The focus of this thesis is to characterize the variability of the helium ion fraction in the topside ionosphere using incoherent scatter radar (ISR) from Arecibo Observation, Puerto Rico. The thesis centers on two aspects: The first one is to present the phenomenon of helium ion fraction with solar cycle, season, and day-and-night. This study firstly reports the seasonal phenomenon of helium ion fraction from 400 km to 700 km in detail at solar maximum over Arecibo. The second one is to analyze the mechanism of seasonal phenomenon of helium ion fraction. The results show downward ion flow plays an important role in seasonal variation of the helium ion fraction.
VARIABILITY OF THE HELIUM ION CONCENTRATION IN THE TOPSIDE IONOSPHERE OVER ARECIBO

A Thesis

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Faculty of Miami University
in partial fulfillment of
the requirements for the degree of
Master of Science in Computational Electrical and Computer Engineering

by

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Chapter 1
Introduction

The Earth’s upper atmosphere where neutral particles are ionized or partially ionized due to solar radiation and cosmic rays is called the ionosphere. The range of the ionosphere is defined from 60 km to several thousand kilometers. The region where particles are totally ionized is called the magnetosphere. Because of the existence of enough ions and electrons, the ionosphere can refract or reflect the propagation of electromagnetic waves when they pass through it [Schunk and Nagy, 2000]. The following part introduces different layers of the ionosphere, the dominant ions in each layer and the major techniques used to detect ionosphere parameters.

1.1 A Brief Introduction of Ionosphere Morphology

The electron density and other basic parameters are used to depict the morphology of the ionosphere. Because these parameters vary with space (latitude, longitude and height distribution) and with time (diurnal, seasonal, and solar cycle), the ionosphere morphology is very dynamic. The vertical structure of the ionosphere is classified according to the distribution of the electron density. A typical electron density profile is shown in Figure 1.1.
The two electron density profiles, shown in Figure 1.1, represent the typical vertical ionosphere structure during day and night, respectively. The height of the electron density peak, commonly known as $h_mF_2$, is almost around 300km at both daytime and nighttime. We note that the electron density in the daytime is much larger than the density at nighttime. The higher electron density is due to intense solar radiation at daytime.

According to the concentration of electron density, the ionosphere can be divided into three parts vertically [Gong, 2012]. The altitude from 50 km to 90 km is called the D region. Because the ionization level is low, the electron density is low in this region. Collisions between electron, ion, and neutral particles in the D-region is frequent. The chemical process in this region is mainly controlled by $O_2$, NO, NO$_2$ and a small proportion of alkali metal materials. Negative ions, mainly $O_2^-$, exist in the D region [Rishbeth, 1988]. The D region electrons usually only exist during the daytime and they...
will disappear at night due to absence of solar radiation and the high combination rate between ions and electrons.

The altitude from 90 km to 150 km is considered the E region. The variation of electron density peak roughly agrees with Chapman’s theory at this region, which means the electron density reaches its maximum value respectively at noon, summer, and solar maximum year [Zolesi and Cander, 2014]. The sporadic E layer, a thin ionization layer appearing irregularly, occurs in the E region. The wind shear mechanism or electric field mechanism may explain its formation [Gong, 2012].

The altitude from 150 km to 500 km is named as the F region. Normally, there are two electron density peaks in F region during the day time. The range of the first layer, named the F1 layer, is from 150 km to 210 km and the upper layer, named the F2 layer, is from 210 km to 500 km. The F1 layer is largely influenced by solar radiation. It appears during day time and becomes much more apparent during summer and solar maximum years. The F2 layer is the main part that can reflect radio waves and affect the propagation of communication signals because of its high concentration of electrons. The maximum electron density value at the F2 region is denoted as \(N_{mF2}\) while the corresponding height is denoted as \(h_{mF2}\). The \(N_{mF2}\) and \(h_{mF2}\) are two crucial parameters to describe the properties of the ionosphere.

1.2 Incoherent Scatter Radar Technique

Scattering of electromagnetic waves by a single free electron is called Thomson scattering or incoherent scattering. According to Gordon’s theory [Gordon, 1958], electromagnetic waves scattered by free electrons in the ionosphere can be superimposed from individual electrons. Bowles [1958] subsequently proved that the bandwidth of the received signal is much smaller than the expected value based on electronic random thermal velocity, which indicates that the scattering is due to plasma random thermal fluctuations rather than electron thermal fluctuations. An Incoherent Scatter Radar (ISR) can detect the weak power from incoherent scattering. Many
important ionosphere parameters, such as electron density, line of sight velocity, electron temperature and ion temperature, can be directly derived from the power spectrum of incoherent scattering echoes. Other parameters also can be observed or indirectly calculated from power spectrum, such as photoelectron flux, electric field strength, neutral atmospheric temperature, neutral wind speed, and ion composition.

The incoherent scatter radar provides a very effective way to study the ionosphere from the ground. The ISR can obtain many ionosphere parameters with high time resolution and altitude resolution. Furthermore, ISR probes the ionosphere beyond 1000 km. It is not only a crucial tool for ionosphere physics research, but also provides important information to study the dynamics of the magnetosphere.

1.2.1 Other Measurement Techniques

In 1925, Breit and Tuve invented the first device, ionosonde, to detect the ionosphere, which vertically transmits high frequency pulses into the ionosphere and receives an echo signal to be analyzed. This device played an important role in studying the ionosphere during the next half century. With the development of new techniques, such as rockets and satellites that can launch probes into space, the ionosphere can be further studied in more detail. For instance, spacecraft carrying sensing devices have been used to directly detect the ionosphere environment.

1.2.2 Principles of ISR

The radar equation is very important because it describes the relationship between the received power and the transmitted power. It enables us to do deterministic research and analysis [Richards, 2005]. The derivation of the ISR power equation described below comes from Mathew [1986] and Zhou [1991].

The peak incidental power density at a target is represented as:
where $P_T$ is the isotropic transmitted power, $G(\theta, \phi)$ is the antenna power gain, $\theta$, $\phi$, $L$ and $R$ are the axis from the beam center, the azimuth angle, the system efficiency and range respectively. Assuming the detection signals are transmitted and received by the same antenna, the backscatter power density at the receiving antenna is:

$$F_i(\theta, \phi) = \frac{P_T L G(\theta, \phi)}{4\pi R^2} \tag{1.2.1}$$

where $\sigma(R, \omega)$ represents the differential back scatter cross section at range $R$ and frequency $\omega$.

