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The Ionosphere – How Does It Form?

Over the years this column has discussed many aspects of propagation. What's been remiss is a look at the ionosphere itself – specifically how it forms and how it is measured. Let's start by looking at how the ionosphere forms. A caveat - the ionosphere is a complicated system and books have been written on this subject, so this will necessarily be restricted to a general view of the topic along with noting important characteristics. Regardless, there will be a lot of theory here involving fundamental and important concepts and processes, and hopefully this will clear up misconceptions that are seen from time to time in the amateur radio literature.

The electron density in the ionosphere depends on two competing processes: electron production and electron loss. The rate of electron production is equal to the number density of the atmospheric constituents times the intensity of the ionizing radiation times the absorption cross-section of the atmospheric constituents times the ionization efficiency. The rate of electron loss involves three factors (more on this later).

The atmosphere is 78.1% nitrogen and 20.9% oxygen, with the other 1% being several other gases. Digging deeper, we find that the atmospheric constituents that we're interested in for ionospheric purposes are atomic and molecular oxygen (O and O_2, respectively), molecular nitrogen (N_2), and nitric oxide (NO). The first three (O, and O_2, and N_2) are referred to as major species, while the last (NO) is referred to as a minor species. Atomic nitrogen (N) is not in the picture because molecular nitrogen does not directly dissociate to the atomic form. Figure 1 plots the number density of the three major species versus altitude.

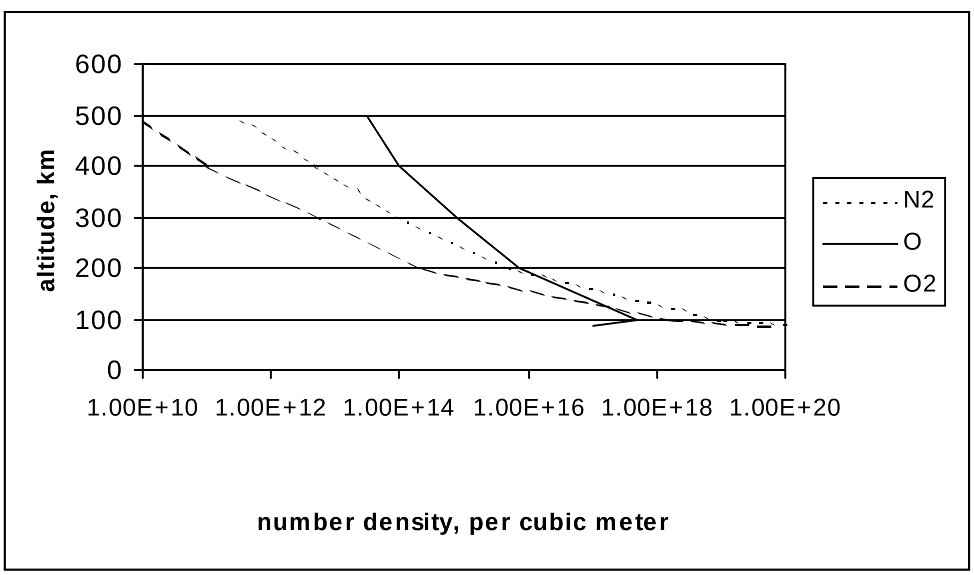

Figure 1 – Number Density of the Major Species

Atomic oxygen is dominant above about 200km. Molecular nitrogen is dominant below about 200km, with molecular oxygen not too far behind. Now we know the number density of the three major species. Next we'll look at the intensity of the ionizing radiation.

Figure 2 shows the intensity of ionizing radiation coming from the Sun at wavelengths between 200 and 1600 Angstroms (this is essentially a picture of the quiet Sun).

