A Review of Equatorial Spread *F*

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Abstract

Equatorial spread F is a spectacular phenomenon in which the equatorial region ionosphere is reshaped after sunset. The plasma instabilities responsible for equatorial spread F are fascinating since they occur on time scales ranging from seconds to hours and length scales from centimeters to tens of kilometers. The plasma irregularities that occur in the F region also influence the performance and reliability of space borne and ground based electronic systems that may cause the disruption of satellite operations, communications, navigation, and electrical power distribution grids, leading to potentially broad economic losses.

Extensive experimental and theoretical research has been performed in the last 30 years to study equatorial spread F. These studies have shown that plasma instabilities play a major role in the generation of the irregularities. This work presents a review of the current theoretical and experimental research on equatorial spread F.

The earth's atmosphere varies in density and composition as the altitude increases above the surface. The lowest part of the atmosphere is called the troposphere and it extends from the surface up to about 10-km. The gases in this region are predominantly molecular Oxygen (O_2) and molecular Nitrogen (N_2). All weather is confined to this lower region and it contains 90% of the Earth's atmosphere and 99% of the water vapor. The highest mountains are still within the troposphere and all of our normal day-to-day activities occur here.

The atmosphere above 10 km is called the stratosphere. The gas is still dense enough that hot air balloons can ascend to altitudes of 15 - 20 km and Helium balloons to nearly 35 km, but the air thins rapidly and the gas composition changes slightly as the altitude increases. Within the stratosphere, incoming solar radiation is able to break up molecular Oxygen (O_2) into individual Oxygen atoms, each of which, in turn, may combine with an Oxygen molecule (O_2), to form ozone, a molecule of Oxygen consisting of three Oxygen atoms (O_3).

The gas becomes increasingly rarefied at higher altitudes. At heights of 80 km (50 miles), the gas is so thin that free electrons can exist for short periods of time before they are captured by a nearby positive ion. The existence of charged particles at this altitude and above signals the beginning of the ionosphere, a region having the properties of a gas and of plasma.

Plasma instabilities, which occur in the postsunset equatorial region of the ionosphere, are collectively termed equatorial spread *F* (ESF). These plasma instabilities occur over a broad range of time and length scales, spanning several orders of magnitude. This makes the ionospheric *F* region an excellent location to test new plasma and fluid turbulence theories. These plasma irregularities have become important to us lately because of its tendency to interfere with the operation of space borne and ground based technological systems. Specifically, a signal emitted from a source above the earth's atmosphere interacts with the ionosphere as it travels through space to the receiving point, usually a receiving station on the ground. The received signal, usually above 40 MHz in frequency, displays rapid fluctuations in phase and amplitude that are not consistent with changes in the source strength and modulation. The analogy used to describe the resulting scintillations is the "twinkling" of a star as observed by the naked eye. In ideal viewing conditions, a star would appear to have a constant brightness. However, what is often seen is a situation in which the brightness of the star fluctuates rapidly. These diffraction effects could cause severe problems in critical systems such as satellite operations, communications, navigation, ballistic missile defense systems, over the horizon targeting methods, and electrical power distribution grids, leading to potentially broad economic losses.

The first detection of an ESF event was reported in the 1930's by *Berkner and Wells* [1934] at Huancayo, Peru using an ionosonde. An ionosonde can be viewed as a HF sweep frequency radar which receives signals from regions where the transmitted frequency is near the electron plasma frequency [*Rishbeth and Garriot*, 1969]. When an ionosonde attempts to measure the reflection height of the *F* region while the instability process is taking place overhead, the resulting ionogram echo trace will be spread out in either frequency or range due to the multiple reflection paths created by the turbulent ionosphere. Thus, the term spread *F* was coined to describe this effect.

Our understanding of ESF has increased dramatically since these early traces on ionograms. Today, ES F is studied by using an armada of instruments, including ground based radar, sounding rockets, conventional ionosondes, topside ionosondes, in situ probes, airglow measurements, and propagation of satellite beacons (phase and amplitude scintillation). ESF can show different features depending on their stage of development and on the particular observational technique that is being used. Therefore, it is important to review the different techniques used to detect an ESF event.