The backscattered power received at the same antenna is:

$$P_r(\theta, \phi, R, \omega) = \frac{P_T L \lambda^2 G^2(\theta, \phi) \sigma(R, \omega)}{64\pi^2 R^3} \tag{1.2.3}$$

where $\lambda$ is the radar wavelength. Eq.1.2.3 is the simple point target radar equation [Gong, 2012]. In the equation, $\sigma(R, \omega)$ is the only undetermined term, it is called the Scattering Cross Section (SCS). The SCS is an important parameter for a quantitative understanding of the incoherent scattering, because it indicates how much energy can be scattered back to the same antenna. The equation of scattering cross section is given by Evans [1969] as follow:

$$\sigma(R, \omega) = N_{e0}(R) 4\pi r_e^2 \sigma_n(\omega) \tag{1.2.4}$$

where $N_{e0}(R)$ is the electron density at range $R$; $r_e$ is the classic electron radius; and $\sigma_n(\omega)$ is the normalized scattering coefficient per electron per Hertz.

Another issue is how to determine the effect of the transmitted radio wavelength. If the wavelength is too long or too short, it cannot meet the condition of incoherent scattering. The use of the Debye length have solved this problem. The wavelength transmitted by the ISR should be less than the Debye length given by:

$$\lambda_D = 69 m_e \sqrt{\frac{T_e}{N_e}} \tag{1.2.5}$$
where $m_e$ is the electron mass, $T_e$ is the electron temperature and $N_e$ is the electron density.

For $\sigma_n(\omega)$, Buneman [1962] and Farely [1966] have derived it as follow:

$$\sigma_n = \frac{\alpha_e^2}{1 + \alpha_e^2} + \frac{1}{(1 + \alpha_e^2)(1 + T_e/T_i + \alpha_e^2)}$$

Equation 1.2.6 can be applied in the case when no negative ions are present and the following condition is fulfilled $1 \leq \frac{T_e}{T_i} \leq 3$, where $\alpha_e^2 = \frac{4\pi \lambda_D}{\lambda}$, and $T_i$ is the ion temperature.

### 1.2.3 ISR Power Spectrum

Other than range, an ISR can only measure the signal’s power spectrum. To obtain the ionosphere parameters, it is very important to analyze the ISR power spectrum. Figure 1.2 is a typical spectrum of the received signals.

![Figure 1.2 Typical power Spectrum](http://www.naic.edu/~isradar/is/aboutis/incoherent_scatter.html)

If the radio waves are transmitted by ISR into the ionosphere, the waves will be reflected by each of the millions of electrons present, as they act like many small targets. The received signal is composed of all the scatterings.
As shown in Figure 1.2, the power spectrum is symmetric. The reason is that the motion of millions of particles is totally random. This means parts of particles move away from the radar and some other part of them move toward to the radar. The width of the spectrum is related to the ion temperature, electron temperature and ion mass through the following equation:

\[ \Delta f \sim \frac{(T_i + T_e)}{m_i} \]  

(1.2.7)

where \( T_i, T_e \) and \( m_i \) are ion, electron temperature and ion mass respectively.

As Figure 1.2 indicates, the central part of the spectrum is lower than the two shoulders. It reflects the relationship of the electron temperature and ion temperature, from which the \((T_e / T_i)\) ratio can be derived.

If there are more electrons in the ionosphere, then more power can be reflected. As shown in Figure 1.2, the total gray area is proportional to the plasma density, which is related to the number of electrons or ions in the ionosphere.

### 1.2.4 Arecibo ISR

Arecibo Observatory is located near Arecibo, in the northwest part of Puerto Rico. It has the world largest single-dish radio telescope whose diameter is 305 meters. We note that another much larger dish, named FAST, has been built in China in 2016. Arecibo Observatory began construction in 1960 and officially opened on November 1, 1963. The original task of the Arecibo radio telescope is to study the ionosphere as conceived by William E. Gordon, a professor of electrical engineering at Cornell University, who was the first to propose the idea of using ISR to study the ionosphere. So, the initial name of Arecibo Observatory was Arecibo Ionosphere Observatory.

However, as time progressed, the Arecibo telescope played a more important role in radio and radar astronomy. The Arecibo radio telescope spends 80% of its operational
time on radio astronomy, where atmospheric research and radar astronomy account for 15%, and 5% of the operational time, respectively.

An aerial view of the Arecibo telescope system is seen in Figure 1.3:

![Arecibo telescope system](http://www.spacenews.com/sites/spacenews.com/files/images/articles/ARECIBO.JPG)

**Figure 1.3** The Arecibo telescope system

The Arecibo ISR is the most powerful and sensitive radar in the world. Its peak power is 2.5 MW. The main antenna is 96 feet long and its effective aperture is 41.7 dB/m², for the linefeed. Its operational frequency is 430 MHZ. In 1997, Arecibo built the Gregorian Dome. This construction extended the observed-frequency up to 10 GHz for radio astronomy. Because of the dual beams, the Arecibo antenna can observe in two co-planar directions simultaneously [Ma, 2015].

