheric echoes detected at high latitudes by VHF radar. As with many exploratory experiments, the results from STATE raised as many new, interesting, and controversial questions as were answered by the data. Appendix A contains the abstracts of eight papers which resulted from this research and were presented at a special session of the AGU, San Francisco, California, December 1984. Appendix A also contains a ninth paper, a program overview, that was published in Advances in Space Research [Proceedings of COSPAR]. The measurement program will be repeated and expanded under a new program to verify its remarkable content and to extend the data base to include measurements of different conditions. These would include simultaneous spatial measurements, temporal measurements, and winter mesospheric echoes. Such a program should shed more light on the underlying physical mechanisms.

As shown in Figure 14, echoes occur in two height ranges. Summer echoes occur near the mesopause (80-90 km) while winter echoes occur from a much lower height. Observations of mesospheric winds by radars are important not only due to the intrinsic merit of understanding a region of the earth's atmosphere, but in the challenge they provide for theoretical advances. For example, the very waves which are heavily filtered out of lower atmospheric

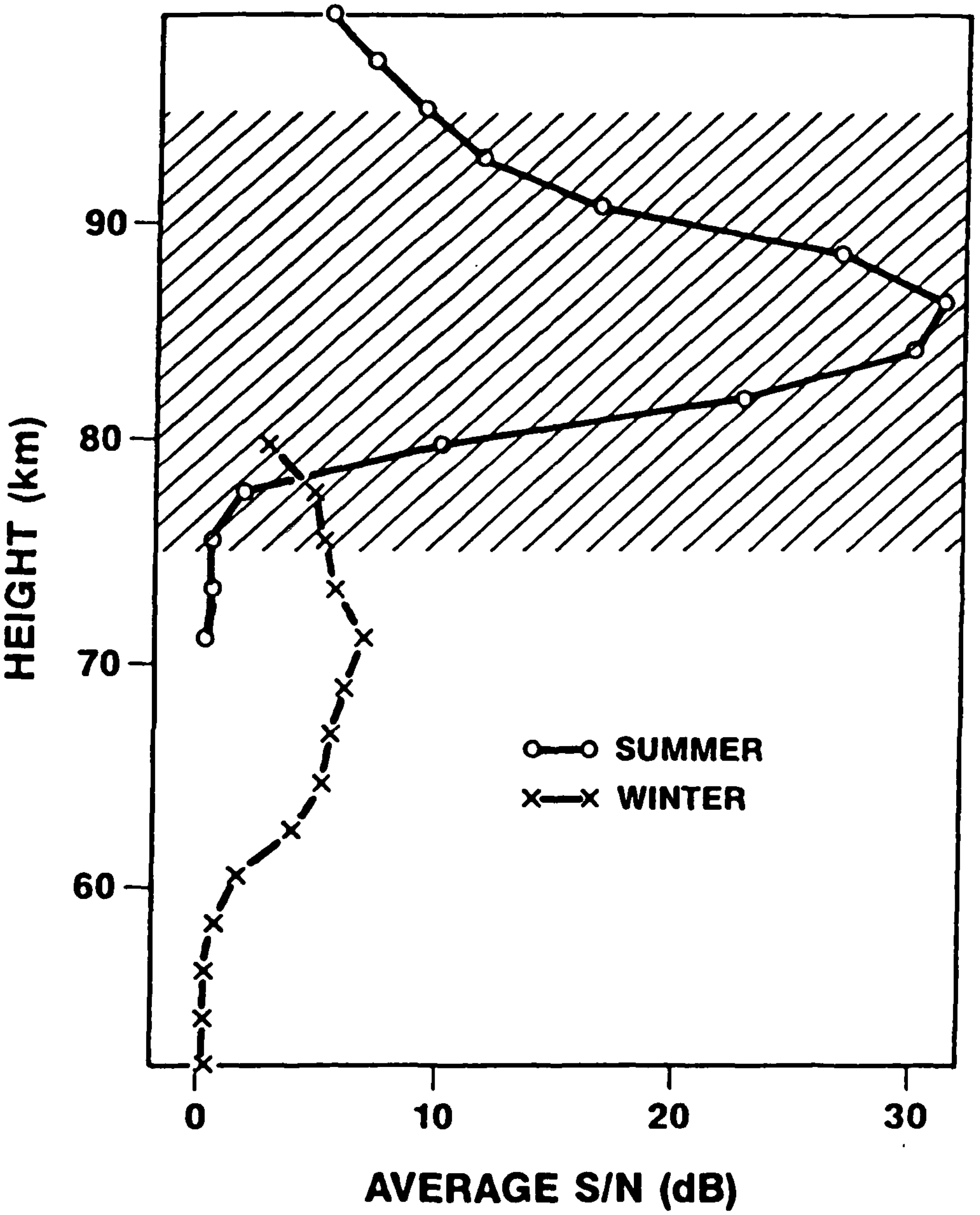

Figure 14. Summer and winter echoes.

models provide important sources of energy and momentum for the mesosphere as they propagate upward and grow in relative amplitude. That is, the mesosphere is a region where understanding how momentum and energy affect the mean flow is essential. Unless we can explain such processes, we cannot truly claim understanding of the atmosphere. The first step in understanding is a data base which now exists. The second step involves understanding how the waves saturate and dissipate their energy and momentum.

The purpose of the STATE project was to make in-situ observations using rockets simultaneously with 50 MHz echoes. Since the wave saturation process is expected to involve the generation of turbulence, the very existence of summer 50 MHz echoes at all was also thought to depend upon this process. The rocket data could therefore provide information on the waves present, their role in generating turbulence, the turbulence structure itself and the atmospheric structure in and around the scattering region.

Although highly successful, the STATE project was so ambitious and the phenomena so rich in complexity that we have raised as many questions as we have answered. We stress that the unanswered questions are just as indicative of progress and are accomplishments equal to the answered questions.

Questions Answered by the STATE Program

