Measurement of Negative Ions in the Lower Ionosphere (*D*-Layer) in the Polar Region

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Results of measurements of the negative ion density and its ratio to the positive ion density in the lower ionosphere (*D*-layer) of the polar region (Andøya) are presented. A comparison is made with previous data in mid-latitude region (KSC), which were obtained by a same instrument. It has been found that the negative ion-dominant region in the *D*-layer is compressed toward lower altitudes in the polar region than that in the mid-latitude by about 16 km. Some mechanisms for this and its relation to the ozone distribution are discussed.

1. Introduction

Several results have been reported on the observation of the *D*-layer in polar regions (Arnold and Krankowsky, 1971; Arnold *et al.*, 1971; Narcisi *et al.*, 1971; Viggiano *et al.*, 1982), in mid-latitude regions (Widdel *et al.*, 1971, 1976; Rose and Widdel, 1972), and in the equatorial region (Sampath *et al.*, 1992). Other observations have been made in the solar proton event (Swider and Kaneshea, 1978), in PCA (Swider and Narcisi, 1975), in the eclipse (Narcisi *et al.*, 1983; Conley *et al.*, 1983; Swider and Narcisi, 1983; Swider, 1988) and at mesopause (Gangly, 1984). In Japan, observations are made by using a Gerdien condenser, which confirmed the existence of negative ions (Takagi *et al.*, 1980). In our previous observation of the *E* region by a Langmuir probe (Amemiya *et al.*, 1985), there was a little trace of negative ions in the second derivative of the probe characteristics at lower regions but data were not accurately taken below 80 km. Our recent experiment in Japan by using a Faraday cup (Amemiya and Nakamura, 1993) showed that the negative ion-layer extended from about 60 km toward the height near 90 km. The upper boundary was higher than that in the polar region.

Distinct differences of the *D*-layer from *E*- and *F*-layers are the existence of negative ions due to frequent ion chemical reactions. There are reactions by which negative ions create and conserve ozone. A recent report gives an estimation to satisfy such a condition (Milkhi and Duncan, 1990). Another paper suggests a correlation between negative ions and ozone (Chakrabarty and Gangly, 1989). Therefore, the *D*-layer is considered to be important from environmental point of view since it is adjacent to the ozone layer.

The aim of the present paper is to present the results of our recent measurements on the density of negative ions and their charge density ratio in the *D*-layer in a polar region (Andøya) and compare them with previous data taken in different latitudes. The mechanism of the *D*-layer structure will be discussed. The creation and conservation of ozone in relation to negative ions will also be considered.

2. Experiment

The measurement has been made by using a set of two sensors, a Faraday cup and a Langmuir probe, on board Japanese rockets of the Institute of Space and Astronautical Science (ISAS). A rocket S-310-22 was launched on Feb. 16, 7h52m (UT), 1994, at Andøya in Norway (69.30°N, 16.05°E).

Fig. 1. Height h vs. range r of the rocket S-310-22. Arrows show the position of nose-cone opening (NC), Faraday cup deploy (FC) and the gain change (GC).

The rocket was launched in the northwest direction just after the local sunrise. The solar zenith angle was $\chi = 89^\circ$. The observation was made during the quiet solar period. The geomagnetism during and just before the observation was calm. Little optical interference due to auroral emission was expected. However, in the previous night, there were auroral storms, and the amplitude of the disturbance in geomagnetic horizontal component exceeded several hundred nT. The auroral storms occurred every night during two weeks before the launching day, although little auroral displays were seen on the ground due to bad weather.

The method for measuring negative ions is similar to that of S-310-20 rocket (Amemiya and Nakamura, 1993) which was launched on Jan. 28, 4h30m (JST), 1990, at Kagoshima Space Center (KSC) in Uchinoura (31.15°N , 131.08°E).

Figure 1 shows the relation of the height h vs. range r of the S-310-22 rocket. NC, FC and GC denote the nose-cone off, deploy of the Faraday cup and the gain change at the E -layer, respectively. The apogee was 192 km at 216 s after the launching.