Ground based radar can be used to examine ESF events in great detail. When directed perpendicular to the magnetic field they are able to detect coherent backscatter echoes from field aligned irregularities that satisfy the Bragg backscatter condition. Thus, λ is the wavelength of the transmitted signal, irregularities of scale size 0.5 λ are detectable. As an example, the Jicamarca 50 MHz radar (λ = 6 m) detects only 3 m wavelength irregularities. Numerous experimenters have undertaken radar studies of ESF.

Woodman and Lahoz [1976] describe four types of ESF as seen with the Jicamarca radar. One of these types is valley spread *F*, which can occur in the valley region of low electron density between the *E*, and *F* layer. Weak bottomside spread *F* is another type that is usually present in a thin layer on the bottomside postsunset density gradient. Another type is developed bottomside spread *F*, which extends from the weak bottomside region through the topside. Finally, bubbles or plumes have been observed which extend from the weak bottomside through to the topside. The upwelling plume has been interpreted as rising plasma bubbles by *Woodman and Lahoz* [1976].

A spectacular example of an ESF event is shown in the range-time intensity (RTI) map of figure 1. This plot, which displays the signal to noise ratio as a function of altitude and time, displays several of the irregularity types that occurred on October 17, 1996. There are two distinct occurrences of ESF in this plot, one before midnight and one after midnight. A bottomside spread *F* event is first seen between 250 - 350 km before 2400 LT. Several recent studies have been undertaken to study bottomside spread F including *Kuo et al.* [1998]. Valley-region echoes can be seen below the bottomside layer between 0000 LT and 0200 LT. These valley region layers have been examined extensively by *Hysell and Farley* [1996]. Finally, spread *F* plumes can be observed occurring at 2300 LT, 0300 LT, and 0500 LT. These spread *F* plumes extend up above 500 km in this example.

Numerous rocket and satellite campaigns have penetrated the bottomside and plume structure of ESF. Satellites and rockets use a variety of instrumentation to measure ESF events. Instruments such as Langmuir probes, retarding potential analyzers and drift meters measure the temperature, concentration and drift velocity of the plasma. For a complete description of the instrumentation the reader is referred to *Hanson and Heelis* [1975] and *Kelly* [1989]. When these in situ instruments fly through regions of ESF, sharp plasma density bite outs of up to three orders of magnitude are observed as the result of the low-density plasma bubbles rising through the *F* region.

When radio propagation methods are used to observe an ESF event, strong scintillations are detected in the amplitude of a constant frequency signal that is transmitted from a satellite located above the instability region. A Faraday rotation of the polarization plane of the signal usually accompanies the scintillation. These features

