Characteristics of O^+ Density Depressions in the Topside Nighttime Ionosphere Revealed by ISS-b Satellite

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The O^+ density data resulting from the ISS-b ion mass spectrometer measurements have been analyzed to obtain the global distribution of the nighttime O^+ densities at a height of 1,100 km and its seasonal variations. The results of the analysis show the existence of distinct O^+ density depression regions in mid-latitudes in the winter hemisphere, two depressions in the northern hemisphere and one depression in the southern hemisphere.

The O^+ density depressions are coincident with the regions of large downward plasma flow identified by the calculation of the worldwide pattern of vertical plasma motion induced by the neutral winds. And the regions of high or low O^+ density are closely connected with the regions with westward or eastward declination of the geomagnetic field in the northern hemisphere, respectively, and vice versa in the southern hemisphere. In addition, the O^+ densities in the depression regions in winter season are maintained at rather low levels till just before the equinox, and increase rapidly to the level near the summer values just after the equinox.

1. Introduction

It is well known that the importance of the roles of neutral air winds and the geomagnetic field on the distribution of ionization in the ionosphere. EYFRIG (1963) showed from the bottom-side sounding data from several stations that the effect of the local geomagnetic field on the evening anomaly in f_0F_2 diurnal variations was important. KOHL and KING (1967) calculated the global pattern of the neutral wind system from Jacchia's atmospheric model and investigated the anomalous ionospheric phenomena such as the midday biteout in f_0F_2 and the maintenance of the nighttime ionosphere by considering the effects of the geomagnetic field declination and the neutral wind pattern.

More recently, many topside ionospheric electron and ion density measurements have been carried out by using satellites. TULUNAY (1973) showed that the observed electron density distribution in the mid-latitude ionosphere at a height of 550 km exhibited a characteristic pattern relating to the longitude and discussed the induced

effects of the horizontal winds on the electron density distributions. TAYLOR (1971) showed that the ion composition results obtained from the OGO-4 during 1967–68 revealed a pronounced longitudinal variation in the composition of the topside ionosphere, and indicated the seasonal asymmetries. TAYLOR *et al.* (1978) also investigated the signature of H^+ in the equatorial anomaly with particular emphasis on the details of the longitudinal variation by using the OGO-6 ion composition data. KÖHNLEIN (1981) studied the diurnal and seasonal variations of the ion and electron densities at a height of 1,400 km by using longitudinally averaged observations of the ISIS-2.

In spite of the above-mentioned research works, longitudinal variabilities of the ionosphere have not been fully investigated by satellite results until now owing to both the limitations in longitudinal resolution in data sampling and the uncertainty in the isolation of temporal versus longitudinal variations. On the contrary, operations of the Ionosphere Sounding Satellite-b (ISS-b) were planned so as to accomplish a worldwide mapping of ionospheric parameters with the aid of an on-board data recorder. Therefore, these data were available to obtain worldwide maps of ionospheric parameters for studying the global structure of the topside ionosphere with enough statistical accuracy.

The purpose of this paper is to show that the global distributions of the nighttime O^+ densities obtained from the ISS-b observations exhibit clearly the density depression in mid-latitudes, whose characteristics are dependent on the season and the longitude and that the neutral air wind pattern and the declination of the geomagnetic field play an important role in these phenomena. The study on the relationship between the O^+ depression regions and the neutral wind pattern serves for the better understanding of the physical mechanism of the mid-latitude ionospheric phenomena.

2. Satellite and Instrumentation

The ISS-b was launched on February 16, 1978 in order to observe worldwide distributions of ionospheric parameters and radio noises. Since April 1978, the ISS-b has been satisfactorily operated on a routine basis by the Radio Research Laboratories and it has furnished us a great deal of ionospheric data for more than four years.

The ISS-b has a nearly circular orbit of a height of about 1,100 km with an orbital period of 107 min, and with an inclination angle of 70° . The orbital inclination of 70° makes the orbital plane rotate westwards at a rate of 3° per day with respect to the sun-earth direction. The local solar time of the orbital point at a certain fixed latitude shifts backward at a rate of about 12 min per day. Therefore, it takes about four months to collect the data covering the worldwide area between $70^\circ N$ and $70^\circ S$ at all local solar times.