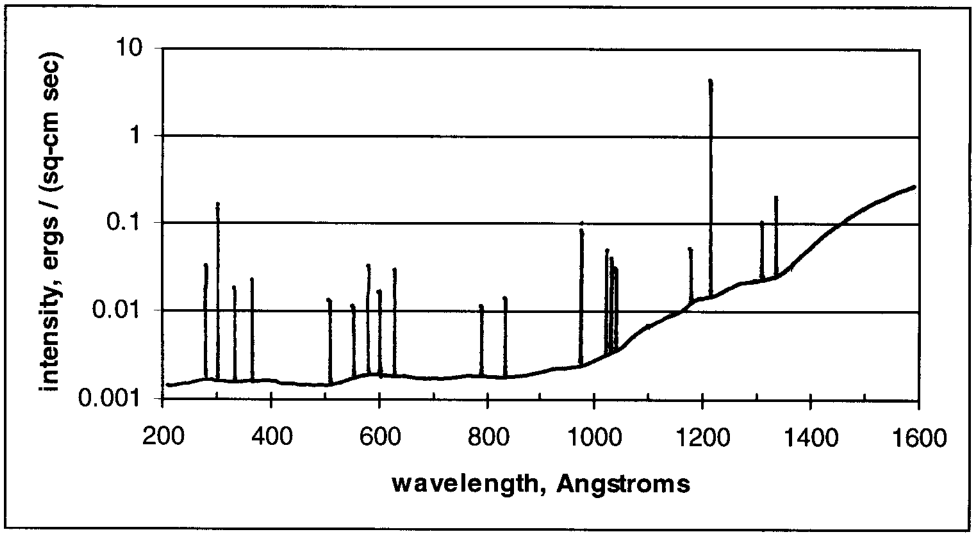

Figure 2 – Intensity of Ionizing Radiation

As can be seen, the intensity is not a smooth function – it has spikes at discrete wavelengths. What we're seeing are spectral lines of the Sun's chromosphere and corona (I've only included the major ones in this graph – those with an intensity greater than 0.01 ergs cm^{-2} sec^{-1}). The most intense spectral line between 200 and 1600 Angstroms is that of hydrogen Lyman-α at 1215 Angstroms – it is at least an order of magnitude more intense than any other radiation in this range of wavelengths.

Do all the wavelengths in Figure 2 ionize O, O_2, N_2, and NO? No, they don't. We have to look at the ionization potentials of our four species and calculate the maximum wavelength that has a quantum of radiation that is greater than the ionization potential (this is done using Planck's constant). Table 1 indicates the maximum wavelength that can ionize each of the four species.

Species	Ionization potential, eV	Maximum wavelength, Angstroms
NO	9.25	1340
O_2	12.08	1027
O	13.61	911
N_2	15.58	796

Table 1 – Ionization Potential and Maximum Ionizing Wavelength

Only wavelengths shorter than 1340 Angstroms can ionize NO (the 1215 Angstrom spectral line in Figure 2 is an important player with NO, as we'll see in a bit). Only wavelengths shorter than 1027 Angstroms can ionize O_2, and so forth for the other two species. There is no ionization at all by any radiation at wavelengths longer than the maximum wavelength, regardless of the intensity (for example, visible light, which is between 4000 and 7000 Angstroms, cannot ionize either of our four species even though its intensity is very high). Now we know the intensity of the ionizing radiation and the maximum wavelength for ionization of our four species. Next we'll look at the absorption cross-section of one of the species.

The absorption cross-section tells us the amount of radiation that is absorbed by the atmospheric constituent. The atmospheric constituent must absorb radiation for ionization to occur. As a result of the radiation being absorbed, the intensity of radiation *decreases* as we go lower in altitude. Going back to Figure 1, we see the number density of atmospheric constituents *increases* as we go lower in altitude. Thus it makes sense that a maximum in the rate of electron production will occur at some altitude since one function is decreasing and the other function is increasing. Indeed, this is what happens in a general sense. I should add that this applies to a simple ionospheric layer – in the real world there are more issues involved.

Figure 3 shows the absorption cross-section of O_2 from 50 to 2400 Angstroms.