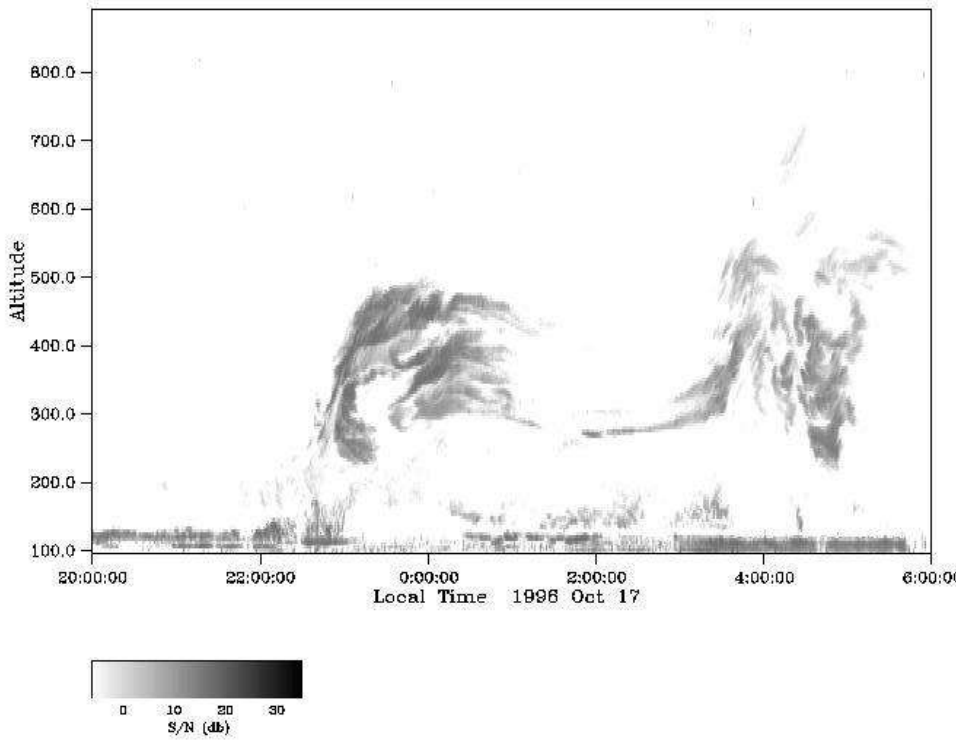

Figure 1: RTI plot of October 17, 1996. This night shows several different types of equatorial spread F.

indicate the presence of a region of density irregularities coexisting with a reduction in the total electron content (TEC) along the raypath from the satellite to the ground receiving station. These scintillation techniques when coupled with radar and in situ measurements have provided evidence on the intermediate wavelength structure (100 m - 1000 m) of ESF [*Basu and Kelley*, 1979]. These studies indicate that large-scale features of ESF can remain in the medium for a considerable length of time. *Mendillo and Tyler* [1983] have also used this technique to make quantitative measurements of the plume tilt. They show that the westward tilt of an ESF plasma plume increases as the plumes rise in altitude.

The advances in experimental technique used to detect ESF have resulted in a clearer picture of the fundamental processes underlying ESF. *Dungey* [1956] was the first to propose that the gravitational Rayleigh-Taylor (GRT) instability was the driving mechanism for ESF. The process was originally discounted by *Farley et al.* [1970] since alone it could not explain the observations that irregularities were generated simultaneously below, above and at the *F* peak. Linear theory predicts that GRT instability occurs only on the bottomside of the plasma density profile where the electron density gradient is upward. However, the GRT instability was reconsidered as the driving process when the topside plumes were considered to be rising plasma bubbles *Woodman and Lahoz* [1976].

Numerical simulations have played a large role in the understanding and testing of ESF theories. Numerical simulations have reproduced the development of ESF and the upwelling of plasma bubbles in the topside of the *F* region. These nonlinear simulations of the GRT instability have produced many of the observed characteristics of ESF. These characteristics include bottomside and topside ESF, bubble formation, and bubble evolution.

These early experimental and theoretical successes have answered some of the questions regarding ESF. These plasma instabilities are known to occur when *F* layer rises rapidly and develops a steep bottomside gradient due the to combined effects of chemical recombination and an increase in the vertical plasma velocity. These conditions result in a *F* layer plasma density profile which may become unstable to the interchange instability and cause high plasma density magnetic flux tubes at the bottomside of the ionospheric F region to change places with lower density flux tubes from below in a situation analogous to the hydrodynamic Rayleigh-Taylor, heavy fluid over light fluid instability.

The similarity of ESF to the hydrodynamic Rayleigh-Taylor instability prompted early theoretical investigators to concentrate on calculating expressions for the linear growth rates of the instability [*Ossakow*, 1981]. These growth rate expressions could be divided into two regimes. The collisional regime is that region in which the ion and electron Pederson drifts, due to ion-neutral and electron-ion or electron-neutral collisions, are the dominant drifts contributing to the plasma current. The inertial regime is that region in which the polarization current, due to time-varying electric field is the dominant effect.