Two modes of the ISS-b operations, real time and recording observations can be attained by command operation. In the recording mode, the start of mission execution can be controlled by the command with a delay of 0, 2, 4 or 6 times the

preset revolution period (105 min). The delayed recording observation modes are executed so that the longitude of the equatorial crossing of the observational revolution can be distributed as widely and uniformly as possible.

A Bennett type of ion mass spectrometer is installed on the ISS-b to measure the ion species from 1 to 20 AMU in the density range of $10^1 - 10^5 \text{ cm}^{-3}$. The shape of the ISS-b spacecraft is a cylinder. Two identical units of the ion mass spectrometer sensors are used; one is mounted at the top-cover and the other at the bottom-cover of the spacecraft. These sensors are facing in opposite directions in order to assure a favorable ram condition for one of the sensors. Measurements by the two sensors are made alternately and eight mass spectra are obtained in 8 sec. The observations by the ion mass spectrometer are executed repeatedly with a period of 64 sec. The absolute calibration is made by equating the total ion number density to the electron density derived from resonance spikes in the topside sounder ionogram. More detailed information on the ISS-b and the ion mass spectrometer experiment can be found in the papers of WAKAI and MATUURA (1980), and IWAMOTO *et al.* (1977).

3. Observational Results

The ISS-b observations made by the recording mode can provide a data base sufficient to draw LT (local time) maps of ion densities. Here, the LT map means the map showing the global distribution of ion densities for fixed local times. LT-maps are constructed by using the spherical surface harmonic expansion method. The smoothed approximate functional representation of the global distribution of the ionospheric quantity is expressed in the form:

$$F(\lambda, \phi) = \sum_{m=0}^M \sum_{n=m}^N [A_{nm} P_n^m(\cos \theta^*) \cos m\phi + B_{nm} P_n^m(\cos \theta^*) \sin m\phi], \quad (1)$$

where λ and ϕ are the geographic latitude and longitude, respectively, $P_n^m(x)$ denotes the associated Legendre function of order n , rank m and argument x , A_{nm} and B_{nm} are the coefficients to be determined according to the observational data by a least squares method. θ^* is the modified colatitude introduced by JONES *et al.* (1969), and given by

$$\theta^* = \cot^{-1} \left[\frac{I(\lambda, \phi)}{\sqrt{\cos \lambda}} \right], \quad (2)$$

where I is the magnetic dip angle. In order to supplement the deficiency of the data points in both the northern and southern polar regions above 70° geographic latitude, the O⁺ densities in the polar regions are given by the extrapolation by Eq. (1). For the derivation of the LT-maps presented here, $N = 9$ (latitudinal) and $M = 2$ (longitudinal) are adopted.

Figure 1 shows the worldwide distribution of the O⁺ densities at local times

between 22 hr and 24 hr at a height of about 1,100 km. The observation period is for the northern winter from Oct. 5, 1978 to Mar. 19, 1979. The data were taken from measurements made in quiet and moderately disturbed magnetic conditions with K_p in the range 0–4₊. Numerical figures on the contour lines show $\log_{10} N_i$ (cm^{-3}). A contour interval is 0.2 in the density range of 10^2 – 10^4 cm^{-3} and it is 0.1 in the density greater than 10^4 cm^{-3} or smaller than 10^2 cm^{-3} . In Fig. 1 are also shown the contour lines of the dip latitudes, 0°, 30°, 50° and 70°, which are calculated from the dip angle of the IGRF-1975 geomagnetic field model at a height of 1,100 km. Figure 2 shows the O^+ density distribution for the northern summer period from Apr. 4, 1979 to Sep. 16, 1979.

It can be seen by these figures that the O^+ densities are higher in the summer hemisphere than in the winter hemisphere, the densities of the summer hemisphere are of the order of 10^4 cm^{-3} and the density gradients are large in the winter hemisphere.