The measurement condition is as follows. At 45 s from the launching, the nose-cone was opened. After 2 s from the opening of the nose-cone, at 47 s, the Faraday cup was deployed to the perpendicular direction with respect to the rocket body. Because the D -layer has low plasma densities and negatively charged particles are massive, the current in the D -layer is much lower than that in the E - and F -layers. In order to cover the large current range, the gain of the Faraday cup was made high up to about 90 km (67 s). The gain was decreased to 1/100 in the E -layer. In each mode (D - and E -layer modes), the measurement was made by three relative gains, 1, 10, 10^2 .

The Faraday cup consisted of a grid and a collector, both of which were mounted within an electrically floated housing. The surface of the cup was made parallel to the flight vector. In this way, the influence of the plasma flow on the current collection was avoided as much as possible. Positive and negative voltages were given alternately to the electrodes with a time interval of 0.2 s and the saturated currents at both biasings were measured as a function of height. From the currents at both biasings and the current ratio, negative and positive ion densities N_- and N_+ were calculated through the comparison of the current ratio with that at $h = 100$ km in the E -layer at which it was assumed that the density of negative ions was almost zero.

3. Results

Details on the method of data analysis, including effective masses of positive and negative ions vs. height and the effect of the angle against the flight velocity, were given previously (Amemiya and Nakamura, 1993). For the data analysis, it was shown there that the effective mass number M_{eff} of positive ions is important, where $M_{\text{eff}}^{-1} = \sum_j \{\beta_j / M_j^{1/2}\}^2$; β_j is the content ratio of each ion. M_{eff} was obtained by collecting existing data (e.g. Aikin *et al.*, 1977, at Michigan 47.4°N, $\chi = 67^\circ$ in Jan. 1971; Swider and Narcisi, 1975, at Fort Churchill 58°N, $\chi > 90^\circ$ in Nov. 1969). At $h \leq 90$ km, hydrates ions $\text{H}^+(\text{H}_2\text{O})_n$, $n = 1, 2, 3$, are dominant positive ions. Above $h > 90$ km, NO^+ and O_2^+ are dominant positive ions. M_{eff} in the above two cases little differ and was commonly applied to the data of KSC and Andøya. Therefore, a fitting was made to M_{eff} as $M_{\text{eff}} = 42 - 11(h - 60)/20$ for $h \leq 80$ km and $M_{\text{eff}} = 31$ for $80 \text{ km} \leq h < 90$ km.

Figure 2 shows the ion current I_+ at the negative bias and the ratio R of the current I_e at positive bias to I_+ ($R = I_e/I_+$) vs. height h . The best fitted curve is drawn for R while a curve for making it easy to see the data is drawn for I_+ . The notation of R here is different from that of the previous paper (Amemiya and Nakamura, 1993) in that the current at positive bias is essentially contributed by electrons and the contribution of negative ions is negligible. The figure shows roughly the E -layer peak at about 100 km. Below this height, the current decreases with decreasing height h . It is seen that R , in spite of scattering, increases with h toward the E -layer at about 97 km, where the existence of negative ions is considered to be almost negligible. The decreasing feature of R with decreasing h indicates the existence of negative ions at lower height $h < 70$ km. The up-leg data where the data were saturated due to a high gain were replaced by data at down-leg. There was a slight difference between the up-leg and down-leg, but it was not large. Unfortunately, due to the setting of the gain too high, the current at the positive bias became too large and saturated above 74 km and R could not be obtained this time.

Figure 3 shows the positive ion density N_+ vs. height h . The positive ion density N_+ is calibrated with

Fig. 2. Positive ion current I_+ (open squares and circles) at negative bias and the ratio R (filled squares and circles) of the currents at positive and negative biases vs. height h . Squares denote upleg data, while circles denote downleg data.