There are two kinds of ISRs: one is mono-static and another is multi-static. Arecibo ISR is mono-static. There are several facilities at the present time. Tables 1.1 and 1.2 show their locations and parameters [Ma, 2015].
<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arecibo Observatory</td>
<td>Arecibo, Puerto Rico</td>
<td>18.3° N</td>
<td>66.8° W</td>
</tr>
<tr>
<td>Advanced Modular Incoherent Scatter Radar (AMISR)</td>
<td>Poker Flat, Alaska, U. S.</td>
<td>65° N</td>
<td>147° W</td>
</tr>
<tr>
<td></td>
<td>Resolute Bay, Nunavut, Canada</td>
<td>74° N</td>
<td>94° W</td>
</tr>
<tr>
<td>European Incoherent Scatter Scientific Association (EISCAT)</td>
<td>TromsØ, Norway</td>
<td>69°35' N</td>
<td>19°14° E</td>
</tr>
<tr>
<td></td>
<td>Kiruna, Sweden</td>
<td>67°52' N</td>
<td>20°26' E</td>
</tr>
<tr>
<td></td>
<td>Sodankylä, Finland</td>
<td>67°22' N</td>
<td>26°38' E</td>
</tr>
<tr>
<td></td>
<td>Longyearbyen, Norway</td>
<td>78°09' N</td>
<td>16°01' E</td>
</tr>
<tr>
<td>Millstone Hill Observatory</td>
<td>Westford, Mass., U. S.</td>
<td>42.6° N</td>
<td>71.5° W</td>
</tr>
<tr>
<td>Jicamarca Radar Observatory</td>
<td>Lima, Peru</td>
<td>11.95° S</td>
<td>76.87° W</td>
</tr>
<tr>
<td>The Sondrestrom Research Facilities</td>
<td>Sondrestrom, Greenland</td>
<td>67° N</td>
<td>51°W</td>
</tr>
<tr>
<td>Facility</td>
<td>Antenna</td>
<td>Operating Frequency (MHz)</td>
<td>Peak Power (MW)</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>--------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Arecibo Observatory</td>
<td>305 m spherical reflector</td>
<td>30</td>
<td>2.5</td>
</tr>
<tr>
<td>Advanced Modular Incoherent Scatter Radar (AMISR)</td>
<td>128 block-like panels</td>
<td>430-450</td>
<td>2</td>
</tr>
<tr>
<td>European Incoherent Scatter Scientific Association (EISCAT)</td>
<td>Four 30×40 m steerable parabolic cylinders (TromsØ)</td>
<td>222.8 - 225.4; 926.6 - 930.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>32 m steerable parabolic dish (TromsØ)</td>
<td>926.6 - 930.5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Three arrays of dipole antennas (TromsØ Heater)</td>
<td>3.85 - 8.00</td>
<td>12x100 kW</td>
</tr>
<tr>
<td></td>
<td>42 m fixed and 32 m steerable parabolic dishes (Longyearbyen)</td>
<td>498.0 - 502.0</td>
<td>1</td>
</tr>
<tr>
<td>Millstone Hill Observatory</td>
<td>68 m parabola</td>
<td>440</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>48 m parabola</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.2 Parameters of the ISRs [Ma, 2015]**
<table>
<thead>
<tr>
<th>Jicamarca Radar Observatory</th>
<th>Array of 18432 dipole elements</th>
<th>49.92</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Sondrestrom Research Facilities</td>
<td>32 m fully steerable</td>
<td>1290</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Chapter 2
Physiochemical Process of Topside Ions

At middle or low latitudes, ions are produced due to neutral gas ionization by Extreme Ultra-Violet (EUV) and X-rays. Electrons and ions can disappear due to recombination reactions. In most cases, neutral winds also play an important role in ion density profiles for a specific region. Thus, ion formation is controlled by chemical and physical process in the ionosphere. In this chapter, ion transport and diffusion are discussed first, then the characteristics of hydrogen and oxygen ions will be introduced.

2.1 Ion Transport

The ion density is a balance between dynamics and various chemical reactions. Generally, it can be described using continuity equation [Zolesi and Cander, 2014],

\[
\frac{\partial N}{\partial t} = q - L - \nabla \cdot (N \cdot V)
\]  

(2.1.1)

where \( q, L \) are production and loss rate respectively; \( N \) is the particle density; \( V \) is the drift velocity vector.

The production and loss rate is decided by chemical processes. Atoms and molecules decompose due to photoionization. The main reactions are:

\[
hv + X \rightarrow X^+ + e
\]  

(2.1.2)

\[
hv + XY \rightarrow XY^+ + e
\]  

(2.1.3)

Ions can recombine with atoms or electrons as follows:

\[
X^+ + e \rightarrow X + hv
\]  

(2.1.4)

\[
XY^+ + e \rightarrow X^* + Y^*
\]  

(2.1.5)

\[
X^+ + Z \rightarrow X + Z^+
\]  

(2.1.6)

Equation (2.1.5) is called dissociative recombination. The reaction splits the molecule into two atoms which are in an excited state.
For a given altitude, the transport process depends on the ion transport, which is mainly caused by neutral wind or electrical field. For instance, when the net ion flow is downward, the ion concentration increases at the lower altitude if other factors remain the same.

Generally, ion flow varies at different times or altitudes. Figure 2.1 is an example of vertical ion velocity at different heights:

![Figure 2.1 Vertical velocity with range and time](image)

In Figure 2.1, the positive velocity is upward. As shown in Figure 2.1, the ion vertical velocity is always changing at different time and altitude.
As shown in Figure 2.2, from 00:00 LT to approximate 9:00 LT, the ion velocity shows a negative trend at 611 km or 688 km, which indicates ions flowed downward.

### 2.2 Ion Diffusion in the Ionosphere

Near the Earth’s surface, composition of the atmosphere are 78% nitrogen gas, 21% oxygen gas and a few other minor species, such as helium gas. Below 100 km, turbulent mixing renders all the gases in equal proportion. There is no turbulent mixing at very high altitude where the distribution of each gas exists on its own. This is the diffusion equilibrium.

Under hydrostatic equilibrium, we have

$$p = nKT$$  \hspace{1cm} (2.2.1)

where $p$ is the pressure, $K$ is the Boltzmann constant ($1.38 \times 10^{-23}$ J/K), $n$ is the number of molecules per unit of volume, and $T$ is the absolute temperature [Zolesi and Cander, 2014].
Each volume of the gas will be in static balance due to its downward gravity and its upper and lower surface pressure difference \( p \), so that
\[
 nm g = - \frac{dp}{dh} = -KT \frac{dn}{dh}
\] (2.2.2)

where \( g \) is the acceleration of gravity and \( h \) is the height.

The above equation leads to
\[
 \frac{1}{n} \frac{dn}{dh} = - \frac{mg}{KT}
\] (2.2.3)

\[
 n = n_0 \exp \left( -\frac{h}{H} \right)
\] (2.2.4)

\[
 H = \frac{KT}{mg}
\] (2.2.5)

where \( H \) is defined as the scale height and \( n_0 \) is the density in reference height [Zolesi and Cander, 2014].

However, temperature will change with time and altitude because solar radiation heat the atmosphere. The relative equations below are derived by Ratcliffe [1972]. When temperature change with altitude, Equation (2.2.2) becomes:
\[
 nm g = - \frac{dp}{dh} = -KT \left( \frac{dn}{dh} + n \frac{dT}{dh} \right)
\] (2.2.6)

where \( H = \frac{KT}{mg} \) represents the variable scale height based on different altitude, there
\[
 n = -H \frac{dn}{dh} - n \frac{dH}{dh}
\] (2.2.7)

When the temperature gradient is uniform, it means the scale height gradient is also uniform,
\[
 H = H_0 + \beta h
\] (2.2.8)

By integrating Equation (2.2.7), we have
\[
 \frac{n}{n_0} = \left( \frac{H}{H_0} \right)^{\left( 1 + \frac{1}{\beta} \right)} = \left( 1 + \frac{\beta h}{H_0} \right)^{\left( 1 + \frac{1}{\beta} \right)}
\] (2.2.9)

where \( H_0 \) is the scale height at \( h_0 \) and \( n_0 \) is the density at \( h_0 \).
Since the gases are completely mixed under 100 km, all components have the same height change. If $m$ is the average molecular mass, the height change is given by Equations (2.2.4) and (2.2.5). Therefore, at sea level, $H$ is about 8 km and remains almost constant near the surface. In the diffusion equilibrium region, however, each of the gases is distributed according to their own scale height. This indicates that components with lower molecular mass, such as hydrogen and helium, have a greater scale height and more numerous at higher altitude, and oxygen is more numerous at lower altitude [Zolesi and Cander, 2014].