1. There are at least two different types of scattering sources: one centered upon the mesopause itself (temprature minimum) and one which peaks well above the mesopause.

2. The latter source is extremely turbulent and yields 10 - 15 db higher backscatter levels than the former.

3. The short-wavelength turbulence in the intense scattering region above the mesopause is organized by a much larger-scale wave-like process.

4. The lower intensity mesopause scattering seems to be organized by sharp gradients in the electron density, possibly due to electron attachment to "cloud particles" at that height.

5. The radar backscatter is in quantitative agreement with the in-situ fluctuation levels measured at the same wavelength.

Questions Raised or Still Open at the Conclusion of the STATE Program

1. Reproducibility: with two different results on two rocket flights we must repeat the experiments to prove that two different scattering sources really exist.

2. The smaller inner scale result is so controversial that we must try to repeat the experiment with a simultaneous absolute density calibration.

3. The small inner scale is so controversial that if we can verify it there may be important ramifications to stratospheric turbulence theory. In other words, if the anisotropy of the turbulence is so crucial to the atmospheric application that it drastically effects the inner scale, we may have to look again at the use of three-dimensional isotropic turbulence to explain anomalous transport in other regions of the atmosphere.

4. Just how does a "passive" scalar like the electron density, which must obey electrodynamic laws as well as fluid laws, form in response to neutral turbulence? The mesosphere is the only region in the atmosphere where this effect truly occurs and maybe we do not understand the physics. Maybe the small inner scale is not present in the neutrals, only in the electrons.

5. How can such steep gradients exist in the electron gas that a 3-meter component can survive and create "edge" backscatter? Is this question really identical to question 4? That is, if a strong turbulent Fourier component can exist at 3 meters due to a small inner scale, the effective Schmitt number must be quite large. This in turn implies a small effective effusion coefficient and therefore the possibility for steep edges.

6. How does the large scale wave field organize the small scale turbulent structure? Does a local Richardson number less than 0.25 develop in response to a mean shear plus the wave motion?

7. What are the origin and character of the variations in the index of refraction which give rise to the winter mesospheric echoes detected by the VHF radar? Is this only a daytime occurrence when particle precipitation is present, or is it always present? Is the inner scale the same as for summer results?