As is evident from Figs. 1 and 2, there exist distinct O^+ density depression regions in the winter hemisphere for both periods around the June and December solstices. There exist two distinct O^+ depression regions in the northern hemisphere, the centers of which are located around 210°E, 40°N, and around 40°E, 40°N as shown in Fig. 1. On the other hand, there exists one distinct O^+ depression region as shown in Fig. 2, the center of which is located around 15°E, 70°S. The depression regions in each hemisphere remain nearly in the same regions during the nighttime.

The observed O^+ density distributions near the equinox conditions are shown in Figs. 3 and 4 in order to demonstrate how fast the winter characteristic features change into the summer characteristic features or vice versa. Figures 3 and 4 show the distributions of the O^+ densities at local times between 20 hr and 22 hr in the periods just before and after the vernal equinox, respectively. Characteristics of the O^+ density depressions shown in Figs. 3 and 4 are nearly the same with those shown in Figs. 1 and 2, respectively. Thus, it is seen that the change in the worldwide O^+ density distributions from the pattern typical of the December solstice to the pattern typical of the June solstice takes place in a rather short term around the vernal equinox. Similarly, the reverse change from the June type to the December type pattern takes place rapidly around the autumnal equinox, though not shown here by figures.

It is very interesting to note that very slight density depression regions are seen around 60°E, 35°N and 220°E, 30°N in the northern hemisphere shown in Fig. 2, which roughly coincide with the locations of the depression regions shown in Fig. 1. Similarly, the local density minimum region in the southern hemisphere shown in Fig. 2 roughly coincides with that shown in Fig. 1. Thus, the positions of the local density minimum and maximum around the June solstice are almost the same with those around the December solstice, and it is clear that the difference in density between the December and June solstices is a result of the rapid increase and decrease in the O^+ densities in those regions around the equinoxes. That is, the densities in the O^+ depression regions in the northern hemisphere in the December solstice increase in a rather short term crossing the vernal equinox. Such a rapid density alternation in the

Fig. 2. The worldwide O^+ density distribution ($\log_{10} N_i$ (cm^{-3})). Apr. 4, 1979–Sep. 16, 1979. 22–24 hr LT.

Fig. 3. The worldwide O⁺ density distribution ($\log_{10} N_i$ (cm⁻³)). Feb. 5, 1979–Mar. 19, 1979. 20–22 hr LT.

Fig. 4. The worldwide O^+ density distribution ($\log_{10} N_i \text{ (cm}^{-3}\text{)}$). Apr. 4, 1979–May 28, 1979. 20–22 hr LT.

depression region also occurs around the autumnal equinox in the southern hemisphere.

The centers of the depressions shown in Figs. 1 and 3, are located around 40°–50°N latitudes, while the centers of the depressions shown in Figs. 2 and 4, are located at much higher latitudes around 70°S. However, the dip latitudes of these depressions in the southern hemisphere are less than about 50°, nearly the same with those in the northern hemisphere.

Figure 5 shows the iso-magnetic map for declination which is calculated from the IGRF-1975 model. Comparing Fig. 5 with Figs. 1 and 2, one can see that the regions of high or low O⁺ density are closely connected with the regions of westward or eastward declination of the geomagnetic field in the northern hemisphere, respectively, and vice versa in the southern hemisphere. Both of the two O⁺ depression centers in the northern hemisphere shown in Fig. 1 are located in the region of the eastward declination of the geomagnetic field.

4. Discussions

As is generally known, thermospheric temperature shows a diurnal variation depending on the solar zenith angle with a diurnal bulge around 14 hr LT and nocturnal antibulge around 03 hr LT. Temperature differences cause pressure

Fig. 5. The contour map of the iso-geomagnetic declination at a height of 1,100 km.

imbalances to produce neutral air wind circulation. Plasmas gain momentum through ion-neutral collisions, and thus plasma flow occurs. The plasma flow patterns alter the global distribution of the plasma density, that is, upward or downward motions of the charged particles in the *F* region change the topside charged particle density. Upward motion increases and downward motion decreases the ion density in the topside region. Thus, the ion density in the topside region remains high in the upward flow regions than in the downward flow regions (YONEZAWA, 1957).