2.3 Important Ions in the Topside Ionosphere

The topside ionosphere is the region above the F region, approximately beyond 500 km. In the topside ionosphere, photo ionization and chemical reaction control the production or loss of ions. The transport process also influences ion density at a specific region. The most important ions usually are $O^+$, $H^+$,He$^+$ at the topside ionosphere [Truhlik et al., 2005], whose features vary with longitude, latitude, local time, season and solar cycle. The variation of helium ion will be discussed in Chapter 3.

2.3.1 Oxygen Ions

The oxygen ion is always the major ion at 400~600km. Its production can be explained by a chemical mechanism as follows [Rishbeth, 1988]

*Production Process:*

\[
O + h\nu \rightarrow O^+ + e \quad (2.3.1)
\]

\[
N_2 + h\nu \rightarrow N_2^+ + e \quad (2.3.2)
\]

*Charge Transfer:*

\[
O^+ + O_2 \rightarrow O_2^+ + O \quad (2.3.3)
\]

\[
O^+ + N_2 \rightarrow NO^+ + N \quad (2.3.4)
\]
Recombination Process:

\[ NO^+ + e \rightarrow N + O \]  \hspace{1cm} (2.3.5)

\[ O_2^+ + e \rightarrow O + O \]  \hspace{1cm} (2.3.6)

The concentration of \( O_2 \) and \( N_2 \) becomes scarce with increasing altitude. So in the topside ionosphere, the absence of \( O_2 \) and \( N_2 \) makes the reactions of E.q.(2.3.3) and (2.3.4) very slow, but \( NO^+ \) and \( O_2^+ \) recombine with electrons quickly, which results in \( O^+ \) being the dominant ion in this region [Rishbeth, 1988].

![Figure 2.3 O\(^+\) fraction in solar minimum and maximum year](image)

As shown in Figure 2.3, the oxygen ion is the dominant ion from 400 km to 600 km, whether it is the solar minimum or maximum year. The H\(^+\) fraction increases significantly at nighttime during the solar minimum year, which leads to the reduction of oxygen ion fraction as seen in the blue region in the upper part of Figure 2.3.
2.3.2 Hydrogen Ions

Hydrogen ions are produced via two ways. One is that hydrogen atoms are ionized by solar ultraviolet radiation whose wavelength is less than 91 nanometers, and the other way is through charge exchange with oxygen ions, namely:

\[ H + hv \rightarrow H^+ + e \]  \hspace{1cm} (2.3.7)

\[ H + O^+ \rightarrow H^+ + O \]  \hspace{1cm} (2.3.8)

Equation (2.3.8) is reversible,

\[ H + O^+ \leftrightarrow H^+ + O \]  \hspace{1cm} (2.3.9)

The H\(^+\) fraction variation as a function of solar cycle, season, and local time can be examined. MacPherson et al. [1998] showed that the H\(^+\) fraction is a sensitive indicator of solar influx in the topside ionosphere. The H\(^+\) composition is extremely large at solar minimum years, so the transition height of O\(^+\) to H\(^+\), defined as the altitude where the concentration of H\(^+\) is equal to the concentration of O\(^+\), can reside near 450 km at night [Heelis et al., 2009].

\[ \text{Figure 2.4 H}^+ \text{ fraction in a solar cycle} \]
As shown in Figure 2.4, the H\(^+\) fraction was large in 2008 and 2010 (solar minimum) in the autumn equinox from midnight to forenoon, but it became much less at 2012 and 2014 (solar maximum).

Fewer researchers focus on the H\(^+\) seasonal variation. The data from the Arecibo ISR can be used to study the hydrogen ion’s seasonal variation from 400km to 700km at low-latitude. For a normal year, comparing H\(^+\) fraction at different seasons and heights, some features may be observed.

![Graph showing H\(^+\) fraction in different seasons](image)

**Figure 2.5** H\(^+\) fraction in different season

As shown in Figure 2.5, the data were taken on April 13 of the spring season, July 8 of the summer season, October 6 of the fall season, and December 8 of the winter season of 2010. The difference is that the upper plot uses the data at 00:00 LT and the lower plot uses data at 12:00 LT. It shows that the H\(^+\) faction is always highest at winter time but lowest at summer time.

For diurnal variation, Macpherson et al. [1998] found that H\(^+\) becomes dominant during midnight to morning, and the transition height of O\(^+\)-H\(^+\) decreased sharply at nighttime. Choosing consecutive days, we plot hydrogen ions’ diurnal variation at solar
maximum year in Figure 2.6 and solar minimum year in Figure 2.7. Figure 2.7 shows that the O\(^+\)- H\(^+\) transition height is extremely low at night and morning during solar minimum year which is below 500km at nighttime and morning, but rises up to 650km in the afternoon. So the diurnal variation is highly correlated with sunset and sunrise.

**Figure 2.6** H\(^+\) fraction on solar maximum days

**Figure 2.7** H\(^+\) fraction on solar minimum days
Chapter 3
Variability of Helium Ion Fraction in the Topside Ionosphere over Arecibo

Helium is considered as the minor ion in the topside ionosphere in early studies [Farley, 1966; Moorcroft, 1969; Ho and Moorcroft, 1971; Hagen and Hsu, 1974]. However, several studies in the last two decades [Erickson and Swartz, 1994; Gonzalez and Sulzer, 1996; Gonzalez et al., 2004] show that helium ion is highly correlated with the solar cycle, and He$^+$ is the dominant ion in the topside ionosphere during solar maximum. In some cases, the relative composition of He$^+$ is beyond 60% of the topside plasma [Gonzalez et al., 2004]. Some satellite measurements also verify that helium ion is dominant in the topside ionosphere at solar maximum [Heelis et al., 1990; Shultchishin et al., 1996; Denton et al. 2002].