The resemblance of a rising plasma depletion to a classical rising bubble in a fluid also lead to a formulation of a classical fluid analogy for ESF [Kintner and Seyler-1985]. The fact that the equations of motion resemble Navier Stokes turbulence has important implications due to the 2D turbulence theory developed by *Kraichnan*, [1967]. Kraichnan was able to show that a two-dimensional fluid stirred at some intermediate scale would lead to an energy and enstrophy cascade. The energy has a reverse cascade to large scales where it builds up, while enstrophy cascades to smaller scales where it is ultimately dissipated by viscosity. The one-dimensional energy spectra scale as $E(k) \propto k^{-3}$ in the enstrophy cascade range and as $E(k) \propto k^{-5/3}$ in the energy cascade range.

However, some key questions remain. Is there an inertial regime in the postsunset topside equatorial ionosphere and if so where is it? Is it a function of altitude, longitude, time, or seasonal condition? If there is an inertial regime, does a two-dimensional cascade region exist?

As recently as five years ago, a plasma bubble could be considered in the collisional regime if

$$R > \frac{4g}{\nu_{in}^2}$$

where R is the bubble radius, g is the acceleration due to gravity, and ν_{in} is the ion-neutral collision frequency. The above equation predicts that a rising plasma bubble would always enter the inertial regime if its altitude were high enough since at a certain point the ion-neutral collision frequency would be small enough that the inequality would no longer be valid. As an example, for a 50km radius bubble would enter the inertial regime around 550km. As recently as two years ago, the inertial regime was predicted never to occur by Sultan [1996]. His result was based on the ratio of Rayleigh-Taylor instability growth rate to ion-neutral collision frequency and predicted that the collisional instability is dominant at all ionospheric heights. However, his model is not appropriate for the topside ionospheric *F* region since it is a linear model.

Recently, *McDaniel and Hysell* [1997] predicted the location of the inertial regime using a realistic computer model, which took into account dynamic effects along with the flux-tube integrated Pedersen conductivity of the ionosphere. They then found that the spectra of density fluctuations measured by the Dynamics Explorer II satellite within the altitude/local-time windows prescribed for the inertial regime had universal $k^{-5/3}$ spectral indices, constituting evidence of a turbulence cascade. Spectra of data from outside those windows did not. However, the theoretical model put forward to describe the inertial regime flow differed substantially from the Navier Stokes equations, containing cubic nonlinearities and requiring large amplitude plasma density fluctuations for inertial effects to be important. The inertial regime may therefore support turbulence, but evidently not classical Navier Stokes turbulence.

The results presented by *McDaniel and Hysell* [1997] change the current view of the ionospheric F region. The inertial regime exists. However, it is not a place but a set of geophysical conditions that depend upon local time, apex height, longitude, density depletion amplitude, and solar condition.

The predicted inertial regime window is rather narrow. It occurs most frequently from 2000 to 2100 local time and at an altitude from 600 to 900 km, where the average plasma depletion rise velocity in the inertial regime window exceeds 170 m/s. How likely is a rocket or satellite to fly through an inertial regime? A review of 91 days of JULIA radar data from August 1996 to April 1997 showed that while 9 of 91 had irregularities in the inertial regime window only 1 of 91 had significant vertical velocity. Therefore, we conclude that the probability of encountering an inertial regime bubble with "in situ" probes is small.

While the inertial regime window is small in physical size, its effect on the propagation of optical signals is clear. These ionospheric plasma irregularities act as a diffraction screen [*Briggs*, 1958; *Chytil*-1968]. This has an enormous effect on any signal that must propagate through the ionosphere. How does the existence of an inertial regime change this picture? The structures produced by inertial regime flow are more organized and coherent than the collisional regime flow, and there is enhanced small-scale structure. The increased small-scale structure has a large impact on the diffraction of optical signals since the diffraction screen is changed from the collisional case. The diffraction screen for inertial regime flow has a finer grid separation and its effect on optical signals is increased. The numerical and optical techniques, which will be developed to deal with collisional regime flow, must be extended to account for inertial regime flow. If inertial regime flow is not included in the optical correction methods, a disruption of critical systems could result.

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Biography

An assistant professor in the Department of Physics, Rick McDaniels earned his Ph.D. from Clemson University, where he also worked as a research assistant. Publications include articles in *Geophys. Res.* and the *Bulletin of American Physical Society.*