Detection of He^+ Layering in the Topside Ionosphere Over Arecibo During Equinox Solar Minimum Conditions

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Abstract

We describe recent developments in and results from topside incoherent scatter radar (ISR) measurements at Arecibo, PR, emphasizing helium ion measurements. Recent improvements in the data taking modes and the data processing permit isolation of the concentrations of oxygen, helium and hydrogen ions between the *F* region peak and 2000 km with about 10 minute time resolution. The need for the three ion non-linear least squares fits is justified by use of the goodness of fit; a two ion fit is shown to be unacceptable. The new measurements are optimized for the rapid height variations in the solar minimum nighttime ionosphere by replacing the traditional 1 ms pulse with a 500 μs pulse. We show results from one day of a five day experiment during the Spring of 1994. For these equinox solar minimum conditions, the altitude distribution of the helium ions usually has a maximum near the O^+ to H^+ transition altitude (h_t), forming a distinct layer, most noticeable during the night. The maximum helium ion concentrations tend to be quite low, 2 or $3 \times 10^3 cm^{-3}$, or 10-20% of the topside plasma at the peak of the He^+ layer. The transition altitude, h_t, varies from about 1200 km to 1400 km during the day to near 500 km at night, and the He^+ layer follows this altitude variation. Finally we show that the location of the layer near h_t and its intensification during the night can be explained using ambipolar diffusion equations.

1 Introduction

The earliest experimental studies of the topside ionosphere were done in the early 1960's using spacecraft and incoherent scatter radars, both emerging technologies at the time. *Taylor et al.* [1968] used measurements from the OGO-2 spacecraft to study the topside ionosphere and suggested that at low and mid latitudes (below 60$\deg$) the topside ionosphere consisted mostly of H^+ and He^+ with the helium ion concentration being quite sensitive to solar activity.

Historically, most of the incoherent scatter measurements of the topside ionosphere were done during solar minimum conditions when [He^+] is a small fraction of the total plasma. At Jicamarca, two early studies [[*Farley*, 1966, *Farley et al.*, 1967]] found He^+ to be negligible (less than 10%) and h_t to have a diurnal variation from 700 to 900 km in December, and from 650 to 1150 Km during equinox solar minimum, in general agreement with a more recent statistical study of equatorial topside ion distributions [[*González et al.*, 1992]] that used spacecraft results. These and other early Jicamarca results are reviewed by [*Farley*, 1991]. [*Carlson and Gordon*, 1966] used the Arecibo incoherent scatter radar to estimate the topside He^+ concentrations and found that [He^+]/n_e was never higher than 15%. Interestingly, their data suggest that the He^+ ions are floating in a layer at about 900 km but they do not discuss this feature. In another study, [*Moorcroft*, 1969] used data from the same year (1965) and also found that [He^+]/n_e was never higher than 15%. [*Ho and Moorcroft*, 1971] studied 30 hours of data from an Arecibo topside experiment and found only trace amounts of He^+ during the day and maximum percentages of about 20% at about 700 km at night. The small concentrations reported by these researchers caused the community to dismiss He^+ as a minor species that could be neglected.

Recently, there has been renewed interest in the measurement of helium ions in the topside using the Arecibo ISR. [*Erickson and Swartz*, 1994] show data for winter solar maximum conditions and found peak He^+ fractions of 30%. We now know that this fraction is highly variable and can reach peak values of over 50% of the total plasma depending on season and solar cycle level, these variations will be discussed in another paper. There has also been renewed interest in studying the topside using spacecraft, for example [[*Heelis et al.*, 1990, *Greenspan et al.*, 1994]] that used data from the Defense Meteorological Satellite Program.

In addition to correctly specifying the light ion partitioning in the topside, the inclusion of He^+ in the ISR spectral analysis produces correct topside ion temperatures (T_i) as suggested by [*González*, 1994]. This parameter is essential to the effort to determine thermospheric and exospheric neutral species densities at Arecibo via quantification of the ion-energy balance and charge exchange equilibrium equations. Studies like those of [*He et al.*, 1993] and [*He*, 1995] of the exosphere hydrogen density and escape flux will be significantly improved by more accurate values of T_i.