Fig. 3. Positive ion density N_+ and the electron density N_e against the height h . Open squares denote upleg data, while open circles denote downleg data of N_+ . Solid squares denote N_e by impedance probe, while open triangles denote $N_e = N_+ - N_-$ by Faraday cup.

Fig. 4. Negative ion density N_- measured by S-310-20 and S-310-22 rockets at mid-latitude and polar regions, respectively. Open squares denote upleg data, while open circles denote downleg data of the S-310-22 rocket. Solid circles denote data of the S-310-20 rocket.

the electron density N_e obtained by an impedance probe (Ono, private communication, 1994) on board the same rocket at $h = 100$ km, above which it is assumed that the plasma is free from negative ions. The profile of N_+ vs. h reflects structures of E -layer around 100 km. This is followed by the E - F valley around 140 km and the F -layer above about 170 km. N_e obtained by the impedance probe is plotted together for $h < 100$ km. Since N_e by the impedance probe was obtained only above $h = 74$ km, N_e was calculated from the difference $N_+ - N_-$ obtained by the Faraday cup. Below $h < 60$ km, the difference between N_+ and N_e becomes remarkable.

Fig. 5. Negative ion density ratio $\alpha = N_-/N_+$ against height h . Open squares denote upleg data, while open circles denote downleg data of the S-310-22 rocket. Solid circles denote data of the S-310-20 rocket. Curves show models for *D*-region (Spjeldvik and Throne, 1975, $L = 4$, $\Lambda = 60^\circ$) where S and Q stand for storm and quiet night time.

Figure 4 shows the negative ion densities N_- measured by S-310-20 and S-310-22 rockets at the mid-latitude (KSC) and at polar region (Andøya). Arrows indicate the upper limit of the negative ion layer in the *D*-layer in both polar and mid-latitude regions, 74 km and 90 km, respectively. There is a difference of height of about 16 km.

Figure 5 shows the ratio α of negative ion density N_- to positive ion density N_+ ($\alpha = N_-/N_+$) in comparison with that by S-310-20 rocket. It is seen that α decreases with h in both polar and mid-latitude regions, but the maximum height of the negative ion layer is lower in the polar region by about 16 km. Curves indicate the results of modelling (Spjeldvik and Throne, 1975) in *D*-region of mid-latitude at quiet (Q) and storm (S) times at night. It was expected that the model at a high solar activity would correspond roughly to the *D*-layer in the polar region. The case of S-310-22 (Andøya) is nearer to the model at storm time. However, the comparison here is only for the reference, since the modelling at polar region is lacking. In the figure, a model for day is also shown for comparison.

The negative ion ratio α is evaluated through the relation between the saturation current ratio R and α , which depend on the effective mass M_{+eff} of positive ions. M_{+eff} used here for $h < 90$ km is obtained from the data at Michigan for normal *D*-region (47.4°N , $\chi = 67^\circ$) (Aikin *et al.*, 1977) and at Fort Churchill for PCA event (58°N , $\chi > 90^\circ$) (Swider and Narcisi, 1975). In the *D*-region for $60 \text{ km} \leq h \leq 80 \text{ km}$, positive ions consists mainly of $\text{H}^+(\text{H}_2\text{O})_n$; $n = 1, 2, 3$ and for $h > 80 \text{ km}$ water clusters diminish and O_2^+ and NO^+ appear as dominant ions. The above two data coincide rather well, although the condition is different. In the present data analysis, it is assumed that the distribution of M_{+eff} vs. h follows this normal condition.

