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Plasma bubbles in the topside ionosphere: Estimations of the survival possibility

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ABSTRACT

The question about the survival possibility and the life duration of the topside ionosphere equatorial spread F (ESF) plasma bubbles observed in the separate ion component (He^+) is investigated. For this aim the main aeronomy processes, in which plasma bubbles and their He^+ ions are involved, were under consideration. It was obtained that the main competition takes place between the He^+ loss reactions (He^+–N_2 reaction) and the uplift during linear growth phase (~10 min) of the Rayleigh–Taylor (R–T) instability, when the plasma bubbles are forming. It was revealed that the ambipolar diffusion of the He^+ ions inside the plasma bubble is the fastest (~1–2 min) in the altitude region up to 500 km and becomes slower (~1 h) above 500 km. On the other hand, the plasma bubbles seen in He^+ density are pretty stable structures against the cross-field (Bohm) diffusive collapse. It was concluded that the ESF plasma bubbles, reaching the "ceiling" heights, can exist for a night and several morning hours (~10–13 h) and that there is a principal opportunity to observe them in the separate ion component (He^+).

1. Introduction

There are numerous indications (e.g., Woodman and La Hoz, 1976; Tsunoda et al., 1982) that the equatorial spread F (ESF) plasma bubbles can reach the topside ionosphere altitudes. However there is no common opinion about the "ceiling" altitudes of this lifting. Some investigators believe that the statistical "ceiling" altitude is ~2000 km (e.g., Su et al., 2006). Other investigators inform about the plasma bubbles detected at higher topside altitudes, e.g., ~2500 km (Sahai et al., 1994) and ~3500 km (Burke et al., 1979). According to Burke et al. (1979) the wide scatterings of the observed "ceiling" altitudes are directly connected with variability of the observation conditions. First of all it depends on the local time of the observations. It was pointed out that it is "impossible to observe the plasma bubbles at altitudes greater than 2000 km in the early evening local time sector" because the time is not enough for such lifting. However, lifting up to 3000 km is possible after post-midnight (Burke et al., 1979). It has also been pointed (McClure et al., 1998; Gentile et al., 2006) that some conditions depending on the solar activity level, season and longitude favor the plasma bubble development and lifting to extreme high topside altitudes.

It is known that the plasma bubbles spread due to diffusion processes along the magnetic tubes in the process of their uplifting. Such field-aligned bubbles look like "bananas" with the extremities reaching the ionosphere altitudes possibly in both hemispheres (Abdu et al., 2000). (Some authors (e.g., McClure et al., 1998) specify these structures, calling them as "aneurisms".) So extended bubbles surrounded by a halo of more small-scale irregularities (Aggson et al., 1992) can be detected by satellites not only above the equator but also in the low-latitudinal region and partly in the mid-latitude region. It means that the apexes of the plasma bubbles can reach altitudes up to 4000 km. However, nobody has seen the plasma bubble apexes above 3500 km though their extremities are often detected far away from the equator (e.g., Su et al., 2006). It is reasonable to suggest that there is a problem in their detection. Perhaps, it is impossible to see the plasma bubbles if we try to measure their local electron component (*Ne*) only since the background local electron density of the topside ionosphere becomes comparable with the same bubble density.

Some investigators (Ott, 1978; Ossakov and Chaturvedi, 1978) consider that the equality of the plasma bubble density (*Ne*) and the background density means that bubble rise stops (a buoyancy argument) and the bubble disappears soon. However, Mendillo et al. (2005) pointed out that flux tube-integrated electron densities inside and outside the plasma bubble are rather responsible for plasma bubble uplift/stop. More recently, using the

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SAMI3/ESF model calculations, Krall et al. (2010) argued that the main factor of plasma bubble uplift/stop is a balance between the integrated *ion mass density* in flux tube containing the bubble and the density of neighboring undisturbed flux tubes. It was derived that the driving term is proportional to the flux tube-integrated ion mass density. (Moreover, important details of the ESF plasma bubble evolution/motion were also revealed. It was shown that the local "buoyancy" of the bubble at its apex continues to increase after the bubble stops. Krall et al. (2010) suggested that this process can form various "fossil" configurations of ESF plumes/bubbles after upward motion has halted.)