2 Experiment Description

The Arecibo Observatory is located near Arecibo, P.R. ($18.35°$ N, $66.75°$ W), which is at a latitude of about $30°$ N geomagnetic (or 46.7$\deg$ dip latitude). The ISR technique uses the characteristics of the scattered radio wave, which are related to the properties of the electron density fluctuations in the ionosphere to infer various parameters of the medium such as the plasma density (n_e), the ion and electron temperatures (T_i and T_e), ion-neutral collision frequency (ν_{in}), the composition, and the drift velocity of the plasma [[*Farley*, 1969]].

The incoherent scatter radar can be operated in many different modes, and the parameters must be chosen carefully if one wants to obtain good spectra in low signal-to-noise (S/N) conditions in the upper part of topside ionosphere without causing unacceptable smearing in the lower part. The March 1994 data were obtained by interleaving two pulsing schemes, one for the topside and the other for *F* region. The antenna was pointed to zenith during both modes, and the the second mode was used to provide n_e calibration for the topside data. The topside mode obtained data from 450 to 2200 km; the transmitter used 500 μs pulses with a 15 ms IPP (inter-pulse period). This mode uses 125 Khz bandwidth, and we obtain 38.4 km range gates (32 8μs lags).

In Figure 1 we show a spectrum from below 1000 km where the signal to noise ratio

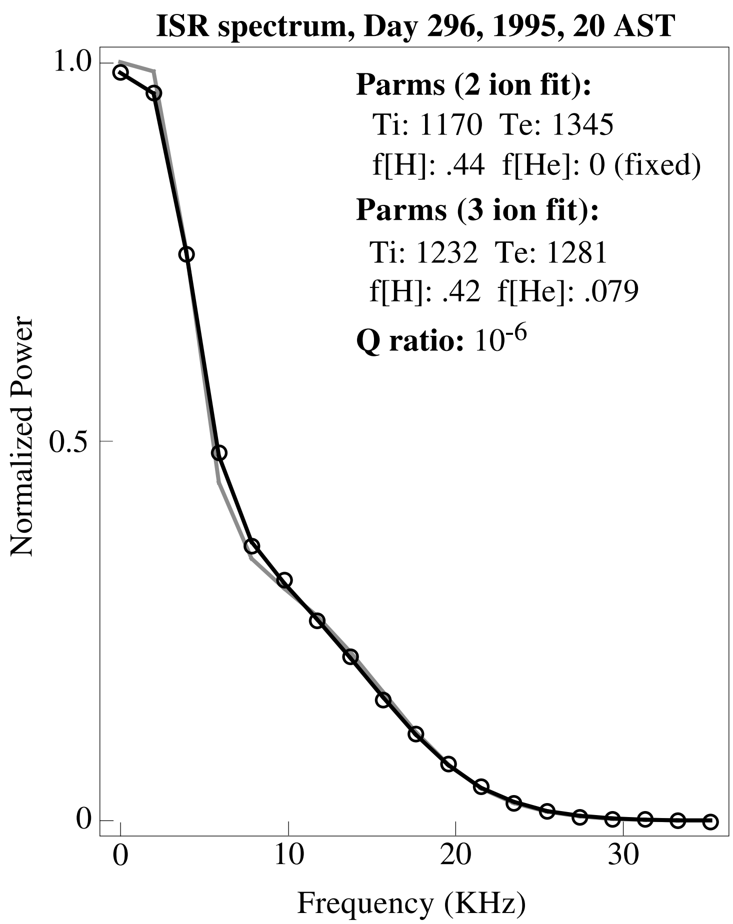

Figure 1: Typical ISR measured spectrum (circles) for high S/N in the lower topside. This particular spectrum is from range 7 (near 700 km altitude). The vertical axis is normalized power and the horizontal axis is frequency. Since the spectrum is symmetric, only half is shown. The spectrum is truncated to 35 KHz in the figure but is really 62.5 KHz wide (125 KHz total). There are two additional lines on this figure, the gray line shows the best fit using a two ion (O^+ and H^+), the black line is the best fit using a three ion model (i.e. including He^+).

is high ($S/N > 1$). The horizontal axis is frequency (KHz), and the vertical axis is arbitrary power on a linear scale. The measured spectrum is given by the circles, while the gray line is a non-linear least squares fit assuming only protons and oxygen ions. The spectrum has the appearance of two spectra superposed, a narrow spectrum (4 KHz wide) that corresponds to O^+ and a wide spectrum (about 16 KHz) that corresponds to H^+. In between, near 10 KHz, there is power in the measured spectrum not present in the two ion model. By trying to fit for this power, the fit at low frequencies (lower than 1 KHz) deteriorates, leading to incorrect temperatures. The black line is a fit for the model that includes helium ions in addition to the other two, and appears to be a perfect fit, as demonstrated by the Q value of .87. In this case there is about 8% helium ions in the topside plasma. The proton fraction is hardly affected, but the ion and electron temperatures are now more realistic (T_e/T_i is about 1).

