Sporadic E—A Mystery Solved?

In Part 1 of this *QST* exclusive, one of the world's leading ionospheric scientists explains the physics of sporadic E and discusses unresolved problems in understanding its causes.

By Dr David Whitehead

Sporadic E (E_S) remains quite a mystery, even though it has been studied extensively by professionals and amateurs for more than 50 years. This curious form of ionization is called sporadic because its appearance is erratic and unpredictable. The E indicates that it forms within the E region of the ionosphere, generally at heights between 95 and 150 kms (roughly 60 to 90 miles altitude). The electron densities in E_S areas are very high, perhaps 100 times greater than what normally appears in the E region. These high densities often occur in small patches, sometimes called clouds, but E_S can occasionally cover a whole continent.

The main problem for understanding E_S is accounting for the unusually high electron densities in relatively small areas. This article explains how this comes about from the point of view of atmospheric physics, but the question mark in the title suggests that not everything is known about the causes of sporadic E.

Three Sporadic-E Regions

Sporadic E is not a single phenomenon, but a general term for several E-layer conditions that exhibit different properties in various parts of the world. Normal E-region ionization forms a layer about 10 km thick during daylight hours as a result of solar ultraviolet (UV) and soft X-ray radiation. When the sun sets, ionization ceases and ions quickly recombine to form neutral air molecules. Even at mid-day in summer, normal E-layer electron density is insufficient to reflect radio signals back to Earth at a maximum usable frequency (MUF) higher than 22 MHz or so.

Energetic electrons and protons that enter the upper atmosphere around the north and south poles create the ionization required for two types of auroral-zone sporadic E. The first appears as a rather thick layer, rather like normal E-layer ionization, but it usually occurs at night and is irregular in time and space. For this reason it is called *night ES*. The MUF of night E_S can get as high as 20 MHz, about the same as the normal E layer in daytime. The second type, known as auroral E_S, can be observed from scattered radar echoes up to 200 MHz. Radio amateurs have used *auroral ES* at least as high as 144 MHz.

Over the magnetic equator, a similar type of sporadic E forms during daylight hours in a narrow band a few hundred kilometers wide called *equatorial ES*. It gives rise to weak scattering of radio waves below 60 MHz. Its usefulness for communications is limited, because equatorial E_S occurs only in a narrow band close to the magnetic equator. Both auroral E_S and equatorial E_S are caused by a complicated phenomenon called a *plasma instability*, which is discussed in greater detail later.

Sporadic E that forms in mid-latitudes (between the magnetic equator and the auroral zones) is perhaps the most familiar to radio amateurs. It consists of very thin layers of unusually dense ionization only one or two kilometers thick. These dense, thin layers reflect radio waves like a mirror, with greater efficiency and less absorption than the normal E region. The MUF for *mid-latitude ES* can reach 150 MHz and higher. Transmissions via mid-latitude E_S are often stronger and at higher frequencies than nearly any other ionospheric propagation mode.

Explaining how mid-latitude E_S forms is very tricky. Indeed, we physicists have difficulty explaining even the most obvious characteristic of mid-latitude sporadic E—its summer maximum. Nevertheless, much of the basic physics of sporadic E is well known.

Some Ionospheric Physics

It is necessary to look at the E-region atmosphere in order to understand in greater detail the causes of the different types of sporadic E. Most of the E-region atmosphere is composed of ordinary air, primarily oxygen and nitrogen molecules, but about a million times thinner than the air near the ground. Solar UV radiation, as well as liberating electrons from oxygen molecules, also splits a few of the oxygen molecules into atoms, which react with the nitrogen molecules to form nitric oxide. Energetic UV radiation easily liberates an electron from each nitric oxide molecule to create a gas that includes positively charged nitric oxide ions and negatively charged free electrons.

Now we come to some curious physics. Normal (nonionized) molecules, positive ions, and electrons behave like three different gases that can move in different directions simultaneously! The wind in the normal air, called the neutral wind, may be quite different from the ion and electron winds. An electric field will have no effect on the neutral wind, for example, but it will move electrons easily, producing an electron wind (technically, the *mean drift velocity* of the electrons).

