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Subsonic Probe Measurements of Middle-Atmosphere Electrical Parameters

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Investigations of middle-atmosphere electrical properties have been conducted using subsonic Gerdien condensers and blunt probes. Variability in electrical parameters is observed for quiescent, midlatitude conditions as well as in response to ionization source perturbations. Noticeably, a sunrise buildup in positive conductivity occurs at lower altitudes where ionization by solar ultraviolet radiation is relatively insignificant. Corresponding ion mobility data possibly indicate a photodissociation process by which smaller, more mobile ions are formed. At high latitudes during geomagnetically disturbed conditions, conductivity enhancements are observed in the region of auroral energy deposition. The variations in conductivity demonstrate the spatial and temporal dependences of these auroral ionization sources. Possible coupling of auroral effects to lower altitudes is suggested by the conductivity measurements. This variability in middle-atmosphere electrical parameters measured for different conditions is important when considering electrical coupling and transmission processes through the region.

Introduction

MEASUREMENT of electrical conductivity and its constituent parameters, ion mobility and charge number density, are important for understanding the electrical structure of the middle atmosphere. These parameters impact on ionospheric radio wave propagation studies and ion chemistry models. Also, they are fundamental to global electrical circuit models which may relate to such weather phenomena as thunderstorm activity. Presently, middle-atmosphere electrodynamics studies are being conducted to investigate electrical coupling mechanisms and their possible role in solar-terrestrial processes.

Two sensors used for the in situ measurement of middle-atmosphere electrical parameters are the blunt probe and the Gerdien condenser. Rocket launchings of blunt probes have been conducted since the 1960's,[1-3] while the use of Gerdien condensers dates back even earlier.[4-11] This paper will consider these probe systems and some of our recent results, with emphasis on measurements of such transient phenomena as sunrise and auroral events.

Probe Systems

The blunt probe and the Gerdien condenser are essentially two-electrode instruments. The blunt probe uses a planar collector geometry consisting of a disk and a circular concentric guard ring (Fig. 1). A known voltage waveform—typically, a ramp function—biases the collector with respect to the return electrode. Measuring the charged particle current to the collector enables one to determine both polar components of electrical conductivity.[12-13]

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The Gerdien condenser's concentric, circular cylindrical electrode geometry (Fig. 2) consists of an inner collecting electrode which is biased with respect to the outer return electrode. The charged particle current response in the linear region of operation is used to determine electrical conductivity.[6] The linear region of operation for a Gerdien condenser occurs at sufficiently low probe voltages such that no ion mobility group is completely collected from the air sample flowing through the aspirator. For a well-defined flow geometry and a sufficient range of collection voltages, it is possible to additionally measure the ion mobilities and charge number densities of the air sample.[6,14]

Although these sensors occasionally have been flown as a part of coordinated scientific balloon packages for measuring stratospheric parameters,[15-16] they more often are launched on rockets. Upon reaching apogee (nominally, 70-85 km), the probe separates from the rocket and descends to Earth on a stabilized parachute (see Figs. 1 and 2). Subsonic probe techniques obviously lengthen the data collection period as compared to supersonic measurements. Also, smaller collection voltages and reduced flow velocities associated with subsonic probes lessen the possibility of altering the ambient ion species to be measured.

Recent theoretical and experimental investigations have enhanced the measurement capabilities of these probe systems. Studies of electron collection by the blunt probe have resulted in the determination of electron density from its current-voltage characteristic.[17-18] The values derived from the probe data agree well with electron density measurements from other in situ and remote sensing techniques.[19]

On occasion, mesospheric vertical electric fields of several volts per meter have been deduced from blunt probe data by measuring displacements in the probe's current-voltage characteristics.[20] Recent measurements by electric field probes support these earlier observations.[21-22]

Measurement capabilities also have been enhanced by including additional sensors and sources with the existing probe systems. A small hemispheric collecting electrode inserted at the tip of the nose cone is being studied as a possible supersonic probe technique for measuring conductivity and charged particle density. The nose-tip probe is electrically