Consider the equation for χ^2, the sum of the squared differences between the model and data, weighted by the statistical errors. The model is $y = y(x; \mathbf{a})$, where x is the independent variable and $\mathbf{a}$ is a vector of parameters. The error associated with data point j is σ_j. The χ^2 merit function is

$$\chi^2 = \sum_{j=0}^{N-1} \left[\frac{y_j - y(x; \mathbf{a})}{\sigma_j} \right]^2 . \tag{1}$$

In applying Equation 1, it is assumed that the data points are independent, certainly very close to true for all but closely spaced points in a spectrum, since spectra are essentially filter banks, ideally wth no coupling. However, the lengths of the data samples are short, as determined by the length of the radar pulse, and so the filters are far from perfect and the responses must overlap in order to get all of the information about the shape of the process. The effect of the remaining dependence must be allowed when evaluating χ^2 An alternative would be to fit autocorrelation functions, but the merit function for a fit to an ACF is quite complicated because the samples of an ACF can be highly correlated over long delays when the signal to noise ratio is high [[*Huuskonen and Lehtinen*, 1996]], as it is at the altitudes of interest.

For the case of a good model and known values of the σ_js, χ^2 has a definite expected value which is greater than zero since the noise causes a finite χ^2 no matter how the parameters are adjusted. We can compute $Q(\chi^2)$, the probability that a particular value χ^2 or lower is obtained in a fit when the model is good. If a very low value of Q is obtained (large χ^2), then it is very likely that the noise is not the only cause of the deviation from zero, meaning the model is not correct. For good fits Q is expected to be $.5$ [*Press et al.*, 1994].

We calculate $\sigma^2(f) = S(f)/N$, where S is the power density at frequency f, and N is the number of independent samples included in the estimate of S. We checked the computed results against measured variations at the edges of the spectra. It is possible to identify problems with the σs in a trial fit, checking for reasonable values of Q across the entire altitude range of the experiment. Regions where the fit is simple (e.g. nighttime at high altitudes with nearly all H^+ and daytime low altitudes with mostly O^+) can be used as checks on the goodness of fit.

Typical values for the ratio between the 2 ion and 3 ion fit Q's in the altitude region where He^+ is important are on the order of 10^{-4}. It is the spectra that contain similar amounts of H^+ and O^+ that give the largest differences between the two-ion vs. the three ion values of Q. The data are less sensitive to He^+ at other altitudes, certainly because there is less to measure, but also because of other factors. For example, the signal to noise ratio is lower at higher altitudes, and also the decrease in O^+ means that the temperatures become noisier.

Although the values of Q confirm the visual results of Figure 1, they do not make them irrelevant, since it is the graphical results that suggest what changes in the model are required in order improve the fit. When we fit spectra rather than autocorrelation functions, the changes in the parameters correspond closely to localized changes in the spectrum even for relatively subtle effects.

Although the three-ion fits to single height spectra give good results in the lower part of the topside, it is more difficult at higher altitudes where the signal to noise ratio is lower and there is less O^+. We use a technique similar to that described in [*Erickson and Swartz*, 1994], in that the temperatures are constrained in order to prevent large variations that can cause excessive noise in the He^+ fraction. Our improvements to this technique make use of the σs, required for the determination of Q, to control the effects of the temperature constraints, so that the degree of range smoothing introduced in the profile is easily determined.

