Physical Properties of the Polar Winter Mesosphere Obtained From Low-Frequency Propagation and Partial Reflection Studies [1]

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During the winter of 1963–64 observations of partial reflections at a frequency of 2.66 Mc/s were made at Resolute Bay (invariant magnetic latitude $84\frac{1}{4}°$) near local midnight. Utilizing the different amplitudes of the ordinary and extraordinary backscattered waves, information was obtained about electron densities and electron collision frequencies. Electron densities range from 10 cm^{-3} at 80 km to 1000 cm^{-3} at 110 km. Collision frequency values are a factor of 2–4 times greater than average daytime results at lower latitudes. These observations, together with some indirect inferences based on low frequency propagation between Thule and Churchill (invariant magnetic latitude $79\frac{1}{2}°$ at path midpoint) are discussed and it is concluded that (1) galactic cosmic rays are responsible for electron production below 90 km, (2) ionization rates in excess of galactic cosmic ray production are required for heights above 90 km, (3) effective electron loss rates below 90 km are markedly more rapid than dissociative recombination, and (4) the polar winter mesosphere is hotter than previous data suggest.

1. Introduction

The Radio Physics Laboratory has during several years been making studies of the high latitude D-region by the propagation of low-frequency radio waves and the partial reflection of medium frequency pulses from ionization irregularities within the region. The results so far reported [Belrose and Burke, 1964; and Belrose and Hewitt, 1964], were obtained by the method of partial reflection, at Ottawa ($L=3.6$ or invariant magnetic latitude 58.2°). There have been only a few studies of the lower ionosphere at latitudes above the auroral zone ($L>10$ or invariant magnetic latitude $>71\frac{1}{2}°$). In one of these [Gregory, 1962], partial reflections of MF radio waves made at Scott Base, Antarctica (79°S geomagnetic latitude). From an analysis of partial reflection data and Forbush decreases in the flux of galactic cosmic rays, Gregory attempted to show that the residual ionization during the polar night on undisturbed days was due to galactic cosmic rays, although his estimated electron densities, according to present estimates of electron loss rates, required ionization rates in excess of cosmic-ray production.

During the winter of 1963–64, observations of partial reflections at a frequency of 2.66 Mc/s were made at Resolute Bay, Cornwallis Island, N.W.T. ($L\simeq100$ or invariant magnetic latitude $84\frac{1}{4}°$). Utilizing the different amplitudes of the ordinary and extraordinary backscattered waves, information is obtained about electron densities and electron collision frequencies. The experimental technique and method of analysis [Belrose and Burke, 1964], and the experimental equipment employed in the study [Belrose et al., 1964] have been previously described, and will not be discussed here. These observational data differ from those of Gregory, who observed partial reflections with linearly polarized antennas and could therefore only make estimates of the electron densities from the received echo amplitude versus height data.

This paper gives the results of an analysis of partial reflection observations made near local midnight during the middle of the polar winter. These data are discussed in the light of present knowledge of lower ionosphere processes. The paper begins with a description of some studies of very high latitude low-frequency propagation, since these data reveal some interesting features about changes in the electron densities near the base of the ionosphere.

2. Low-Frequency Propagation Studies

The field strengths of CW transmissions, at frequencies of about 80 kc/s propagated to distances of about 2000 km, have been routinely recorded, since the summer of 1960, for a number of circuits extending over a range of latitudes in Canada. These recordings have shown that when the LF transmission path lies entirely within the polar cap, i.e., over transmission paths inside the auroral zone or at geomagnetic latitudes $>70°$, the daily variations in field strength are quite different from those for similar transmissions at lower latitudes.

The experimental observations with which we are concerned are the recordings of the USAF 77.15 kc/s transmissions from Thule, which are recorded at Fort Churchill at a distance of 2210 km. The midpoint of this path is at $L \simeq 30$ or invariant magnetic latitude of 79.5°. Figure 1 shows typical undisturbed diurnal variations of field strength for winter (January), equinox (March), and summer (July), at midmonth. Some individual days vary widely in detail from these typical variations, but in general the variations for undisturbed days are more regular than those recorded at lower latitudes. The times for solar zenith angles of 102°, 98°, 94°, and 86°, as well as ground sunrise (SR) and sunset (SS) at 90°50′, are shown by short vertical bars. The following features of these data are worth discussion:

(1) The D-region is always sunlit in summer ($\chi < 86°$), so that no strong diurnal variation is evident.