However, it is known that M_{+eff} behaves differently under some special conditions. As for M_{+eff} at mid-latitudes, in the 1979-eclipse case (Swider and Narcisi, 1983), $\text{H}^+(\text{H}_2\text{O})_n$ with $n = 2, 3, 4$ have higher contents than $\text{H}^+(\text{H}_2\text{O})$, which increases M_{+eff} at $h = 70\text{--}80 \text{ km}$ by a maximum factor of about 30%. This increases N_- and α by 14% there. In the case of including the tidal effect (Forbes, 1981) for the ion chemistry for the daytime *D*-region, $\text{H}^+(\text{H}_2\text{O})_n$ and $\text{NO}^+(\text{H}_2\text{O})_n$ with high values of n dominate at lower regions. M_{+eff} increases at lower heights of $h < 80 \text{ km}$: from the normal value of 31 at $h = 85 \text{ km}$ to about

68 at $h = 70$ km. For such M_{eff} , N_- and α would be higher at lower altitudes of $h < 80$ km by 33% to 18%. As for M_{eff} in polar regions, the cold summer is a special case (Reid, 1989), where in correlation to icy clouds $\text{H}^+(\text{H}_2\text{O})_n$ with $n \geq 4$ dominates at $h = 80\text{--}90$ km while $\text{H}^+(\text{H}_2\text{O})_n$ with $n = 2, 3$ dominates at $h < 80$ km. The temperature of the polar mesosphere varies quite largely in seasons: below 160 K in summer and above 230 K in winter. Through three-body reactions, the formation of $\text{H}^+(\text{H}_2\text{O})_n$ are controlled by temperatures. The negative ion layer in the D -region would extend to 90 km as in the mid-latitude region if the existence of such heavy water cluster ions is assumed at $73 \text{ km} < h < 90 \text{ km}$. However, super heavy clusters in winter season may be excluded. Then, our finding of the difference of the saturation current ratio R between mid-latitude and polar regions suggests that the negative ion layer is compressed toward lower altitudes if M_{eff} follows the normal height distribution.

4. Discussion

4.1 Difference of D -layer between mid-latitude and polar regions

Figure 6 summarizes the negative ion density N_- in polar, mid-latitude and equatorial regions and in some special cases. Namely,

Polar region;

Andøya '70 (Arnold and Krankowsky, 1971, 69°N , 23:58 LT, $\chi > 90^\circ$ in March 1970),

S-310-22(Andøya) 7:52 LT, $\chi = 89^\circ$ in Feb. 1994,

Mid-latitude regions;

T-K-I (at Kagoshima by Takagi *et al.*, 1980, 31.15°N , sunset $\chi \sim 90^\circ$ in Jan. 1979,

Sardinia (Rose and Widdel, 1972, 39.45°N , 12:24 UT in May 1968),

S-310-20 (KSC) 31.15°N , 4:35 LT, $\chi > 105^\circ$ in Jan. 1990,

Fig. 6. Negative ion density N_- in polar region "Andøya '70" (March 1970 at Andøya by Arnold *et al.*, 1971), mid-latitude regions "T-K-I" (Jan. 1979 at KSC by Takagi *et al.*, 1980; "Sardinia" (May 1968 at Sardinia by Rose and Widdel, 1972) and an equatorial region "Thumba" (Nov. 1988 at Trivandrum in India by Sampath *et al.*, 1993) and N_- in solar active times "SPE '69" (Nov. 1969 at Fort Churchill by Swider and Kaneshia, 1978) and "Eclipse '79" (Feb. 1979 at Red Lake by Swider and Narcisi, 1983) together with the data by "S-310-20" (Jan. 1990 at KSC) at mid-latitude and the data by "S-310-22" (Feb. 1994 at Andøya) in polar region.

Equatorial region;

Thumba (Sampath *et al.*, 1992, 8.5°N, 8:40 LT, $\chi = 59.4^\circ$ in Nov. 1988),

Solar active times;

SPE '69 (Swider and Narcisi, 1975; Swider, 1978; Swider and Kaneshia, 1978; Swider, 1988, Fort Churchill, 58°N, 6:05 UT, $\chi \sim 90^\circ$ in Nov. 1969),

Eclipse '79 (Narcisi *et al.*, 1983, Red Lake, 51°N, 11:41 CST, $\chi = 61^\circ$ in Feb. 1979).