During the solar maximum years, we can get more detailed description of He$^+$ below 700 km by using ISR. In this chapter, we will first discuss its solar cycle and diurnal variation, and then present the seasonal variation of helium ion fraction and its unique characteristics at solar maximum year.

3.1 Solar Cycle Variation of He$^+$ Fraction

Several studies [Erickson and Swartz, 1994; Gonzalez and Sulzer, 1996; Gonzalez et al., 2004] over Arecibo show that helium ion concentration is highly correlated with solar cycle, and He$^+$ is the dominant ion in the topside ionosphere during solar maximum years. In this section, different data sets from solar minimum: 2008, 2009; moderate: 2011, 2012; maximum: 2013, 2014 years near winter solstices are compared. The analysis illustrates the solar cycle variations of He$^+$ fraction in the same season (November and December, winter time).
Figure 3.1 He\(^+\) fraction on solar minimum days

As shown in Figure 3.1, He\(^+\) almost cannot be detected during solar minimum from 400 km to 700 km throughout the day. This indicates that H\(^+\) or O\(^+\) is the dominant ion in this region and He\(^+\) is of little importance during solar minimum year.

Figure 3.2 He\(^+\) fraction on moderate solar activity days

Figure 3.2 does not show the apparent feature of the helium ion fraction. Although the helium ion fraction seems to be high above 550 km on November 29, 2011, we
compared other days in November and October, 2011 and found they all do not have a remarkable pattern and higher value. So it may be a just single case due to a detection error or other ionosphere interference. Therefore, He\(^{+}\) is also a minor ions during moderate solar years.

As shown in Figure 3.3, it is obvious that the He\(^{+}\) fraction becomes the dominant ion from 500 km to 700 km and from midnight to noon. The bulge of the helium ion fraction began at midnight and it lasted until noon. It is extremely strong from 550 km to 700 km and from 06:00 LT to 12:00 LT.

We have presented six data sets near winter solstice from six different years to illustrate the solar cycle variation of helium ion fraction. It shows that He\(^{+}\) fraction will be much larger than solar minimum or moderate years.

### 3.2 Diurnal Variation of He\(^{+}\) Fraction at Solar Maximum

The diurnal variation of Helium ions has been studied by many researchers [Carlson and Gordon, 1966; Erickson and Swartz, 1994; Gonzalez and Sulzer, 1996; Gonzalez et al., 2004] over Arecibo. Their work suggested that the helium ion fraction is dominant in the nighttime and tend to form a layer close to the O\(^{+}\) - H\(^{+}\) transition height.
Heelis et al. [1990] also showed that the dominant light ion is helium at 900km during nighttime by using satellite data.

We characterize the diurnal variation of helium ion fraction by ISR data near the autumn equinox. Three continuous days have been plotted as follow:

![Figure 3.4 He⁺ fraction at three continuous days in autumn](image)

As shown in Figure 3.4, helium ion fraction becomes significant from 06:00 LT to 12:00 LT and in the altitude range from 500 km to 700 km. We also noticed that helium ion fraction is large for a longer time at high altitudes. However, helium ion fraction is largest at forenoon (from 06:00 LT to 12:00 LT), which is different from early studies that the helium ion fraction is dominant during nighttime. This contradiction may result from that the data used by early works from winter time at solar maximum [Carlson and Gordon, 1966; Erickson and Swartz, 1994; Gonzalez et al., 2004] or spring equinox at solar minimum [Gonzalez and Sulzer, 1996] at higher altitudes (from 600km to 2000km).

We note that the high helium ion fraction will lead to a lower O⁺- He⁺ transition height. The [O⁺] to 10%[He⁺] transition height which is defined as the altitude where helium ion fraction is equal to 10% of total plasma density at solar maximum is plotted as follows:
As shown in Figure 3.5, from midnight to noon, there is a minimum peak of O$^+$ to 10% He$^+$ transition height, which indicates that the helium ion fraction reaches its maximum value near 06:00 LT. After sunrise, the O$^+$ to 10% He$^+$ transition height increases gradually from 500 km to 700 km, which means the concentration of helium ion becomes less important during 18:00 LT to 22:00 LT at the range of 500 km to 700 km. So the phenomenon of helium ion fraction near winter solstice matches the early researchers’ reports that helium ion fraction is dominant during nighttime and the transition height is below 600 km and reaches its minimum altitude at about 04:00 LT [Gonzalez et al., 2004].

### 3.3 Seasonal Variation of He$^+$ Fraction at Solar Maximum

Despite the abundance of helium ions at solar maximum, few studies have been performed to study the seasonal variation of helium ion below 700 km. Goel and Rao [1984] reported that helium ion concentration is higher in the winter hemisphere than in
the summer hemisphere at an average height of 1100 km. West et al. [1997] and Borgohain and Bhuyan [2010] found that helium ion concentration is high in the evening in the summer hemisphere in the whole solar cycle. Bhuyan and Borgohain [2005] also noted that helium ion concentration is higher in December than June in the forenoon at 500 km. Borgohain and Bhuyan [2010], however, suggested that the helium ion concentration is higher in winter compared to summer in the forenoon hours at the height of 800 km. Su et al. [2005] studied seasonal and latitudinal distribution of light ions at 600 km during the solar maximum, they claimed that the infrequent observations of significant helium ions in many seasons make it inconclusive on the seasonal distribution of the helium ion. On the other hand, the observation of a seasonal variation of helium ion at Arecibo was summarized by Carlson and Gordon [1966] over Arecibo. They found that the height of 20% He\(^+\) fraction is at about 450 km in December and 600 km in July.

In this section, we report the new seasonal phenomenon of helium ion fraction by comparing equinox with solstice condition over Arecibo. In this work we compare September (equinox) data set with December (solstice) data set. These data sets are representative of solar maximum condition seen over Arecibo.
Figure 3.6 Comparison of He$^+$ fractions (top for Sep, bottom for Dec)
Figure 3.6 shows that helium ion fraction as a function of time and altitude for three consecutive days in September (equinox) and December (solstice) during solar maximum. Figure 3.7 shows helium ion fraction as a function of time at 687 km (Blue curve). From Figure 3.7, we notice that the time range of He⁺ ratio larger than 15% is from ~06:00 LT to ~12:00 LT in September, but the time range is from ~00:00 LT to ~18:00 LT in December at 687 km.