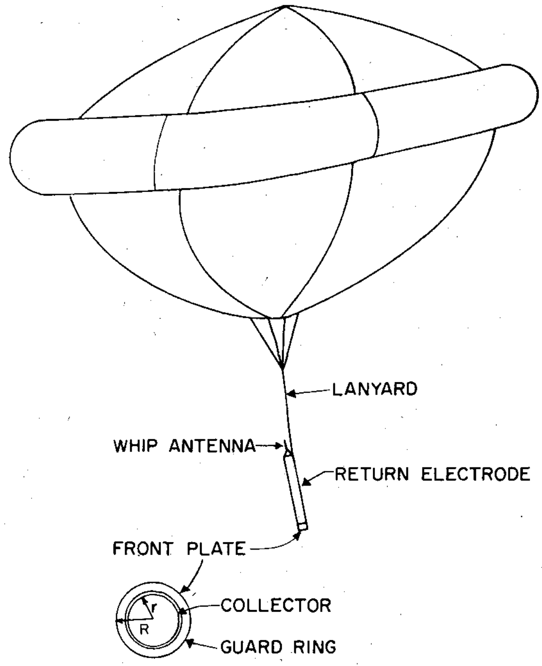

Fig. 1 Parachute-borne blunt probe (launched with a super Loki rocket).

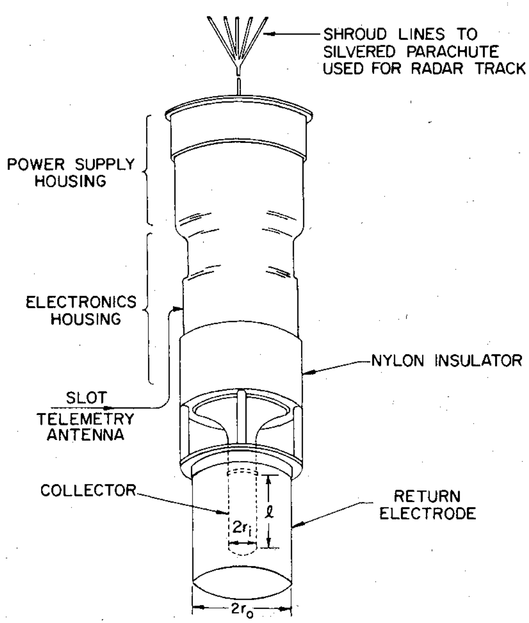

Fig. 2 Parachute-borne Gerdien condenser (launched with a super Arcas rocket).

connected to the Gerdien condenser which provides the necessary electronics and telemetry functions while housed inside the nose cone. Thus, supplemental data are obtained during ascent when the Gerdien condenser is not probing the plasma.

Finally, probes have been flown on parachutes and balloons with ultraviolet and visible lamps to measure their ionization effects on the atmosphere. This application is important for investigating atmospheric constituents ionizible by the sources.[23-24]

Midlatitude Experimental Results

The various atmospheric studies in which these probe systems are used may be generally divided into two categories: studies to determine the effects of such parameters as latitude, temperature, time of day, season, and altitude on the quiescent electrical structure; and investigations of electrical parameter responses to different energy source perturbations, often of a transient nature, such as an auroral event or a solar eclipse. A brief description of our more recent investigations is presented in Table 1. Midlatitude results for quiescent conditions, with emphasis on the morning twilight period, are now considered.

The nighttime conductivity data shown in Fig. 3 are useful for understanding midlatitude processes. The blunt probe measurements demonstrate the expected absence of free electrons and show the negative ions to be relatively more mobile at higher altitudes. Under quiescent nighttime conditions, the principal source for ions in the measurement region is galactic cosmic ray ionization. The height dependence for conductivity below 45 km is approximately inversely proportional to that for neutral number density, which is indicative of a region where ion-ion recombination is primarily a three-body process.[25] When compared to the extrapolated dashed line, the relatively smaller conductivity values at higher altitudes demonstrate additional ion loss (two-body) and/or less mobile ions.[8]

Variations in electrical conductivity are observed to be significant even under quiescent conditons. Latitude and solar cycle effects on conductivity largely reflect the dependence of this parameter on galactic cosmic ray ionization. Positive conductivity is also dependent on temperature, particularly in the 45-55 km region where its temperature coefficient is nominally 4%/°K.[26] A value of this size, which is primarily thought to be an ion mobility effect, has been interpreted as indicating the presence of immobile charged particulates, possibly ice crystals.