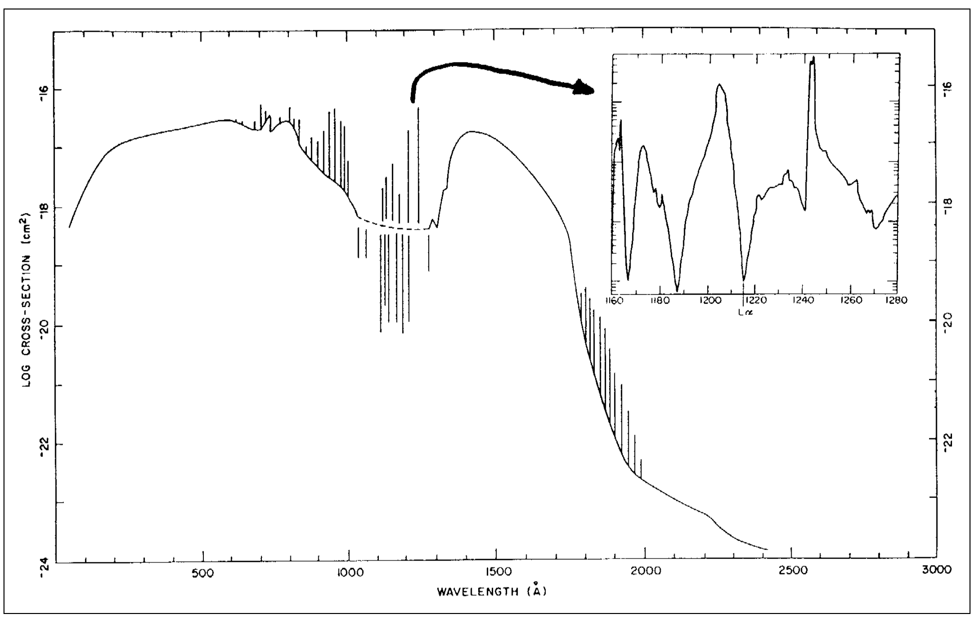

Figure 3 – Absorption Cross-Section of O_2

From Table 1, we know that we only need to consider radiation at wavelengths shorter than 1027 Angstroms for O_2. Figure 3 shows a broad continuum of wavelengths that are absorbed by O_2 – from roughly 100 to 700 Angstroms. From 700 to 1027 Angstroms, we see many discrete lines of increased absorption. Now we know the absorption cross-section of one of our four species, and we could look up the other three. Before looking at ionization efficiency (the last of the four factors that determines the rate of electron production), note the inset in the upper right hand corner of Figure 3.

The inset takes an expanded look at the absorption cross-section of O_2 between 1160 and 1280 Angstroms. The important point here is that the absorption cross-section decreases significantly around 1215 Angstroms (which is the one of the spikes extending below the dashed line in the larger picture). From Figure 2, we know that intense radiation occurs at the hydrogen Lyman-α spectral line at 1215 Angstroms. Thus radiation at 1215 Angstroms isn't absorbed by O_2 (interestingly, it isn't absorbed by any other atmospheric constituent, either) – thus it goes right on down to the lower altitudes where it ionizes NO to give us the daytime D region. Now let's move on to ionization efficiency.

The ionization efficiency takes into account the fraction of the absorbed energy that goes into producing ionization. For example, the ionization efficiency for atomic oxygen is such that all the absorbed energy goes into ion production at the rate of one ion-electron pair for every 34eV of energy. From Table 1, the maximum wavelength to ionize O is 911 Angstroms. Figure 2 shows that the most intense radiation at wavelengths shorter than 911 Angstroms is the spectral line at 304 Angstroms. It's about 0.163 ergs cm^{-2} s^{-1}, which is equal to 1.0 times 10^{11} eV. At 34eV per ion-electron pair, radiation at 304 Angstroms, which atomic oxygen absorbs very well, can create a lot of ionization.

Working out the rate of electron production per the four factors just described (number density of the atmospheric constituents, the intensity of the ionizing radiation, the absorption cross-section of the atmospheric constituents, and the ionization efficiency) is just the first step in calculating the electron density in an ionized layer. The rate of electron loss needs to be figured in to give us the total picture.

The three factors affecting the rate of electron loss are the recombination of electrons with positive ions (important in the E and F1 regions), the attachment of electrons to neutral atmospheric constituents to form negative ions (important in the D region), and the change in electron density due to the bulk movement of plasma (important in the F2 region).

Now you should understand the general process (but maybe not all the details!) to determine what the ionosphere looks like. To work it out in detail, we would have to know the four electron production rate factors for each species at each wavelength. We'd then sum the results for all species over all the wavelengths to determine the total production rate. We'd then determine the electron loss rate. This would then give us the equilibrium electron density versus altitude. Throw in time of day, the season, where we are in a sunspot cycle, and where we are in the world says this is a very complicated calculation. Physical models that do this exist, and they are continually being refined to give us a better model of the ionosphere.