However, from Figure 3.6, we find that the O⁺-10% He⁺ transition height (transition region from green region to blue region in Figure 3.6) seems not different in winter or autumn, which is ~ 500 km. In order to confirm the different penetration time between the two seasons, we present additional data during solar maximum years (April and November at 2013; April, February, September and December at 2014).
Figure 3.8 He\(^+\) fraction with seasons at solar maximum

As shown in Figure 3.8, the time of prominent helium ion fraction always begins between 00:00 LT and 06:00 LT at winter time, but it occurred between 06:00 LT and 12:00 LT at spring or fall time at solar maximum year. It is also obvious that the large helium ion fraction lasts a longer time in winter than in spring or fall from \(~550\) km to \(~700\) km. The phenomenon that the duration of large helium ion fraction varies in different season at solar maximum from \(~500\) km to \(~700\) km has not been reported before. In the following, we will primarily use data sets from September and December in 2014 for further analysis.
Chapter 4

Analysis of Seasonal Variation of He\(^+\) Fraction

In Chapter 3, we report a new phenomenon about the seasonal variation of the helium ion fraction at the height range from ~500 km to ~700 km over Arecibo. Due to the complex physicochemical process in the topside ionosphere, the seasonal variation may be caused by multiple factors. Considering the seasonal difference occurs at nighttime as well, the photoionization rate is not the likely cause. Because all the data was obtained during a solar flux condition, the solar flux is also not an important factor. In this chapter, we will analyze the seasonal variation of helium ion fraction during solar maximum from two aspects: ion temperature and ion flow.

4.1 Ion temperature Effect on Seasonal Variation of He\(^+\) Fraction

4.1.1 The Correlation between Ti and He\(^+\) Fraction

Ion temperature (Ti) is an important parameter that influences the scale height of the electron density profile. It is thought that a cooler temperature will lower the O\(^+\) profile so that the He\(^+\) appears more dominant from ~500 km to ~700 km [Su et al., 2005]. So it is reasonable to believe Ti is one of the causes for seasonal variation of He\(^+\) fraction. We compare September data set with December data set during solar maximum to study the relation between Ti and He\(^+\) fraction.
**Figure 4.1** Comparison of He$^+$ fraction (blue curve) and Ti (red curve) at 534km (top panel) and 610km (bottom panel) during September 27- October 1 at 2014. (Autumn season)
Figure 4.2 Comparison of He+ fraction (blue curve) and Ti (red curve) at 534km (top panel) and 610km (bottom panel) during December 16-22 at 2014. (Winter season)

Figures 4.1 and 4.2 show that when the ion temperature decreases, the He+ fraction will increase in any season and altitude. A negative correlation between the helium ion fraction and ion temperature can be seen. For a quantitative analysis, we use Pearson
Correlation Coefficient (PCC) to measure the linear dependence between helium ion fraction and ion temperature. The PCC definition is defined as [Cohen, 1988]:

\[ \rho_{x,y} = \frac{\text{cov}(x,y)}{\sigma_x \sigma_y} \]  

(4.1.1)

where

\[ \text{cov}(x, y) = E[(x - \mu_x)(y - \mu_y)] \]  

(4.1.2)

is the covariance; \( \sigma_x \) and \( \sigma_y \) are the standard deviation of \( x \) and \( y \); \( E \) is the expectation operator; \( \mu_x \) and \( \mu_y \) are mean of \( x \) and \( y \), respectively. The PCCs between He\(^+\) fraction and Ti are shown in Table 4.1.

**Table 4.1** The PCCs between He\(^+\) fraction and Ti

<table>
<thead>
<tr>
<th></th>
<th>September (autumn equinox)</th>
<th>December (winter solstice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>534km</td>
<td>-0.5933</td>
<td>-0.6595</td>
</tr>
<tr>
<td>610km</td>
<td>-0.6319</td>
<td>-0.6498</td>
</tr>
</tbody>
</table>

Table 4.1 shows a negative value of all three PCCs at about -0.6. The interpretation of PCCs depends on relative background or application purpose. For a real complex phenomenon, a correlation coefficient of -0.6 is considered to be strongly anti-correlated [Cohen, 1988].

We use the data from 20:00 LT to 08:00 LT (~ nighttime) for two continuous days at 649 km to further explore the relationship between temperature and He\(^+\). Ion temperature is the independent variable and helium ion fraction is the dependent variable in Figure 4.3. During the nighttime, the absence of solar radiation simplifies the dynamical-chemical process in the topside ionosphere. From Figure 4.3, we notice that when Ti increased from 1000K to 1500K, the He\(^+\) fraction did not change significantly in the nights of September 27/28 or 28/29. The flat part (i.e., no change in He+
irrespective of change in temperature) always occurs from 20:00 to 00:00 LT. When the
range of Ti is from 800K to 1000K or from 1500K to 1700K, however, the He\(^+\) fraction
decreases linearly with ion temperature. This behavior is largely the same during the
winter season as well. The difference is that the flat part is from 1100K to 1400K, but
the slant part is from 800K to 1100K or 1400K to 1700K. For the daytime, Figure 4.4
shows He\(^+\) fraction is linear with ion temperature from 1300K to 1700K on winter or
autumn during the daytime.

Figure 4.3 He\(^+\) fraction vs Ti during 20:00LT to 08:00LT (~nighttime) for two
consecutive days at 649km. (Top two panels are for autumn, bottom two panels for
winter
Figure 4.4. He$^+$ fraction vs Ti during 08:00LT to 20:00LT (~daytime) for two consecutive days at 649km. (The top two panels are for autumn, the bottom two panels are for winter.)

To ascertain the seasonal variation of Ti, we further examine the Ti at four different nights, two autumn and two winter, but at 649 km. As shown in Figure 4.5, there is no obvious difference in Ti (red curve) between autumn and winter from 20:00 to 06:00 LT,
which suggests a lack of seasonal variation in Ti. But we notice a difference between two seasons at 24:00LT. That is Ti is ~1400K in winter compared with ~1300K in autumn. If the lower Ti can increase He\(^+\) fraction as we assumed, the He\(^+\) fraction at 24:00LT should be larger in autumn. So we present the corresponding helium ion fraction at same altitude from 20:00LT to 08:00LT.

As shown in Figure 4.5, we focus on the value of He\(^+\) fraction (blue curve) at 24:00LT. We find that He\(^+\) fraction is ~5% in autumn, but ~15% in winter. This observation is a sharp contrast to our assumption. Therefore, we believe that the cooler ion temperature may not be a dominant factor to affect the difference of helium ion fraction dramatically between autumn and winter during the nighttime.