One of the more variable periods at midlatitude occurs during sunrise when overall positive conductivity enhancements of an order of magnitude have been observed at some altitudes (Fig. 4).[11] The four profiles for different solar zenith angles (χ) represent early morning conductivity data obtained either by a blunt probe (1971 flights) or a Gerdien condenser (1975 flights). Although the measurements occurred over approximately a four-year period, the general agreement in the data at 30 km indicates relatively small changes resulting from possible variations in galactic cosmic ray ionization. Above 60 km, the increases in conductivity during sunrise demonstrate the expected ionization effects associated with solar ultraviolet radiation. Interestingly, the large solar-dependent buildup in conductivity between 30 and 60 km is mostly at altitudes too low for ionization by solar ultraviolet radiation to be significant. Furthermore, the source for positive ions—galactic cosmic ray ionization—appears relatively constant, even over this four-year measurement period.

The positive ion mobility and number density data for the two Gerdien condenser flights are shown in Figs. 5 and 6, respectively. For altitudes at which two distinct ion mobility groups were measured on Sept. 26, 1975, the shaded circles represent the less mobile species. The dashed line in Fig. 5 indicates the Gerdien condenser's measurement sensitivity which is the possible upper limit for ion mobility values in this region. Although there is some spread in the measurements, the ion mobility values for Sept. 26, 1975, are relatively smaller than those of July 15, 1975, while the ion density values for the two days are generally comparable. Thus, the buildup in conductivity as the solar zenith angle changes from 90 to 75 deg largely results from an increase in ion mobility. This is thought to suggest the presence of a sunrise photodissociation process resulting in the formation of smaller, more mobile ions. Since the blunt probes measure only conductivity, the extent to which the further conductivity buildup continues to be a mobility effect is undetermined. Actually, a more conclusive study involving Gerdien condenser flights over a much shorter measurement period is needed to better understand the sunrise processes.

Table 1 Recent atmospheric studies using Gerdien condensers and blunt probes

Program	Launch site (coordinates)	Launch period	Launch vehicles
Sunrise measurements	White Sands Missile Range, N. Mex. (32°N, 106°W)	July and Aug. 1975	Rockets
D-region winter ionization variability	Wallops Island, Va. (38°N, 75°W)	Jan. 1976	Rockets
High-latitude auroral energetics (Aurorozone I)	Poker Flat Research Range, Alaska (65°N, 147°W)	Sept. 1976	Rockets
Stratospheric variability (Stratcom VII)	Holloman Air Force Base, N. Mex. (33°N, 106°W)	Sept. 1976	Balloon and rocket
D-region winter ionization variability	Wallops Island, Va. (38°N, 75°W)	Jan. 1977	Rockets
High-latitude measurements	Poker Flat Research Range, Alaska (65°N, 147°W)	June 1977	Rockets
Stratospheric variability (Stratcom VIII)	Holloman Air Force Base, N. Mex. (33°N, 106°W)	Sept. 1977	Balloon and rocket
High-latitude auroral energetics (Aurorozone II)	Poker Flat Research Range, Alaska (65°N, 147°W)	March 1978	Rockets
Solar eclipse	Red Lake, Ontario, Canada (51°N, 94°W)	Feb. 1979	Rockets
Sunrise measurements	Wallops Island, Va. (38°N, 75°W)	Sept. 1979	Rockets
Solar eclipse	San Marco Range, Kenya (3°S, 40°E)	Feb. 1980	Rockets
Middle-atmosphere electrodynamics	Andoya Rocket Range, Norway (69°N, 16°E)	Oct. 1980	Rockets

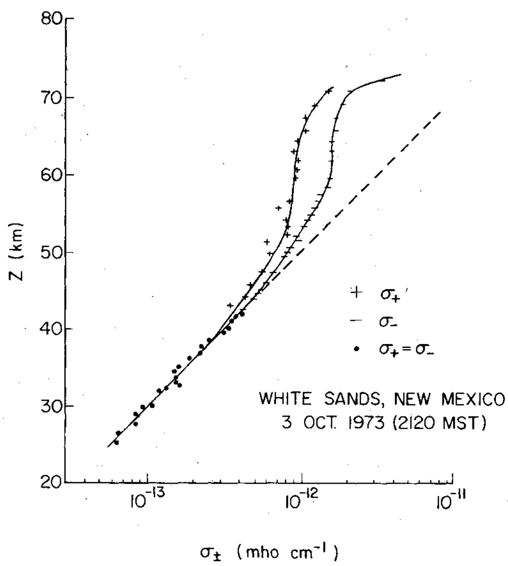

Fig. 3 Nighttime electrical conductivity measurements.