The direction of the electron wind depends on the direction of the electric field. A tiny electric field oriented in the direction of the Earth's magnetic field produces such a strong electron wind along the magnetic field that it tends to short out the electric field. The result is that in the E region, all steady electric fields are nearly at right angles to the Earth's magnetic field.

The movement of individual electrons depends on the forces acting upon them. In the absence of any electric field, electrons move in a spiral, the result of a combination of circular motions at right angles to the magnetic field and a steady movement along the field (see **Figure 1A**). All electrons take exactly the same time to complete one rotation, so that fast electrons move in larger spirals than slower ones.

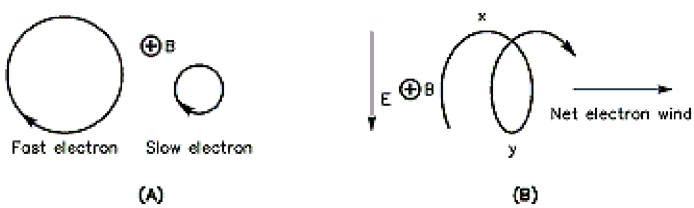

Figure 1—The net motion of electrons in the presence of a magnetic field B, perpendicular to the page, and electric field E, parallel to the page. At A you can see that in the absence of an electric field, the spiraling motion of electrons is primarily at right angles to the magnetic field. At B you'll see that with the addition of an electric field, electrons move at variable speeds. They speed up at point x and slow down at y, thus tracing out spirals with constantly changing diameters. The resulting net electron wind is at right angles to both the magnetic and electric fields.

If there is an electric field perpendicular to the magnetic field (the most common configuration in the ionosphere), electrons spiral at variable speeds. An electron moves fastest when accelerated by an electric field (point x in **Figure 1B**) and so begins a large spiral. When the electron is slowed down by the electric field force (point y), the spiral is more tightly curved. The net result after many spiral revolutions is that all electrons move at right angles to both the magnetic and electric fields at the same net velocity, creating an electron wind.

Electrons sometimes collide with neutral atoms, but these collisions are relatively infrequent and their effect on the electron wind in the E region can usually be ignored. Nevertheless, these collisions account for the absorption of radio waves passing through the ionosphere and they play an essential role in the production of equatorial E_S.

In contrast, ion collisions with neutral molecules are more frequent and have a greater effect on the way the ions move. The ions hardly start on their curves before they collide with air molecules and on average come to rest. So ions make a whole series of small slightly curved tracks broken with each collision. See **Figure 2**. The net ion wind flows mostly in the direction of the steady electric field, but there is also some movement in the same direction as the electron wind.

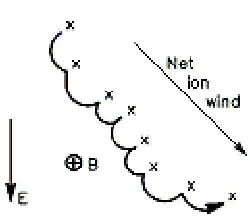

Figure 2—The net motion of ions in the presence of magnetic and electric fields. Ion motions are interrupted by frequent collisions with netural air molecules at the points marked x. The resulting ion wind is partly in the direction of the electric field and partly in the direction of the electron wind, but at lower speed.

A neutral wind perpendicular to the magnetic field hardly moves the electrons at all, but the effect of such a wind on ions is much greater. The resulting ion wind flows mostly in the direction of the neutral wind, but also a little bit sideways due to the effect of the magnetic field, as shown in **Figure 3**. The sideways ion wind is vital to the formation of mid-latitude E_S in wind shears.

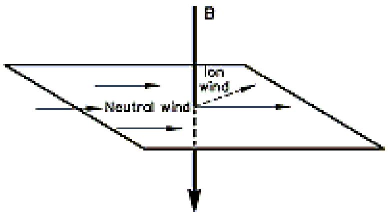

Figure 3—A neutral wind perpendicular to the magnetic field B creates a slightly skewed (and slightly slower) ion wind.