![Figure 4.5](image-url)  
**Figure 4.5.** Ti (red curve) compared to He\(^+\) fraction (blue curve) at different season during 20:00LT to 08:00LT at 2014 (two top panels are September, two bottom panels are December)
To further explore the relation between Ti and He\(^+\) fraction, we compare the daily variation of Ti and He\(^+\) fraction by subtracting the daily average of the three days from the original data according to the local time. It can be seen that \(\Delta\text{Ti}\) is inversely correlated with \(\Delta\text{He}^+\) fraction in September and December in Figure 4.6. This suggests that Ti can affect He\(^+\) fraction. In consideration of Figure 4.5 and Figure 4.6, we believe that the negative correlation between \(\Delta\text{Ti}\) and \(\Delta\text{He}^+\) fraction proves that Ti is one of causes for the day-to-day variability in He\(^+\) fraction but not the cause for the seasonal variation.
4.1.2 Summary and Conclusion

Ion temperature is a very important parameter in the topside ionosphere. It plays a crucial role in O\(^+\) layer scale height. We compare September data set with December data set during solar maximum to study the relation between Ti and He\(^+\) fraction. Major characteristics of He\(^+\) fraction and ion temperature include:

- He\(^+\) fraction shows stronger negative correlation with ion temperature for five continuous days in autumn and for six days in winter. Furthermore, ΔTi is also inversely correlated with ΔHe\(^+\) fraction in September and December.
- When we check the relation between the ion temperature as the independent variable and the helium ion fraction as the dependent variable for nighttime and daytime, we find that there is always a linear part and a flat part for both seasons. The linear relationship is more obvious during the daytime.
- Ion temperature does not show seasonal variation obviously at nighttime. The only difference that can be noticed is ion temperature is lower at 24:00 LT in
autumn (~1300K) compared with the winter at the same time (24:00 LT, ~1400K). However, He$^+$ fraction is larger (~15%) at 24:00 LT in winter but smaller (~5%) in autumn at the same time.

Our observation clearly indicates that the ion temperature does not lead to the seasonal variation of He$^+$ fraction, because the ion temperature does not show seasonal variation and the lower ion temperature in autumn does not guarantee the larger He$^+$ fraction. However, considering the negative correlation between Δ Ti and Δ He$^+$ fraction, we believe Ti can affect the changing of He$^+$ fraction due to the lower Ti resulting in the contracted O$^+$ layer or different chemical reaction rate.

### 4.2 Ion flow Effect on seasonal variation of He$^+$ Fraction

#### 4.2.1 The Correlation between ion flow and He$^+$ Fraction

Ion flow represents the transport process in the topside ionosphere which can dynamically change ion concentration in a specific zone. Because of the large vertical wavelength and the large field line conductivity, ions at the upper altitudes move along with the ions in the lower altitudes in general. Gonzalez et al. [2004] have studied the characteristic of helium ion at solar maximum over Arecibo, they found that helium ion peaks over an altitude range from 700 km to 1000 km. When the vertical motion of the ions is downward in the lower region (below 700 km), ions move from above 700 km to below 700 km. Therefore helium ion fraction will increase in the lower region because of the large concentration at the higher altitude. The seasonal behavior of the vertical ion flow will lead to seasonal variation in helium ion fraction below 700 km.

As discussed in Chapter 3, helium ion fraction becomes prominent earlier (~ 00:00 LT to ~03:00 LT) on December 18-19 in winter than on September 28-29 in autumn (~06:00 LT to ~09:00 LT). Furthermore, the range of prominent He$^+$ fraction is wider (from 00:00 LT to 18:00 LT) in winter than in autumn (from 06:00 LT to 12:00 LT) at upper altitudes.
We assume that the reason why prominence occurred earlier in winter is due to the downward ion flow that occurred more early in winter. So we focus on the vertical velocity of ions at nighttime (from 18:00 LT to 09:00 LT of next day) for the corresponding days to verify this in Figure 4.7.

**Figure 4.7** Vertical velocity of ions and He\(^+\) fraction (blue dot curve) on September 27/28 and on September 28/29 (top panels) and on December 17/18 and 18/19 (bottom panels) at 572km (green curve) and 649km (red curve)

Figure 4.7 shows the vertical velocity is almost same from 18:00 LT to 24:00 LT for four days, but from ~01:00 LT to ~05:00 LT, it shows an obvious difference that the average vertical velocity is ~0 m/s in autumn, but ~30 m/s in winter. This indicates that
the trend that ions move vertically downward is more significant in winter than autumn. Therefore, we find that the value of He\(^+\) fraction keeps increasing from 00:00 LT to 06:00 LT and is beyond 15% at ~ 03:00 LT, but the value of He\(^+\) fraction begins to increase significantly at ~ 03:00 LT and is above 15% at ~06:00 LT. We believe that the helium ions are concentrated earlier below 700 km after midnight in winter, because helium ions move downward at this time from high concentration regions. Therefore, we suggest that downward ion flow result in the phenomenon that helium ion fraction is larger at post-midnight in winter.

In order to find the reason why the prominent He\(^+\) fraction lasted longer time in winter, we focus on the vertical velocity of ions in the whole day for the corresponding four days. Figure 4.8 shows the vertical velocity is essentially all negative in winter from 09:00 LT to 18:00 LT. This means helium ions continue to move downward after sunrise in winter. However, in autumn, the vertical velocity becomes positive at 09:00 LT and keeps this state until 18:00 LT. This means the motion of ions turns upward at 09:00 LT and they keep moving upward from 09:00 LT to 18:00 LT. Therefore, we believe that the downward ion flow during the day time (~09:00 LT to ~18:00 LT) leads to the phenomenon that the prominent He\(^+\) fraction lasts a longer time in winter. Upward ion flow at day time (~09:00 LT to ~18:00 LT) makes the He\(^+\) fraction negligible in autumn below 700 km.
During the daytime, however, the helium ion fraction decreases from ~08:00 LT to ~18:00 LT below 700 km even though ion flow is downward in winter. One hypothesis is that photoionization during the day will produce more oxygen ions, which...
makes O+ more abundant from ~500 km to ~700 km. Figure 4.9 shows, during the day, even if He+ density increases in winter at corresponding time range (09 LT to 18 LT), the He+ fraction that almost equals to He+/O+ decreases significantly at the same time. It indicates that O+ increases significantly from 09:00 LT to 18:00 LT, which verifies our hypothesis. Furthermore, the rapid rise of ion temperature after sunrise will increase the scale height of oxygen ion, which also results in that oxygen ion appears more abundant from ~500 km to ~700 km. Therefore, we believe that the decay of helium ion fraction during day time is caused by a combination of ion temperature, photochemical process and ion flow.