It may be too much to claim that our present program will answer all these items. However, the program will provide continuity for future mesospheric work in Alaska in conjunction with ground-based optical studies and with the strong European efforts which include radar probing.

3.0 PUBLICATIONS

These publications are listed according to the three major campaigns: 3.1 Energy Budget Campaign, 3.2 STATE Campaign, and 3.3 MAP/WINE Campaign.

3.1 Energy Budget Campaign Publications

1. Ulwick, J.C., and K.D. Baker, Infrared radiation and energy transfer in the auroral mesosphere and lower thermosphere, Sixth ESA Symposium on European rocket & balloon programs (ESA AP-183), 65-75, Apr 1983.

2. Ulwick, J.C., K.D. Baker, and E.R. Hegblom, Rocketborne measurements of auroral pulsations, Trans. Amer. Geo. Union, 64, 18, May 1983.

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3.2 STATE Campaign Publications

1. Philbrick, C.R., D.P. Sipler, B.B. Balsley, and J.C. Ulwick, The STATE experiment--mesospheric dynamics, Advances in Space Research, 4, 129, 1984.

2. Ulwick, J.C., K.D. Baker, and M.C. Kelley, Electron density irregularities of the polar mesosphere--STATE campaign, Trans. Amer. Geo. Union, 65, 45, 6 Nov 1984.

3. Baker, K.D., J.C. Ulwick, M.C. Kelley, B.B. Balsley, Comparison of rocket-probe electron density and MST radar polar mesospheric measurements, Trans. Amer. Geo. Union, 65, 45, Nov 1984.

3.3 MAP/WINE Campaign Publications (In process or planned)

1. Investigation of Hydroxyl Excitation Processes with IR Rocket and Ground-based Measurements, Ulwick, J.C., K.D. Baker, D. J. Baker, all at Utah State University, Logan, UT, and K.U. Grossman, University of Wuppertal, Wuppertal, West Germany.

2. Rocket Measurements of Atomic Oxygen in the Mesosphere and Lower Thermosphere, Ulwick, J.C., K.D. Baker, and L.C. Howlett, Utah State University, Logan, UT.

3. Oxygen Chemistry, Ulwick and Baker.

4. Non-LTE EMissions, ($CO_2^{\ddagger}$, $NO^{\ddagger}$), Ulwick et al.

5. Temperature in the Mesopause Region as Deduced from N_a-LIDAR and $OH^{\ddagger}$ spectroscopy, USU co-author W. Pendleton.

4.0 APPENDIX A

4.1. THE MAP/WINE CAMPAIGN RESULTS

4.2. THE STATE CAMPAIGN RESULTS

4.1 MAP/WINE CAMPAIGN

The following abstract was submitted for presentation at the twenty-sixth COSPAR meeting. A paper will be published in the COSPAR journal, Advances in Space Research.

Investigation of Hydroxyl Excitation Processes with IR Rocket and Ground-based Measurements Ulwick, J.C., K.D. Baker, D. J. Baker, all at Utah State University, Logan, UT, and K.U. Grossman, University of Wuppertal, Wuppertal, West Germany.

As part of the MAP/WINE campaign, the infrared hydroxyl airglow layer was investigated at Kiruna, Sweden, by simultaneous measurements with rocket probes of OH infrared emission and concentration of odd oxygen species (O and O_3) coordinated with OH emission spectra and time history measured from the ground. Not only did the rocket-borne 1.6-μm radiometer provide the volume emission rate of OH it also gave data on the nonuniformity and structure of the layer which peaked at about 86 km with a maximum emission rate of about 10^5 photons/sec.cm^3. These data coupled with in situ measurements of the concentrations of atomic oxygen and ozone and temperature, spectra and time history measured from the ground provide the basis for studying the formation processes of the excited OH. The atomic oxygen showed a peak density of about 10^{11} cm^{-3} near 89 km. The implication of the observed variations due to spatial structure in the OH emission from both the rocket and ground based results will be discussed.