(2) There is a marked diurnal asymmetry (particularly clear in this figure during March), in that the main decrease in field strength before sunrise occurs in about ¾ hr, for solar zenith angles between 101° and 97°, whereas after sunset it takes more than 4 hr for the field strengths to reach their presunrise values. LF propagation studies over paths of similar length at lower latitudes show a fairly abrupt onset of nighttime propagation conditions for solar zenith angles greater than 102°.

(3) And finally, the nighttime recordings exhibit only shallow fading.

In figure 2 signal amplitudes for several transmissions (for circuits as marked) recorded during an undisturbed night are shown. The large nocturnal irregular variation of field strength is clearly evident for all transmissions, except the Thule-Churchill path. These recordings show a small disturbance, observed for the paths near the auroral zone (L between 4½ and 9), which shows in the recordings as a rapid fluctuation of field strength for a period of about an hour (0815–0915 UT). Larger disturbances also affect lower latitude paths, but not in general the Thule-Churchill path. Large nocturnal signal amplitude decreases, lasting an hour or so, are sometimes observed on this transmission. These have not yet been correlated with other geophysical data. They are not in general observed at lower latitudes.
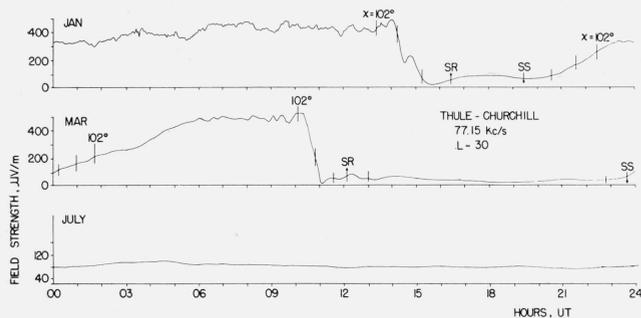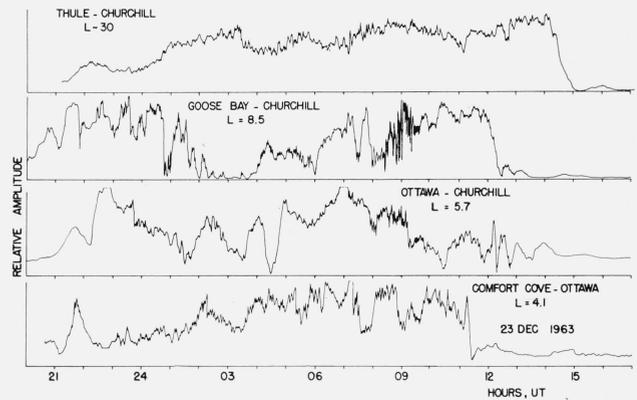

FIGURE 2. *Low frequency (70 to 80 kc/s) field strengths for an undisturbed night for various transmissions as marked.*

During solar proton events, the nocturnal signal amplitude on this circuit becomes weaker, and the fading even less pronounced. Signal strength reductions have been observed for as long as 15 days after a series of major solar proton events [Belrose and Ross, 1962]. The nocturnal LF amplitudes of high latitude transmissions are in fact a most sensitive method of detecting the presence of solar protons in the ionosphere.

Time variations associated with Forbush decreases of cosmic radiation have not yet been looked for. Nevertheless, the sensitivity of the data to solar proton influxes, and the quasi-constant nocturnal field strengths, has led [Belrose, 1963] to the suggestion that protons are responsible for electron production at low heights under both undisturbed and disturbed conditions. The marked diurnal asymmetry suggests that there are important differences at high latitudes in electron decay processes compared with middle latitudes, but without the more direct observational data of electron density as deduced by partial reflection over sunrise and sunset, this feature of the low-frequency propagation data cannot be directly interpreted.