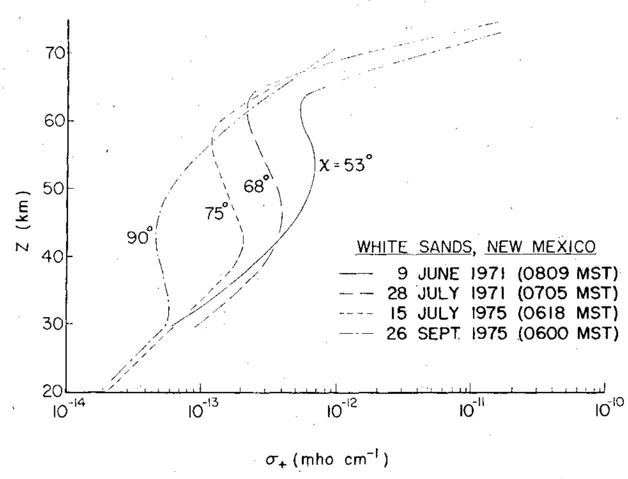

Fig. 4 Early morning profiles of positive electrical conductivity.

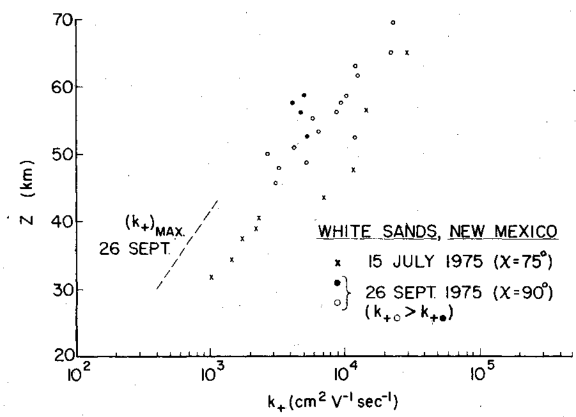

Fig. 5 Positive ion mobility measurements during sunrise.

Finally, support for the sunrise observations comes from data obtained by Gerdien condensers operating in conjunction with ultraviolet sources which measured appreciable enhancements in both stratospheric ion mobility and density when the lamps were radiating.[28]

Electrical Parameters at High Latitudes

Middle-atmosphere electrical parameters at high latitudes are strongly affected by auroral energy deposition in the region. Two coordinated rocket programs—Aurorozone I (September 1976) and Aurorozone II (March 1978)—were conducted at Poker Flat, Alaska to measure both the high-latitude auroral ionization sources and the resulting atmospheric electrical responses. The Gerdien condenser and blunt probe flights mostly occurred during periods of auroral activity.

Representative positive nighttime conductivity measurements for high-latitude, geomagnetically disturbed conditions are shown in Fig. 7. The straight-line fit to the data at lower altitudes shows the height dependence in the region where ionization is primarily by galactic cosmic rays. The solid straight line fitted to the data at higher altitudes demonstrates the enhancements in conductivity above the extrapolated galactic cosmic ray background level (shown by the dashed line). In contrast to the midlatitude nighttime measurements (Fig. 3), the curve for these conductivity values breaks to the

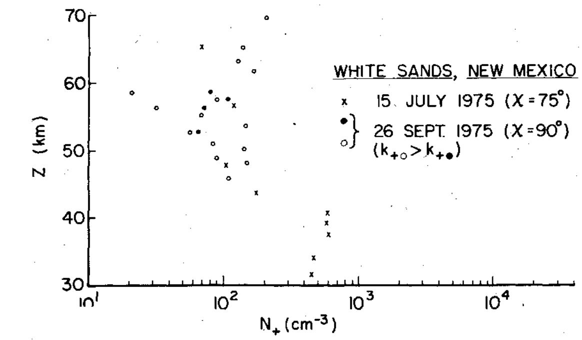

Fig. 6 Positive ion number density measurements during sunrise.