We can summarize everything we've talked about here with a table of the important atmospheric constituents that determine each of the various regions of the ionosphere, along with the wavelengths of radiation that are involved. Table 2 shows this data.

Region	Wavelength of radiation	Atmospheric constituents
D	1215 Angstroms	NO
	2 – 8 Angstroms	O_2, N_2
E	800 – 1027 Angstroms	O_2
	10 – 100 Angstroms	NO, O_2
F1	200 – 900 Angstroms	O
	304 Angstroms	NO, O_2
F2	200 – 1027 Angstroms	O, O_2, N_2

Table 2 – Ionospheric Regions and the Major Players

Before wrapping this up, let's take a look at another interesting characteristic of the ionosphere. Figure 4 adds a typical daytime electron density to Figure 1 (which showed the number density of the major species).

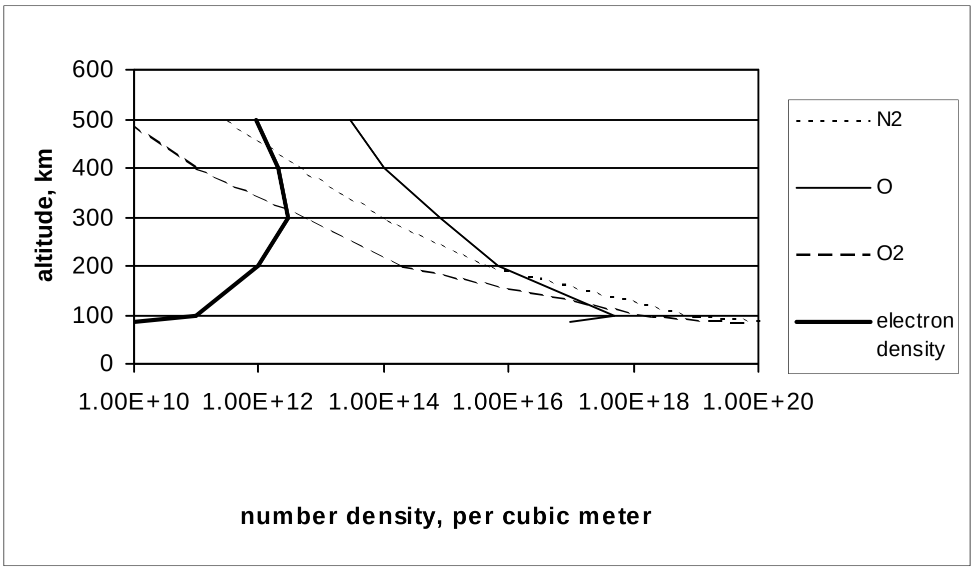

Figure 4 – Typical Daytime Electron Density Compared to Number Density of Major Species

Figure 4 shows us that a typical daytime electron density is orders of magnitude less than the total number of atmospheric constituents (N_2 + O + O_2 plus the others not plotted). At F region altitudes, the electron density is about 4 orders of magnitudes less that the total number of atmospheric constituents. At E region altitudes, the electron density is about 8 orders of magnitude less. In other words, on average, only about one millionth of the atmospheric constituents are ionized - but fortunately that's enough to allow skywave propagation on our HF bands.

This interesting fact is probably the reason why the day-to-day variability of the ionosphere is tied to the neutral atmosphere (which was discussed in the August 2004 column). As we've just seen, neutral constituents (neutrals for short) outnumber electrons and positive ions by about a million to one. Since positive ions have the same mass as the neutrals and collide with them at a high rate, positive ions are carried along by the motions of the neutrals. Electrons then follow the positive ions to maintain charge neutrality. Thus the ionosphere essentially ‘floats’ in the atmosphere, following the non-ionized neutrals. Events in the troposphere, stratosphere, and mesosphere can couple up to and affect the ionosphere – unfortunately these are processes that we don’t have a good handle on yet.

This is a good place to end the topic “how the ionosphere forms.’ In a future column we’ll look at how the ionosphere is measured. Next month we’ll get back to a more practical topic in propagation.