3. Partial Reflection Experiment

3.1. Experimental Observations

The partial reflection data made at Ottawa have not so far given information about the nighttime lower ionosphere, because of high nighttime noise and station interference levels. The noise levels at Resolute Bay are very low, even at night, and partial reflection observations can be made on most days. Figure 3 shows data for the received echo amplitudes versus height for the two magneto-ionic components Ax and Ao made on a particular low noise night, the 2 January 1964, compared with the average data for Ao observed on nine undisturbed nights during 22 December 1963 to 4 January 1964. These data are judged to represent undisturbed conditions on the basis of the Thule-Churchill LF transmissions and the Resolute Bay ionosonde data. Data for 4
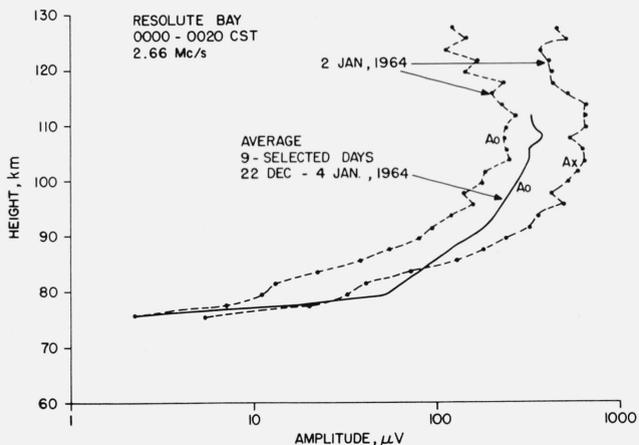

FIGURE 1. *Low frequency field strengths observed at Churchill from a 77.15 kc/s transmitter at Thule.*

FIGURE 3. *Amplitude of ordinary and extraordinary back-scattered waves with height measured at Resolute Bay.*

FIGURE 4. *Amplitude ratio* Ax/Ao *with height measured at Resolute Bay.*

days were not included in the average because of the presence of sporadic-E, which showed on our recordings as a rapid increase in echo strengths to off-scale values for heights greater than 90 to 100 km and as regular Es traces on the routine ionograms made by the Department of Transport operated ionospheric sounder at Resolute Bay.

These observations were made near local midnight, during a time of the year when the lower ionosphere had not been illuminated by solar ultraviolet radiations for about 1½ months. The minimum solar zenith angle at local midday was not less than 98° for the period of the observations. In the absence of a nocturnal electron production, therefore, the electron densities would have decayed to very low number densities.

Figure 4 shows the average amplitude ratio Ax/Ao for the nine undisturbed nights. The points plotted are the three point running average of mean data. Ax/Ao first increases with height, over a height range 75 to 87½ km. It is this part of the curve which provides a measure of electron collision frequency, since differential absorption is negligible. Above 87½ km differential absorption begins, and Ax/Ao sharply decreases. It is this part of the curve which gives a measure of electron density.

3.2. Electron Collision Frequency

Figure 5 shows values of collision frequency deduced from the observational data just discussed, i.e., for the 2 January 1964, and the 9 average days, compared with data measured at lower latitudes, at various times and by various methods. The Resolute Bay values for collision frequency are markedly greater than the range of values measured at lower latitudes. The values for 2 January are about 2 times greater, and the average values are about 4½ times greater, than those given by the continuous curve, which has been calculated using laboratory determined relations between collision frequency and
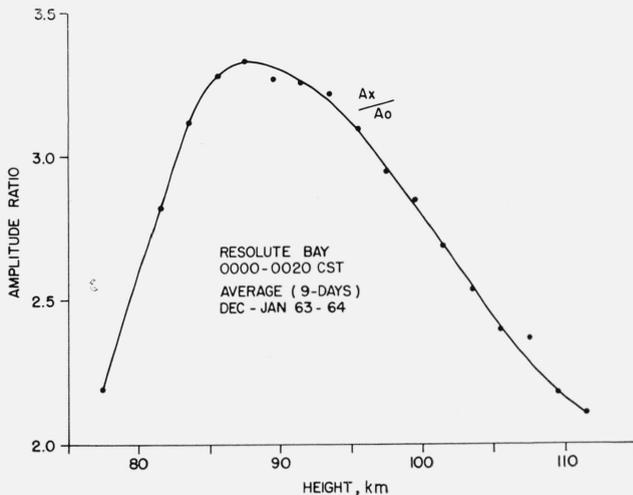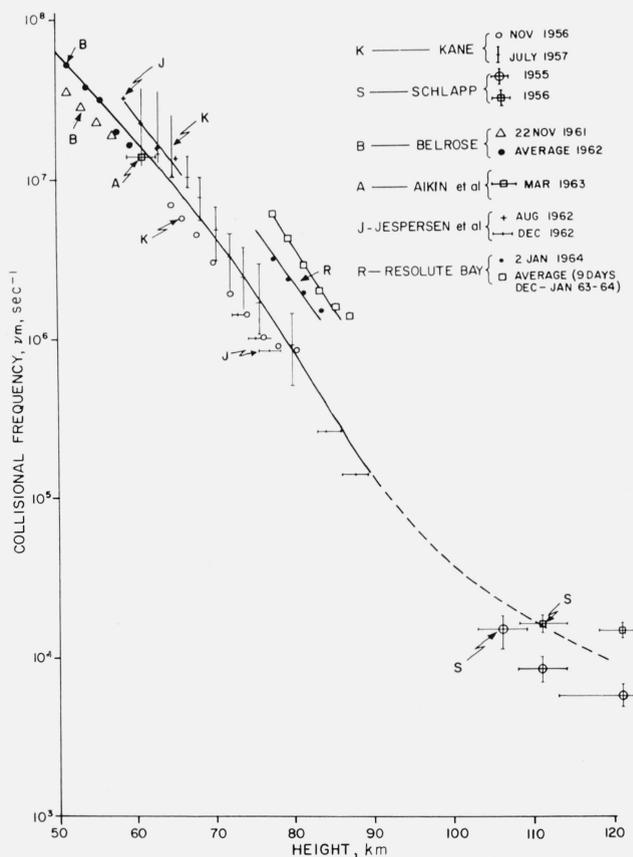