The spectra are a complicated average over a range determined by the radar pulse length. The data are best expressed as an ACF when considering the range smearing because it is possible to describe the smearing as a one dimensional convolution for each value of delay. This is much simpler than the description required in the frequency domain. We have used a 500 μs pulse in order to minimize these effects. We have simulated the effects of the range smearing on He^+ and have found that the errors that could be caused using a 500 μs pulse are considerably smaller than the statistical errors. For H^+, if one convolves a typical nighttime (and thus rapidly changing) proton altitude profile with a 500 μs pulse, the result is almost identical to the original profile. Convolution with a 1 ms pulse however results in a profile with a slope that is 75% of the original. Surprisingly large relative errors are produced at the bottom of the profile, for example 3% becomes 8% .

3 Results

Figure 2 shows the ion temperature (top panel), proton fraction (middle panel), and helium ion fraction (bottom panel), for the topside ionosphere over Arecibo. The vertical axis in all the panels is altitude (from 450 to 2200 Km). All the panels have time in the horizontal axis from about 17 to 9 Atlantic Standard Time (AST).

The top panel shows several basic features of the thermal structure. During the day the temperature increases with altitude from the O^+ F region at about 1500 K to the protonosphere where the protons are over 3000 K. Typical error bars go from a few tens of degrees at the lower altitudes to few hundreds at the highest. The constraints mentioned in the last section increase the distance between independent measurements to about 300 km at the higher altitudes; it is 75 km at the bottom. The topside cools rapidly near 20 AST, about 1500 K in less than one hour, leading to the collapse of the ion transition altitude from about 1400 km to near 700 km.

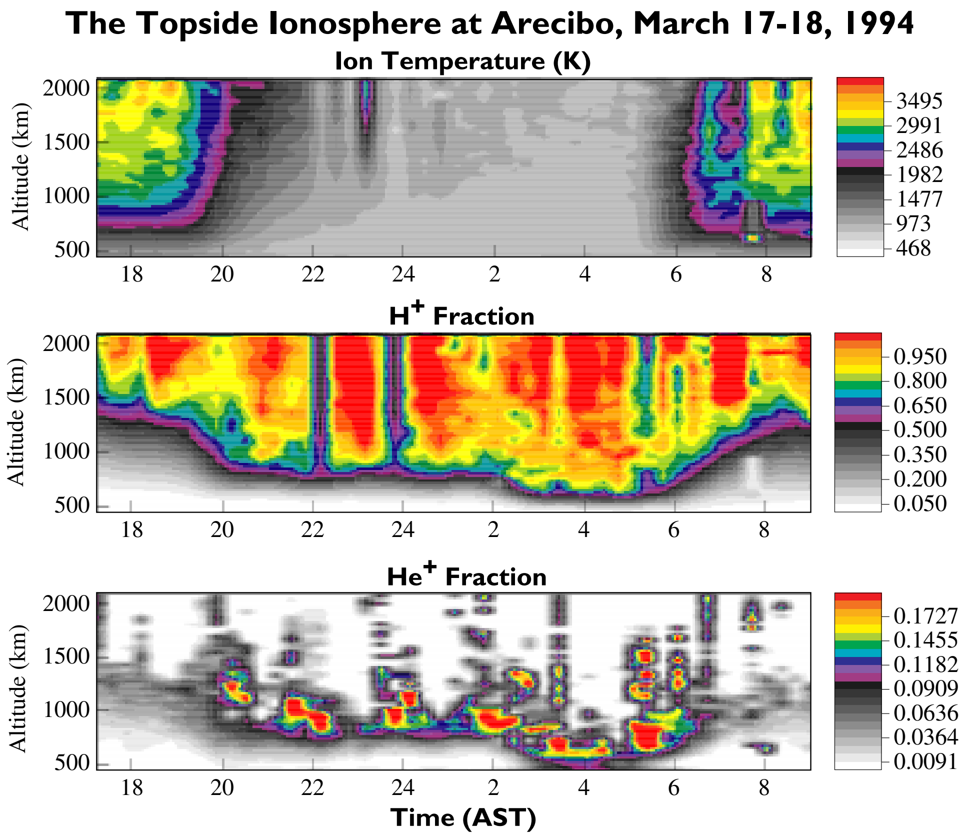

Figure 2: These 3 panels show typical results for our measurements of the topside ionosphere over Arecibo. Shown are the ion temperature (top panel), proton fraction (middle panel), and helium ion fraction (bottom panel). The vertical axis in all the panels is altitude (from 450 to 2200 Km). All the panels have time in the horizontal axis from about 17 to 9 Atlantic Standard Time (AST).