The following abstract was published in the EOS Transactions, American Geophysical Union (AGU), 66, 46, November 12, 1985. The paper was presented at the AGU fall meetings in December 1985.

Rocket Measurements of Atomic Oxygen in the Mesosphere and Lower Thermosphere

Ulwick, J.C., K.D. Baker, and L.C. Howlett, Utah State University, Logan, UT.

The altitude distribution of $O(^3p)$ have been investigated in situ by a technique involving the use of a rocket-borned OI 1304Å resonance-scattering technique. The experiment consisted of a closed, flowing rf excited, modulated oxygen resonance lamp producing on the order of 10^{13} photons/sec sr of 1302, 1304 and 1306Å oxygen triplet radiation. Measurements were made at Kiruna, Sweden, in February 1984 as part of the MAP/WINE campaign during quiet precipitation backgrounds. Ascent and descent profiles of [O] were made from 78 km to peak rocket altitude of 180 km with excellent agreement and with a peak concentration of 10^{11} cm^{-3} between 90 and 100 km. Comparison with the CIRA model shows that from 100 km to peak altitude the rocket results are consistently an order of magnitude less than the model. However, comparison of the rocket results with earlier results obtained at White Sands, New Mexico, under similar conditions (nighttime, no particle precipitation and winter) showed less than about 15 per cent difference in the results, even in gross structure, over the altitude range 85 km to KSAR peak rocket altitude of about 125 km. Comparison with previous measurements during auroral particle precipitation show wide discrepancies and these will be presented and discussed.

4.2 STATE CAMPAIGN

COMPLETED PROJECT SUMMARY

1. Infrared Airglow Clutter

2. Prof. James C. Ulwick
Center for Space Engineering
Utah State University
Logan, UT 84322

3. 15 July 1983 - 30 November 1985

4. Contract F49620-83-C-0122

5. $99,924 FY 83 -- $20,000 FY 84

6. Dr. K.D. Baker

7. Mr. Glen Berg (graduate student)

8. Publication:

Ulwick, J.C., and K.D. Baker, Infrared radiation and energy transfer in the auroral mesosphere and lower thermosphere, Sixth ESA Symposium on European rocket and balloon programs (ESA SP-183), 65-75, April 1983.

Ulwick, J.C., K.D. Baker, and M.C. Kelley, Electron density irregularities of the polar mesosphere--STATE campaign, Trans. Amer. Geo. Union, 65, 45, November 1984.

Philbrick, C.R., D.P. Sipler, B.B. Balsley, and J.C. Ulwick, The STATE experiment--mesospheric dynamics, Advances in Space Research, 4, 129, 1984.

Baker, K.D., J.C. Ulwick, and L.C. Howlett, Rocket measurements of atomic oxygen in the mesosphere and lower thermosphere, Trans. Amer. Geo. Union, 66, 46, 1985.

Ulwick, J.C., K.D. Baker, D.J. Baker, and K.U. Grossmann, Investigation of hydroxyl excitation processes with IR rocket and ground-based measurements, Trans. Amer. Geo. Union, 66, 46, 1985.

9. An infrared rocket and ground-based measurement program was conducted to investigate the infrared airglow as part of the international MAP/WINE campaign in northern Scandinavia. The mean OH Meinel rotational temperature from the ground interferometer measurements during a stratospheric warming event was about 199° K which is approximately 30 to 40 degrees cooler than non-event measurements and confirms the coupling theory that stratospheric warming results in mesospheric cooling. The rocket atomic oxygen profiles showed a peak concentration of approximately 10^{11} cm^{-3} between 90 and 100 km. The rocket results from 90 to 180 km are consistently almost an order of magnitude less than what the models predict. However, the rocket results are consistent with other measurements under similar conditions - winter, night and no particle precipitation. The results from 85 to 100 km show considerably more structure than what the models predict. The 1.6-μm rocket-borne infrared radiometer also provided excellent altitude profiles of OH emissions showing a peak at 86 km and a maximum volume emission rate of about 10^5 photons/sec/cm^3. These data also show a nonuniformity and structure within the layer.

10. AFOSR Program Manager: Dr. Francis Wodarczyk

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