FIGURE 5. *Collision frequency of monoenergetic electrons with height measured at Resolute Bay compared with various data (see Belrose and Hewitt, 1964).*

particle number density and temperature, and the COSPAR International Reference Atmosphere (CIRA 1961). The calculated curve is in reasonable agreement with the average results at middle latitudes.

It should be stressed, at this point, that the experimental measurements of partial reflection show a difference between low and high latitudes in the ratios for Ax/Ao in a height range where differential absorption is negligible. The ratio between the reflection coefficients for the two magneto-ionic components, on the assumption that the scatter is from a turbulent region irregular in electron density, is determined by electron collision frequency, but independent of the actual electron density [Belrose and Burke, 1964]. On this assumption the observed ratios are interpreted to mean a difference in collision frequency.

3.3. Electron Density

Figure 6 shows the average electron density-height curve deduced from the observational data, compared with calculated electron density-height curves by Webber [1962], which are discussed in the next section. The measured data, shown in the upper part by the continuous curve, give electron density values deduced from the measured different amplitudes Ax and Ao in the height range where differential absorption is measurable; and the lower broken curve assumes, with reasonable theoretical justification [Belrose and Burke, 1964], that the electron density, in the height range where differential absorption is negligible, is proportional to the O-mode echo amplitude.

4. Discussion

Detailed examination of figures 5 and 6 show that there are marked differences between electron collision frequency and electron density in the polar winter mesosphere from those expected. Let us first discuss the differences in collision frequency.
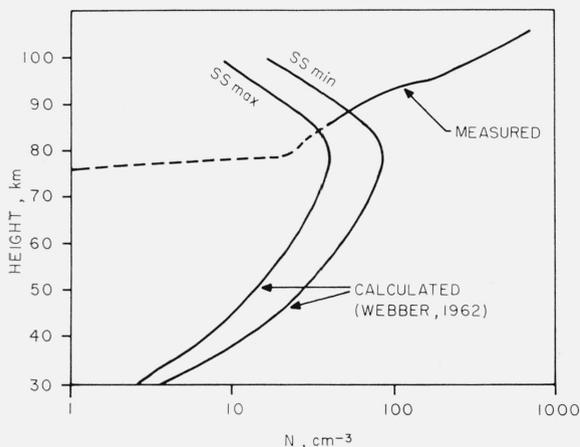

FIGURE 6. *Midnight electron density-height curves measured at Resolute Bay, compared with calculated curves assuming electron production by galactic cosmic rays for geomagnetic latitudes > 70° and maximum and minimum epoch of the solar cycle.*

It is already fairly well established that the polar winter mesopause region is warmer than the CIRA reference atmosphere model, by some 40 to 60 °K [Murgatroyd, 1957], and this warming is variable from day-to-day. There are meteorological phenomena which could account for the amount of expected heating (e.g., chemical heating by recombination of atomic oxygen, Kellogg [1961], Young and Epstein [1962], and Maeda [1963]; or dynamic heating by atmospheric acoustic waves from the polar night jet stream [Maeda, 1964], and by turbulence or internal gravity waves [Hines, 1963]. On the assumption that the pressures at the 20 km level are not different from the CIRA model, the local gas densities, even with heating, will also not be different in the polar winter mesopause region. The temperature difference alone can account for an increased collision frequency by about a factor of 1.3. The observed larger differences, by a factor of 2 to 4, cannot therefore be explained on the basis of present estimates of mesospheric heating. It seems probable, therefore, that:

(1) The polar winter mesopause region is hotter than previously thought, and or

(2) The electron and gas temperatures are not equal.