![Figure 4.9 He+ density (m^-3) on September 28-29 (two top panels) and on December 18-19 (two bottom panels) at 649km](image)

Figure 4.9 He+ density (m^-3) on September 28-29 (two top panels) and on December 18-19 (two bottom panels) at 649km
4.2.2 Summary and Conclusion

Ion transport will directly decide ion concentration in a specific zone. We use the four days data (Sep 28–29, Dec 18–19) to observe the difference of vertical velocity and corresponding He\(^+\) fraction. Major characteristics of He\(^+\) fraction and vertical velocity include:

- Helium ion fraction becomes prominent approximately from midnight in winter while the beginning time is ~ 04:00LT in autumn from 550 km to 700 km. The vertical velocity is negative (~ -30 m/s) from 00:00LT to 04:00LT in winter but it is ~0 m/s from 00:00LT to 04:00LT in autumn. Then both of them stay negative from 04:00LT to 09:00LT.

- The prominence of He\(^+\) fraction almost ends at 18:00LT in winter from 600 km to 700 km while it almost ends at 12:00LT from 600 km to 700 km in autumn. The vertical velocity keeps negative from 09:00 LT to 18:00 LT in winter (average value is ~ -20 m/s) but it turns positive from 09:00 LT to 18:00 LT in autumn (average value is ~ 18 m/s).

- He\(^+\) density approximately remains constant (~7 × 10\(^9\) m\(^{-3}\)) from 09:00 LT to 18:00LT in two days of autumn, while it increase from ~5 × 10\(^9\) m\(^{-3}\) to ~15 × 10\(^9\) m\(^{-3}\) from 09:00 LT to 18:00 LT in two days of winter. However, the He\(^+\) fraction continues to decrease at corresponding time range in both season.

From our observation, it clearly proves our assumption that ion flow has effect on seasonal variation of helium ion fraction. During the night, the negative vertical velocity in winter from 00:00 LT to 04:00 LT led to downward ion flow, which caused the prominent phenomenon occurring after midnight in winter. But the vertical velocity was almost 0 m/s from 00:00 LT to 04:00LT and then became negative after 04:00 LT in autumn. So the downward ion flow occurred after 04:00 LT, which resulted in the beginning of prominent phenomenon from 04:00 LT. During the day, because the continuous downward ion flow from 09:00 LT to 18:00 LT can offset the influence of the increasing scale height of oxygen ion and more oxygen ion produced by
photoionization form 600 km to 700 km, the interaction leads to a slower decay of He\(^+\) fraction at this time range in winter. In autumn, the vertical velocity turned to be positive from 09:00 LT to 18:00 LT, so the quick decay of helium ion fraction from 09:00 LT to 12:00 LT is due to the upward ion flow, increasing of scale height of oxygen ion and increasing the photoproduction rate of oxygen ion.
Chapter 5
Conclusions and Future studies

5.1 Conclusions

This thesis focuses mainly on two topics: the variability of helium ion fraction and analysis of seasonal variation of helium fraction. The first focus point studies the helium ion fraction variation as a function of time and altitude. We present the dependence of helium ion fraction on solar cycle, day to night and season from 400 km to 700 km. The second one analyzes the seasonal variation of helium ion fraction from two aspects: ion temperature and ion flow. The data used in this thesis is based on Incoherent Scatter Radar (ISR) from the Arecibo Observatory.

The first part of the thesis presents the morphology of the ionosphere, especially its vertical structure. Then we introduce the Incoherent Scatter Radar (ISR) at Arecibo. Additionally, we discuss the dynamic process of ions in the ionosphere, including production, loss and transport. A diffusion process also plays an important role in the distribution of ions.

The second part of the thesis presents the variability of helium ion fraction from 400 km to 700 km, such as solar cycle variation, seasonal variation and diurnal variation. We show helium ion fraction will be prominent during high solar flux condition and it is hard to observe any unique pattern of helium ion fraction during solar minimum or moderate years. Then we present the diurnal and seasonal variation of helium ion fraction at solar maximum. We show helium ion fraction will be distinct from midnight to noon. The helium ion fraction penetration, however, occurs earlier and lasts longer in solstice than equinox from 550 km to 700 km.
The third part of the thesis is to analyze the seasonal variation of helium ion fraction. A lower ion temperature will decrease the scale height of oxygen ion and there is a strong negative correlation with helium ion fraction in both seasons. Although this may indicate that ion temperature might be one of the causes for seasonal difference of helium ion fraction, there is a lack of seasonal variation in Ti and higher ion temperature (~1400K) corresponds to higher value of helium ion fraction (~15%) at 24:00 LT in winter compared with autumn at the same time (~1300K, ~5%). Both of these observations suggest that temperature is not the major factor controlling the He+. Ion flow can affect ion concentration at a specific region. During night, the negative vertical velocity after midnight results in the downward ion flow, which causes the occurrence of helium ion penetration early from 550 km to 700 km in winter. During the day, the continuous downward ion flow in winter from 09:00 LT to 18:00 LT lowers the decay rate of helium ion fraction due to the increasing scale height of oxygen ion when temperature increases and more oxygen ions are produced by photoionization. So the long-time presence of significant He+ fraction during the day is caused by downward ion flow from 09:00 LT to 18:00 LT in winter. In conclusion, ion flow is the important factor for seasonal difference of He+ fraction in winter and autumn from 550 km to 700 km.

5.2 Future studies

The data set used in this thesis is obtained by incoherent scatter radar, from a single station, Arecibo Observatory, Puerto Rico (18.3° N, 66.8° W). The limited altitude range is from ~150 km to ~700 km and it misses complete data in the summer. We can only compare the phenomenon between autumn equinox and winter solstice. Furthermore, we do not analyze the cause for vertical ion flow. Therefore, in order to overcome the limitations of current study, some future work can be done:

- Find ISR summer data from another solar maximum to analyze He+ penetration phenomenon.
• Study the feature of He\(^+\) fraction above 700 km during solar maximum years. In 2000 or 1988, the Arecibo ISR has data sets with the measurement range from ~150 km to ~2200 km.

• Analyze the reason why there is significant vertical velocity during night in winter. It may be caused by meridional wind which is a wind pattern that turned northward around sunset then turned equatorward, before midnight with velocity in excess of 100 m/s, and turning poleward again after midnight [MacPherson et al., 1998]. The downward velocity may be due to the abatement and subsequent reversal of prevailing equatorward wind after midnight.
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