The vertical component of the field-aligned plasma flow, V_z , is expressed as follows:

$$V_z \propto V_n \cos I \sin I \cos \phi, \quad (3)$$

where V_n is the velocity of the neutral wind, I is the dip angle of the geomagnetic field and ϕ is the angle between the horizontal component of the neutral wind velocity and the horizontal component of the geomagnetic field (PAPAGIANNIS and MULLANEY, 1971). The vertical motion of the ionospheric plasma induced by the neutral winds becomes nearly maximum at a dip angle of 45° , as far as the dip angle dependency is concerned. In order to obtain V_z in Eq. (3), the calculated results of the neutral wind vector by BLUM and HARRIS (1975) and the IGRF-1975 geomagnetic field model are used.

Figures 6 and 7 show that the calculated global distribution patterns of the vertical components of the field-aligned plasma flow induced by the neutral air wind system at a height of 300 km at 20 hr LT for the December and June solstice conditions, respectively. Positive and negative signs mean upward and downward directions, respectively. The neutral air wind profile at 20 hr LT is adopted to be typical of nighttime wind profile because the magnitude of wind velocity becomes maximum in the period from evening to midnight (BLUM and HARRIS, 1975). As the geomagnetic field lines are curved, the global patterns drawn in Figs. 6 and 7 do not directly coincide with those in the region near the dip equator at a height of 1,100 km. But these figures show qualitatively the features of the global patterns in mid-latitudes.

Figure 6 shows that in the December solstice the maximum downward flow and upward flow regions in mid-latitudes are located around 240°E , 15°N , and around 230°E , 35°S , respectively.

Comparing Fig. 1 with Fig. 6, one can see that regions of the O^+ density depressions or local minima roughly coincide with the regions of maxima in the downward flow. Although the O^+ depression region around 40°E , 40°N shown in Fig. 1, is distinct, the downward flow in the calculated result of the neutral wind pattern shown in Fig. 6 is not so large.

Figure 7 shows that in the June solstice the maximum downward flow and upward flow regions are located around 50°E , 70°S and around 320°E , 25°N , respectively. The O^+ density depression region shown in Fig. 2, roughly coincides with the region of maximum downward flow in the southern hemisphere shown in

Fig. 6. The global pattern of computed vertical components of the field-aligned plasma flow at a height of 300 km for the December solstice conditions. 20 hr L.T. Units: m/sec.

Fig. 7. The global pattern of computed vertical components of the field-aligned plasma flow at a height of 300 km for the June solstice conditions. 20 hr LT. Units: m/sec.

Fig. 7, and the maximum upward flow region around 320°E, 25°N corresponds to the relatively high density region, 290°–360°E.

5. Conclusions

Observations of the ion composition by the ion mass spectrometer on the ISS-b have revealed the global topside ionospheric structure, and the following is the summary of the present study of prominent features seen in the nighttime O⁺ density distributions.

(1) There exist distinct O⁺ density depression regions in the winter season. Two distinct depression regions are found in the northern winter hemisphere, the centers of which are located around 40°E, 40°N and 210°E, 40°N, while one depression region takes place in the southern winter hemisphere, the center of which is located around 15°E, 70°S. These dip latitudes are between 30° and 50°.

(2) The positions of the O⁺ depression regions do not change very much with the seasons, but the O⁺ densities are very changeable according to the season. The O⁺ densities become low in the northern hemisphere and become high in the southern hemisphere around the December solstice. On the contrary, the O⁺ densities become high in the northern hemisphere and become low in the southern hemisphere around the June solstice. The O⁺ densities in the depression regions change rather quickly at about the equinoxes.

(3) These features can be interpreted in terms of the global pattern of the neutral air wind circulation and its interaction with ions under the influence of the geomagnetic field. The change in the O⁺ densities in the depression regions can be attributed to the change of the global circulation pattern of the neutral air wind system.

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