We have already suggested [Belrose and Hewitt, 1964] that other experimental evidence suggests that the electron and gas temperature in the mesosphere might not be equal (at least during the day). This suggestion is new, and is not yet theoretically justifiable. There is clearly a need for in-situ measurements by rockets of the gas pressures and temperatures in the polar winter mesosphere.

The marked differences between the theoretically computed electron densities, and the measured electron densities, also warrant discussion. The calculated curves, shown in figure 6, have been computed by Webber [1962], and are for nighttime, at latitudes >70° geomagnetic, for two epochs of the solar cycle. The calculations assume that electron production is by galactic cosmic rays. There are marked differences at both low and high heights in the mesosphere between the calculated and measured electron densities. The absence of measurable electron densities below 75 km might be because of an absence of turbulent scatterers, but the rapid increase above this height suggests that there are indeed few electrons at low heights.

On the assumption that galactic cosmic rays are the sole electron production mechanism for heights below about 90 km, detailed examination of the available data suggests that there is a marked difference between electron loss processes at 90 km and 80 km and that this difference may be attributed to the formation of negative ions at the lower height. The measured electron density at 90 km, taken together with Webber's curve for the rates of ion production at geomagnetic latitudes >70° and the minimum epoch of the solar cycle, yields an "effective" recombination loss rate of about 1.2×10^{-7} cm^3 sec^{-1}. This may be compared with a value of 1×10^{-7} cm^3 sec^{-1} between 88 and 95 km deduced from experiments

carried on a rocket at Fort Churchill in 1963. Adey et al. [1964] measured, during an auroral absorption event, the ambient electron density at the rocket. McDiarmid and Budzinski [1964] measured electron flux as a function of altitude at certain energies above 10^4 eV, from which they could compute the ionization production rate. Using the measured free electron densities, and the computed ionization production, the "effective" recombination loss rate was computed. The apparent agreement between the two sets of different data give support to the suggestion of a cosmic ray production below 90 km, and, further suggest that at 90 km there is negligible loss of electrons to form negative ions, i.e., the electron removal process is one of dissociative recombination, which is currently thought to have a rate coefficient in the D-region of about 2×10^{-7} cm^3 sec^{-1} [Reid, 1964].

Similar computations for a height of 80 km yield a loss rate of about 6×10^{-5} cm^3 sec^{-1}, which may be compared with the rocket results (extrapolated below 83 km) of about 10^{-4} cm^3 sec^{-1}. The Resolute data and the Churchill rocket data agree within a factor of two, and both are considerably larger than the "minimum" nighttime loss rate of about 10^{-6} cm^3 sec^{-1} at 80 km obtained by using a "maximum" collisional detachment rate [Crain, 1961] or the value of about 1.6×10^{-6} cm^3 sec^{-1} deduced by Webber [1962].

The calculated electron densities at low heights in the mesosphere depend very heavily on the collisional detachment coefficient for O_2^-. The value used by Webber of 2×10^{-17} cm^3 sec^{-1}, which is something like the Bailey and Branscomb [1960] value deduced from polar cap absorption, is 500 times larger than the Phelps and Pack [1961] laboratory measurements which gave 6×10^{-20} cm^3 sec^{-1} for O_2^- at 230 °K. Using this latter value would give much lower electron densities [Crain, 1961; Arnold, 1964]. Crain has emphasized that for negligible detachment "effective electron loss rate" has no meaning. The values given for 80 km height in the preceding paragraph are not therefore strictly correct.

The apparent agreement between the rocket data and the Resolute data, which are for quite different ionization processes and ionization rates are taken to mean (1) the undisturbed nighttime electron densities below 90 km can reasonably be accounted for by ionization by galactic cosmic rays, and (2) there is a rapid change in the way electrons are lost at 80 km compared with 90-km heights, and this difference might be associated with a large change in the effective role of negative ions at the two heights.

The height range 90 to 100 km poses other problems. Some additional source of ionization is required, which might be electron fluxes in the 10^4–10^5 eV energy range. The electron fluxes required are very small, some 10 cm^{-2} sec^{-1} sterad^{-1} [Gregory, 1962], which are well below the threshold of existing rocket and satellite detectors. These fluxes must be arriving quite uniformly with time; recall the quasi-constant nocturnal field strength of LF propagation.

It is hoped that observations over sunrise and sunset, which have been made at Resolute Bay during March 1964, and which are currently being analyzed, will provide results pertaining to the above discussion.

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