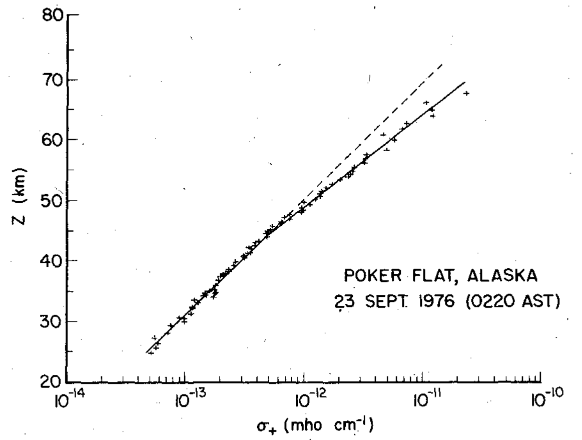

Fig. 7 Positive electrical conductivity measurements during an aurorally active period.

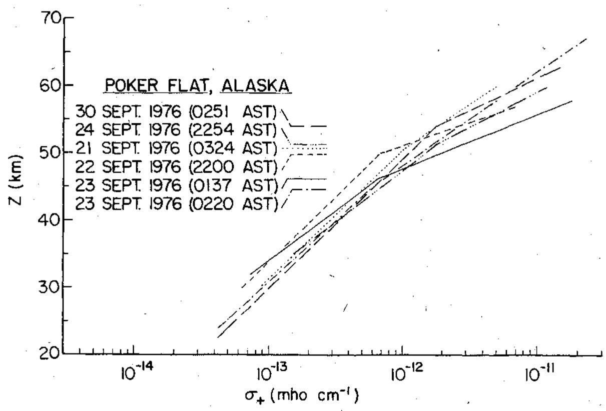

Fig. 8 Piecewise linear profiles of electrical conductivity from the Aurorozone I program.

right of the dashed line which would suggest increased ionization levels at the higher altitudes. The breakpoint for the resulting piecewise linear fit to the data thus indicates the altitude down to which auroral ionization effects are directly observed on conductivity.

In comparing these measurements with corresponding energy deposition data from another rocket flight, the conductivity enhancements appear to result from two auroral ionization sources. Specifically, for the measurement period on Sept. 23, 1976, bremsstrahlung x-rays are the dominant ionization source in the 40-55 km region while energetic electrons primarily of a 100 keV level were measured at the higher altitudes.[29]

The general characteristics described for the conductivity data in Fig. 7 were observed for all of the flights in the Aurorozone I program. A composite of the piecewise linear fits, constructed to the different data sets, is shown in Fig. 8.

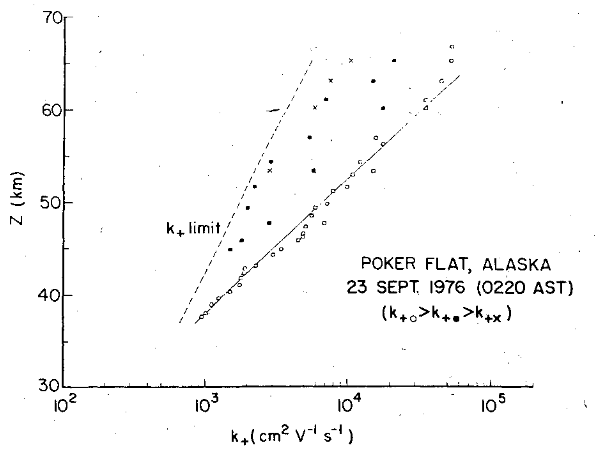

Fig. 9 Positive ion mobility measurements during an aurorally active period.

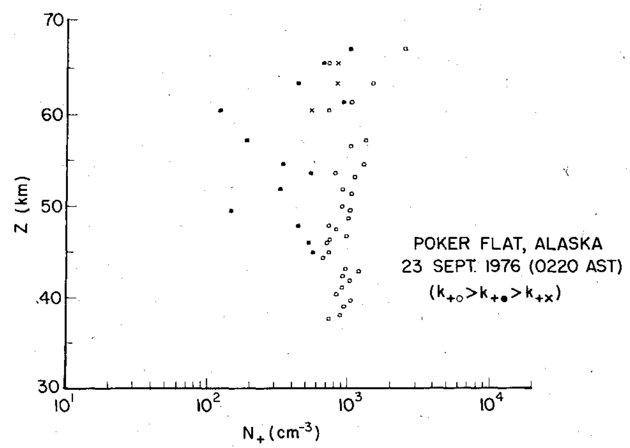

Fig. 10 Positive ion number density measurements during an aurorally active period.