The error bars in the proton fraction range from less than 1% at the lower altitudes to around 4% maximum after the protons become dominant at the higher ranges. The transition altitude h_t is at the level of the first color contour (between black and purple). It collapses from near 1400 km during the day, to around 700 km and remains there until after midnight when a downward flux of protons occurs and h_t descends to near 500 km. At sunrise it quickly returns to 1200 or 1300 Km, somewhat lower than the day before. Notice that during the day the transition from a mostly O^+ plasma to mostly H^+ happens over a 1000 km altitude range, but at night this transition can occur over a range as small as 200 km. This day/night difference affects the He^+ layer as shown in the next section.

It is fairly obvious that the height of maximum helium fraction closely follows h_t. Typical errors in this measurement can reach 4 to 5% at the peak of the layer and are smaller at lower heights. As the night progresses the helium fraction increases. The absolute helium ion concentration (not shown here) also increases. This is related to the width of the O^+ to H^+ transition, as we will show in the next section. The vertical features evident in these three panels are caused by radio frequency interference that contaminates the ISR spectrum.

3.1 Ambipolar Diffusion

In order to explain the physics behind the layer, we begin with the continuity and momentum equations. For diffusive equilibrium the concentration of a given species n is given by:

$$\frac{1}{n}\frac{\partial n}{\partial z} = -\frac{m_i g}{k(T_e + T_i)} \tag{2}$$

where $\frac{\partial n}{\partial z}$ is the vertical derivative, m_i is the ion mass, g is gravity, and k is Boltzmann's constant. Integrating this equation, identifying the plasma scale height, $H_{pl} = \frac{k(T_e+T_i)}{m_i g}$, and applying to the electron density above the F region, we obtain

$$n_e = n_{e0} e^{\frac{-(z-z_0)}{H_{pl}}} \tag{3}$$

so that the density decreases exponentially with altitude. If we follow the same procedure for two ions instead of one, we obtain the following solution for diffusive equilibrium of the minor species:

$$\frac{1}{n_x}\frac{\partial n_x}{\partial z} = -\frac{1}{H_x} + \frac{T_e/T_x}{H_{pl}} \tag{4}$$

where x denotes the minor ion and $H_x = \frac{kT_x}{m_x g}$; the right hand side has a second term with the opposite sign. Above the *F* region peak but below the transition altitude He^+ is the minor species and O^+ is the major species. If we let $T_e = T_i = T_{\mathrm{He}^+}$, perfectly reasonable at night, and recall that oxygen ions are four times heavier than the helium ions (i.e. H_{He^+} is double H_{pl}) the right hand side becomes $\frac{1}{H_{\mathrm{He}^+}}$. The result is that the helium ion concentrations increase exponentially with altitude. Above the transition altitude, the major species is H^+ which is four times lighter than He^+. In this case, $H_{pl} = 8H_{\mathrm{He}^+}$ and the right hand side becomes $\frac{-7}{8H_{\mathrm{He}^+}}$. Thus, the He^+ concentration decreases exponentially. So we see that the helium ions are constrained between the O^+ on the bottom and H^+ on top. During the day, when the transition region is broad, the helium ions accumulate in a rather large region as a minor species. At night, the transition narrows and as the population of helium ions is forced into a smaller volume its concentration increases.

4 Conclusions

Helium ions can not be neglected when analysing Arecibo ISR topside spectra. During the night, helium ions tend to form a layer near h_t. For equinox solar minimum conditions we show here there is a maximum of between 10% and 20% helium ion fraction at the peak of the layer over Arecibo.

Complete datasets of the major plasma parameters in the topside ionosphere, including He^+ concentrations and the correct ion temperatures will be very useful to verify current theoretical simulations. The ability to measure He^+ will directly assist in evaluating helium escape from the atmosphere. In addition accurate measurements of O^+ and H^+, and their temperatures, together with optical measurements of hydrogen density will allow us to quantify the local charge exchange mechanism that is the dominant source of hydrogen escape during both, solar minimum and moderate conditions. The helium ion measurements contribute indirectly to more accurate quantification of upper atmospheric ion-energy balance and charge exchange equilibrium because the temperatures obtained when helium is neglected are incorrect.

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