It is seen that the negative ion density N_- in polar region decreases remarkably at higher altitudes above 75 km, while N_- in mid-latitude and equatorial regions extends toward 90 km.

The mechanism of causing a difference of height of the negative ion-layer between polar and non-polar regions may depend on if the region is inside or the outside of the aurora oval or not. Inside it, the precipitation of higher energetic particles are probably predominant at higher altitudes. As shown in Fig. 6 when a solar proton event (SPE) and when an eclipse event with the precipitation of higher energetic particles, the *D*-region's plasma density is enhanced much by the precipitation. There is a large difference of N_- by a factor of 10^2 between quiet and active times. However, the effect does not last for a long time and the effect is stressed only in the lower altitudes than 75 km. Our measurement has been made at a quiet time and indicates that N_- of the polar region decreases remarkably above 80 km.

Important chemical reactions on negative ions in the *D*-region may be considered to be (Arnold and Krankowsky, 1971; Thomas *et al.*, 1973; Ferguson, 1974; Massey, 1976; Tohmatsu, 1990)

where k_i are rate constants h.e. denotes high energy and Y^+ denote various ion species. Processes (1) to (6) can be considered to be effective at lower altitudes. O_2^- generated by the three-body attachment by (1) is lost by (2) to (6). (3) is the reverse reaction to (1) but is less frequent than it. Reactions (4) and (5) generate

negative ions by charge transfer and therefore does not lead to a loss of N_- . Only (6) is the loss by recombination. (2) is a loss of negative charge but beneficial to generate O_3 , as later appears again. These processes favor to increase N_- at lower altitudes. On the other hand, at higher altitudes of the polar region, high energetic electrons create O^- by dissociative attachment through the process (7). However, O^- is lost by (8) by O whose density is larger at higher altitudes. The destruction of negative ions is made also by photons, as can be seen from (9) and (10), besides electrons by (11).

An important processes to explain the deficiency of negative ions in the polar region are the reaction (11). Namely, the rate of reaction (1) for O_2^- , which constitutes the major negative ion from which other heavier negative ions are created, can be smaller due to smaller N_e in the polar region, while the rate of reaction (11) which destroy O_2^- increases due to the higher flux of energetic electrons.

As another reason, the recombination process in the polar region would be prompted by charged fine particles (dust) since the dust is likely to gather into the polar region. Rate equations can be written by modifying the previous relations (Pathasarathy and Rai, 1966) as

$$dN_e/dt = q - \beta_e N_e - \alpha_e N_e N_+ + q_D N_- + p_h N_- - D_e N_e + q_h, \quad (12)$$

$$dN_-/dt = \beta_e N_e - \alpha_- N_- N_+ - q_D N_- - p_h N_- - D_- N_-, \quad (13)$$

where q is the ionization rate, α the recombination coefficient, β the attachment rate, D the rate of attachment to dust, e , $-$ and $+$ standing for electron, negative ion and positive ion, respectively, p_h the photodetachment rate, q_D the destruction rate of negative ions and q_h the production rate of electrons by energetic particles. In the polar region, q_h and q_D must be higher, and this increases N_e but decreases N_- . The effect of p_h is negligible in the polar region of measured time. On the other hand, in mid-latitude and equatorial regions, the effects of q_h and q_D are not so high.

Equating the right hand sides of Eqs. (12) and (13) to be zero in the steady state by assuming the charge neutrality, $N_+ = N_e + N_-$, we obtain the effective recombination coefficient for electrons α_{eff} formally as

$$\alpha_{\text{eff}} = (q + q_h) / N_e^2 = (1 + \lambda)(\alpha_e + \lambda \alpha_-) + (D_e + \lambda D_-) / N_e, \quad (14)$$

where $\lambda = N_-/N_e$. It is assumed that the temporal variation of λ is slow compared with the decay time by recombination. The coefficient α_{eff} increases from α_e with increasing λ , D_e and D_- . It is seen that α_{eff} is independent of p_h and q_D . In the polar region where the dust density is high, the rapid loss of N_e occurs. This should reduce the attachment rate $\beta_e N_e$ and decrease N_- . Addition of Eqs. (12) and (13) gives an equation for positive ion density N_+ . Since the dust is floating, the total current to it is zero: $D_e N_e + D_- N_- = D_+ N_+$. From $D_e + \lambda D_- = D_+ N_+/N_e$, α_{eff} increases with N_+ .