The two Gerdien condenser launches occurred during auroral break-ups (0324 AST on Sept. 21, 1976, and 0220 AST on Sept. 23, 1976). The legend for the figure identifies the ionization breakpoint altitudes for the respective flights. It is observed that the height of the breakpoint is associated with the degree of auroral activity; for example, the measurement period of Sept. 21, 1976, was generally not as active as those for Sept. 22-23, 1976. This observation is consistent with available x-ray energy deposition data. During the night of Sept. 22-23, 1976, the ionization breakpoint altitude progressively dropped during the three-launch sequence suggesting a continual penetration of auroral ionization during this period. The presence of an ionization breakpoint for the Sept. 30, 1976 flight indicates the existence of auroral energetic effects even during a period which from ground-based techniques appeared to be geomagnetically quiet.

The spread in the conductivity values above their breakpoint altitudes reflects the temporal and spatial variabilities associated with auroral ionization processes. Interestingly, there is also variability in the conductivity values at lower altitudes where measured auroral ionization is relatively insignificant. Although it does not necessarily correspond to the conductivity variability at higher altitudes, this low-altitude response possibly indicates a form of electrical coupling with auroral effects at the higher altitudes.

The positive ion mobility and number density data for the Gerdien condenser launched at 0220 AST on Sept. 23, 1976, during an auroral break-up are plotted in Figs. 9 and 10, respectively. The solid straight line in Fig. 9 identifies the highest-valued ion mobility group which is observed over the complete measurement altitude region. The dashed line in-

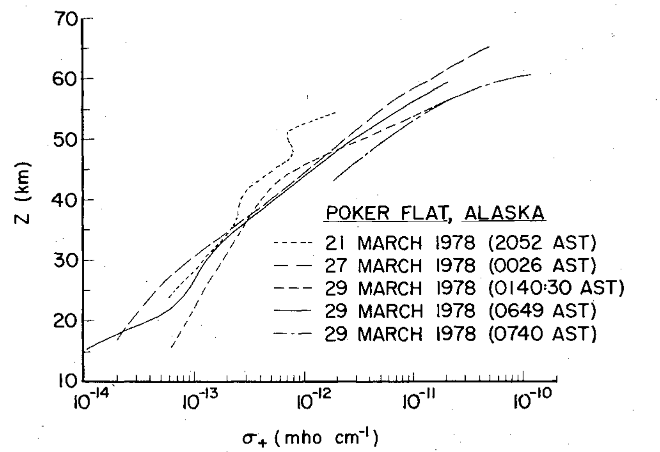

Fig. 11 Positive electrical conductivity profiles from the Aurorozone II program.

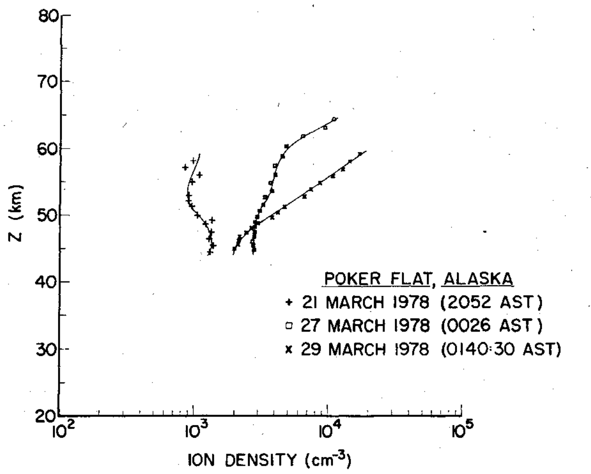

Fig. 12 Total light positive ion density measurements from the Aurorozone II program.

dicates the Gerdien condenser's measurement sensitivity. The presence of one, and sometimes two, less mobile ion groups at the higher altitudes corresponds to the region where auroral-associated conductivity enhancements occur. The number density values (Fig. 10) of these less mobile groups are relatively smaller than for the high-mobility group, which has a concentration of typically 10^3 cm^{-3}. The other Gerdien condenser flight in the Aurorozone I program occurred under similar geomagnetic conditions (0324 AST on Sept. 21, 1976) and provided consistent measurement results. If the conductivity values for the less mobile ion groups are computed, it is observed that they account for the high-altitude conductivity enhancements associated with the auroral energetics. Thus, it appears that the auroral ionization sources not only cause an enhancement in ion density, but they also possibly influence the formation of new ion species. Confirmation of this observation requires further electrical parameter measurements particularly under geomagnetically quiet conditions.