Plasma Instability

The gases in the ionosphere can be considered a *plasma* because they are partially ionized. Instabilities in the E-layer plasma are important to understanding certain types of sporadic E and other strange phenomena. Plasma instabilities are much like many other sorts of more familiar physical instabilities. Imagine cars moving at high speed on a freeway, for example. One car slows down slightly, causing the following cars to slow. In turn, the cars further behind on this stretch of freeway are forced to slow down as well. The cars move dangerously close together. The initial slowing of one car leads to traffic bunching and potential catastrophe—an instability.

In the plasma instability, bunches of ions appear, like the cars on the freeway. Electrons are attracted to the ion bunches in order to keep electric charge neutral everywhere, and thus stronger and stronger bunches of ionization appear. They have the shape of long needles pointing along the Earth's magnetic field and so are called "field-aligned irregularities" (FAI). Radio signals scattered from field-aligned irregularities are strong enough well into the VHF range to be useful for oblique-path communications. Similar bunching gives rise to auroral and equatorial E_S.

The bunches of electrons normally move at nearly the same speed as the electron wind. If the electron wind is slow enough relative to the ion wind, the ions and electrons cannot bunch together. Bunching in the E region (and thus an instability) occurs when the difference between the ion and electron winds exceed the ion sound velocity. The *ion sound velocity* is the speed of sound in a gas composed of ions, or about 400 m/sec (nearly 900 mph) in the E layer—somewhat greater than the speed of sound in the atmosphere near the ground. Doppler shifts of radar echoes scattered from E-layer instabilities have shown the speed of bunches of ions and electrons do, in fact, move at about the ion sound velocity. In the auroral region, ions are heated up enough to increase their sound speed to rather more than 400 m/sec, often exceeding 1000 m/sec. Great instabilities can be expected as a result.

Neutral winds move ions and electrons in the entire E region covering the daylight side of the Earth. A neutral wind in the direction of the magnetic field moves both the ions and electrons at the same speed as the neutral wind, so that there is no electric current flow. In contrast, neutral wind blowing across the magnetic field drives the ion wind at nearly the same velocity as the neutral wind, but hardly moves the electrons at all. Therefore an electric current flows. This quickly builds up electric charges at various places. The resultant electric field now drives the electron wind across both the magnetic field and electric field.

For a given neutral wind pattern, it is possible to calculate the resultant ion and electron wind, although it is quite a complicated business and requires a computer. What is important is that nearly everywhere the ion and electron winds are about the same order of magnitude as the neutral wind, but in different directions. Typical neutral winds vary between 10 and 100 m/sec, with 50 m/sec (about 110 mph) being average. The resulting ion and electron winds also average about 50 m/sec. The ion and electron winds are not exactly in opposite directions, so the difference between the two is usually only a little greater than 50 m/sec. Normally, winds of these velocities are too slow to cause E-layer plasma instabilities, but conditions over the geomagnetic equator and in the auroral zones are somewhat different.

Equatorial Sporadic E

At mid-latitudes, any electric current in the vertical direction (such as created by an ion wind) is readily counteracted by a flow of electrons along the sloping magnetic field lines. This movement prevents any build up of space charge above and below the ionosphere. See **Figure 4**.

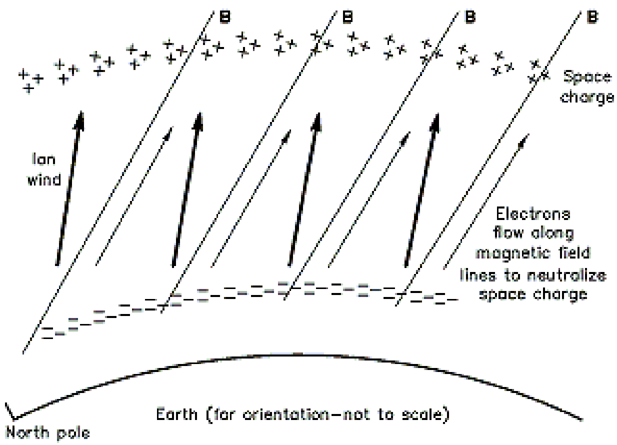

Figure 4—At mid-latitudes, electrons flowing along sloping magnetic field lines B quickly neutralize any charge above or below the ionosphere created by a vertical electric current.