Fine particles such as NLC (noctilucent cloud) may be considered to be a kind of dust in the mesosphere. In the polar region, PMC (polar mesospheric cloud) is considered to be the counterpart of NLC (cf. Reid, 1989 and references cited therein). However, since NLC and PMC appear only in summer, other fine particles such as aerosols and those from meteoric origins etc. should be taken into account.

4.2 Relation of negative ion density to the ozone density

The one of the objectives of the present observation in the arctic region was to prove the effect of NO created by high energetic particles at $h > 90$ km in the polar region (Iwagami *et al.*, 1994). In the winter time of arctic region, NO cannot be dissociated by solar light and falls down to the ozone layer (Solomon and Garcia, 1984) and destroy ozone there. This could be an important mechanism for the destruction of ozone in the polar region. The more importance of the precipitation of high energetic particles than solar Lyman α radiation in polar region is known (cf. Reid, 1989 and references cited therein).

In the lower ionosphere, N_e and N_- are anti-correlated in the diurnal variations (Kaneshea *et al.*, 1970). The variations of N_e and the density of O behave similarly and also those of N_- and the density of O_3 behave

similarly (Rodrigo *et al.*, 1986). In the eclipse time, the density of O_3 increases (Agashe and Rathi, 1982), but N_e decreases due to the interruption of photodetachment from negative ions. Therefore, it can be considered qualitatively that negative ions contribute to the production and protection of O_3 while electrons have the opposite effect. These can be inferred from the following production reactions of ozone (Ferguson, 1974; Massey, 1976; Brasseur and De Baets, 1986; Chamberlain and Hunten, 1987)

where M is a third body, and destruction reactions of ozone

If only reactions (2) and (4) with large rate constants are assumed, the ozone creation prevails over the loss when the densities of O and O₃, $N(\text{O})$ and $N(\text{O}_3)$, satisfy the relation $k_2 N(\text{O}) > 1.3 k_4 N(\text{O}_3)$, as suggested recently (Milikh and Duncan, 1990). This condition is filled in mid-latitude regions above 76 km. On the other hand, the dip of ozone density which appears around 76–78 km measured at Pocker Flat, Alaska, before sunrise (Green *et al.*, 1986) coincides rather well with the upper end height of the negative ion layer in the D-region at Andøya. The ozone density measured by Rikkyo University group by a sensor on board the same rocket has indicated a clear depletion of ozone density around 78 km (Iwagami *et al.*, 1994). These facts would be related to the situation inside open geomagnetic field where high energetic electrons are rich while negative ions are deficient. In such a situation, the reactions (2), (15)–(23), which favor the ozone protection, are not effective but the reactions (4), (24)–(30) which proceed the ozone destruction can be applied.

It has been shown recently (Wong *et al.*, 1992, 1994) that the input of electric charge into plasma is effective to relax the catalytic action of Cl from CFC by transforming it to Cl⁻. A trace of negative chlorine ions (Cl⁻) in the D-region (Arnold *et al.*, 1971; Narcisi *et al.*, 1971) was seen in the lower D-layer. This would not destroy O₃ there.

5. Conclusion

The result of recent observation of the D-layer has been shown and compared with previous data in typical regions on the earth. It has been found that in the polar region the negative ion region in the D-layer is compressed toward lower altitudes. The mechanism has been considered to be partly due to the precipitation of high energetic particles and the existence of dust. Discussion, though qualitatively, has been made on the relation of the density of negative ions with that of ozone there.

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