The Gerdien condensers in the March 1978 Aurorozone II program were flown as part of an integrated instrument package which also included x-ray detectors, guard counters for measuring energetic electrons,[29] and vertical electric field probes.[21] The multiexperiment sensor approach reduces spatial and temporal measurement differences which appear to be significant when investigating auroral phenomena. Profiles of positive electrical conductivity measured by the Gerdien condensers are shown in Fig. 11. The launch on March 21, 1978, followed a three-day, geomagnetically quiet period while the other flights occurred during aurorally active periods.

A wavelike structure—possibly a mobility effect—is observed at higher altitudes in the conductivity data of March 21, 1978; however, the relatively smaller values demonstrate an expected ionization drop in the region. The other four conductivity profiles show auroral ionization enhancements and variability at the higher altitudes. Again, conductivity variations are observed in the lower altitude region (20-35 km) where measured auroral energy deposition is relatively insignificant.

The auroral ionization characteristics for the two nighttime launches are quite different, as are the conductivity values. The conditions for March 27, 1978, correspond to those observed in Sept. 1976; namely, bremsstrahlung x-ray ionization dominated between approximately 40 and 60 km while energy deposition from energetic electrons was important at higher altitudes. The nighttime launch on March 29, 1978, however, occurred while a relativistic electron precipitation (REP) event was in progress.[30] The larger energy deposition levels and corresponding conductivity values result from ionization by relativistic electrons which dominated over the measurement region down to approximately 40 km. The energy deposition component associated with bremsstrahlung x-rays was relatively insignificant during this event.

The two daytime measurements for March 29, 1978, demonstrate the general dominance of auroral ionization effects on conductivity as compared to possible diurnal variations. Some indication of a possible early morning buildup in positive conductivity, however, is observed in the data for 0740 AST.

Because of poor signal-to-noise characteristics for the March 1978 Gerdien condenser data, it was only possible to determine the total light ion density values which are plotted for the three nighttime flights in Fig. 12. The positive ion densities associated with the galactic cosmic ray ionization background level are typically $1\text{-}2 \times 10^3$ cm^{-3} as indicated by the measurements on March 21, 1978. These values are thus consistent with the Aurorozone I high-mobility ion concentrations (Fig. 10) which account for the high-altitude, extrapolated conductivity values (Fig. 7) thought to be associated with galactic cosmic ray ionization. For the other two flights, enhanced ion densities exceeding 10^4 cm^{-3} result from auroral energy deposition at the higher altitudes. The ionization effects associated with the REP event are particularly evident above 50 km as demonstrated by the relatively large ion density values and the noticed gradient in density with altitude.

Conclusions

Subsonically flown Gerdien condensers and blunt probes are useful for investigating electrical properties of the middle atmosphere. Theoretical and experimental developments relevant to these probe systems have gone beyond improving the data accuracy to also expanding the sensors' measurement capabilities and influencing future probe designs.

Significant variability in electrical parameters is measured at midlatitude as well as in the auroral region. A sunrise positive conductivity buildup demonstrates a form of solar control on electrical structure at lower altitudes where solar ultraviolet ionization is relatively insignificant. Corresponding ion mobility data possibly indicate a photodissociation process resulting in the formation of relatively smaller, more mobile ions. At high latitudes, enhanced electrical conductivities and associated variabilities are observed in the region of auroral energy deposition. The auroral ionization sources cause increases in ion density and also appear to possibly influence the formation of new ion species.

These measurement results demonstrate that middle-atmosphere electrical parameters can be highly variable, both in response to ionization source perturbations and, for certain conditions, in regions where ionization sources are relatively constant.

Acknowledgments

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