This process does not happen near the magnetic equator, where the magnetic field is horizontal in a north-south direction. Near the equator, the electric field is also horizontal, but in an east-west direction, because it must be perpendicular to the magnetic field. The ion wind, powered by neutral winds blowing at other latitudes, is roughly 50 m/sec and almost horizontal as well, but the resulting electron wind is vertical! This is because the electron wind must be at right angles to the electric field.

Immediately a strong electric field builds up between the top and bottom of the ionosphere. See **Figure 5A**. This field cannot be shorted out by the electrons flowing along the magnetic field, because the magnetic field is horizontal. The vertical electric field at the equator has to be powerful enough to move ions as fast as the vertical electron wind in order to stop further build up of charge.

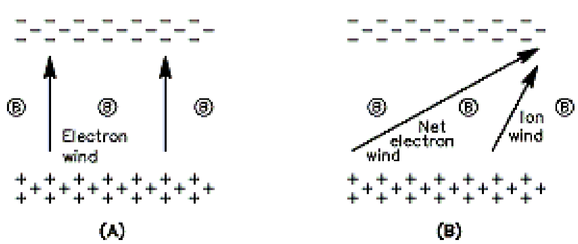

Figure 5—The ionosphere near the equator, where magnetic field lines B are horizontal (perpendicular to the page). Near the magnetic equator (A), the electron wind blows vertically and a strong charge builds up above and below the ionosphere. Electrons are unable to travel along the magnetic field to neutralize the charge because the field lines are horizontal. When the vertical electric field becomes strong enough (B), ions move fast enough to keep up with the electron wind to prevent further build up of a charge. This electric field makes the horizontal part of the electron wind large enough to trigger an instability. Simultaneously, there is a strong horizontal current flow.

At the same time, the strong electric field creates a horizontal electron wind in the east-west direction with a speed about 10 times greater than the original ion wind and in the opposite direction. The resulting electron wind is about 500 m/sec, great enough to cause a plasma instability. See **Figure 5B**. The magnetic field has to be horizontal to within a degree or so for the physics to work like this, and so the effect is only seen very close to the magnetic equator.

The high wind velocity of the electrons causes quite noticeable changes in the magnetic field at the Earth's surface, due to the strong current flow known as the *equatorial electrojet*. The plasma instability that results from the high-speed electron wind bunches the electrons and ions into long, horizontal, needle-shaped irregularities pointing north-south. These irregularities are the source of equatorial E_S, which return only weak echoes in the VHF range and so may not be useful for amateur communications. Magnetic storms often reduce the east-west electric field at the magnetic equator and so prevent the formation of the instabilities that give rise to equatorial E_S. Otherwise, equatorial E_S can be observed during most daytime hours all year round using powerful VHF radars and ionosondes.

Incidentally, during the day, the vertical wind of both the ions and electrons is usually directed upwards and extends right into the F region, like a fountain. The ionization then falls down along magnetic field lines both sides of the equator to give rise what radio amateurs know as F-layer trans-equatorial propagation. An instability here gives rise to FAI in the F region just north and south of the magnetic equator.

Auroral Sporadic E

The action of the solar wind can induce large electric fields in the Earth's magnetosphere many thousands of kilometers over the auroral regions. These electric fields drive the electron wind at speeds of up to 2000 m/sec across the Earth's magnetic field, more than enough to cause insta-bility. According to theory, the irregularities ought to be field aligned, but observation shows that irregularities can be up to 10 degrees away from the field direction. Radio amateurs can observe unusually wide scattering directions when using auroral E_S.

My own explanation for this oddity involves the most unstable needle-shaped irregularities. These rapidly growing irregularities form about a degree off perfect field alignment, but twist further out of alignment due to large-scale irregularities. They reach their maximum strength just as they are moving at the ion sound velocity (rather than the faster electron wind speed). The strongest radio echoes therefore appear just when the irregularities have the ion sound velocity. They then twist further out of alignment and decay.

Stay Tuned!

Next month I'll discuss mid-latitude sporadic E and the role of metal ions, and will propose an interesting hypothesis!

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