The last finding means that the plasma bubble may be detected in separate ion components unbalanced with the same components in surrounding undisturbed flux tubes. The idea about the plasma bubble detection in *the separate ion components*, e.g., in He^+ density, was put forward by Sidorova (2007, 2008) (hypothesis about the equatorial origin of the He^+ density subtroughs). The idea was well supported by statistical studies which pointed that there is genetic connection between the He^+ density depletions (subtroughs) and the equatorial plasma bubbles (Sidorova, 2004, 2007, 2008; Sidorova and Filippov, 2012). According to the above mentioned idea the plasma bubbles become "visible" in minor species (e.g., in He^+ density) since the background He^+ density strongly increases at the upper topside altitudes and shows contrast with insignificant small He^+ density content inside the plasma bubble. So, according to the ISS-b data (high solar activity, 1978–1981), the equatorial plasma bubbles are detected in *the topside ionosphere* as *Ne* density depletions only in 3% of the cases (46 cases in 1700 passes) (Maryama and Matuura, 1980). However, there is a distinctly different picture for the He^+ density depletions (subtroughs) obtained from the ISS-b data. They are observed in 11% of the cases (440 cases in ~4000 passes) (Sidorova, 2007).

The plasma bubbles, reaching their "ceiling" altitudes in the topside ionosphere, are often called as "dead bubbles" (Aggson et al., 1992) or fossil bubble signatures (Sidorova, 2007). It means that the bubbles lost ability for further rise and, as a next step, they tend to collapse. It is reasonable to ask: how soon do they disappear? For example, McClure et al. (1998) has informed about the high-reaching, long-lived bubbles which were observed until after sunrise. So, the main question is about the survival possibility and the lifetime of the plasma bubbles reaching the topside ionosphere altitudes.

We suppose that ESF plasma bubbles can be observed in the separate ion component (He^+). Hence, we should investigate whether this assumption is consistent within the theoretical framework or not. Obviously, for this aim we should estimate and compare the characteristic times of the main processes in which plasma bubbles and their He^+ ions are involved. These estimations can help illuminate the questions about *the principal opportunity* to observe ESF plasma bubbles in the He^+ density and *the duration* of such observations. It seems to us that this approach could be useful in study of the survival possibility of the ESF plasma bubbles at the topside ionosphere altitudes.

2. Numerical estimations

Let us estimate and compare the characteristic times of the main *aeronomy* processes, in which ESF plasma bubbles and their He^+ ions are involved. We will consider the recombination reactions of He^+ ions, the plasma bubble vertical drift transport and the diffusion transport of the plasma bubble minor component (He^+). Namely, we will estimate the ambipolar diffusion (a) and the cross-field (Bohm) diffusion (b). If the plasma bubbles seen in the He^+ ions are capable of "living" until daytime, we shall analyzed the influence of the daytime processes.

It is necessary to make a remark that all estimations will be done under conditions of high and maximal solar activity.

2.1. He^+ recombination processes

It was supposed that ESF plasma bubbles are produced by collision Rayleigh–Taylor (R–T) instability at the bottomside of the F-layer (~350–400 km). Ion composition inside the bubbles indicates that they originated at these altitudes. For example it was found by Hanson and Sanatini (1973) that the metal ions or the ions, which are heavier than O^+ and typical for the bottomside ionosphere, are presented in the bubble ion composition. According to the radar observations in Arecibo (Wilford et al., 2003) the typical value of He^+ density at the bottomside of F-layer (high solar activity, October, 2001) is equal to $(0.25–3) \times 10^3\ cm^{-3}$.

Hence the initial He^+ density of the bubbles, which are just formed and ready to uplift, is rather small. Thus, the He^+ ions are the minor species of the bubble ion composition.

It is known that the He^+ ions most quickly "perish" in the binary recombination reactions with neutral molecular oxygen (O_2) and nitrogen (N_2):

$He^+ + N_2 \rightarrow He + N + N^+ \rightarrow He + N_2^+$

$He^+ + O_2 \rightarrow He + O + O^+ \rightarrow He + O_2^+$.

There are some questions regarding the velocity of these reactions and surviving He^+ ions in the bubble ion composition. Since the background densities of the neutral particles vary with respect to altitude, the velocity constants of the binary reactions also vary. So, it is reasonable to estimate the characteristic times of these loss reactions for two characteristic altitudes, e.g., ~400 km and 700 km. The first altitude is typical for the region of the plasma bubble formation. The second one is the topside ionosphere altitude, where the developed plasma bubble can appear.

The times of the He^+ recombination can be estimated as

$$T \approx (k(He^+,\ N_2)n(N_2))^{-1} \text{ in the reaction with } N_2, \tag{1}$$

$$T \approx (k(He^+,\ O_2)n(O_2))^{-1} \text{ in the reaction with } O_2, \tag{2}$$

where $k(He^+, N_2)$ and $k(He^+, O_2)$ (the velocity constants of the binary reactions) are equal to 1.4×10^{-9} and $10^{-9}\ cm^3/s$, respectively (McEwan and Phillips, 1975); $n(N_2)$, $n(O_2)$ are the density values of N_2 and O_2 taken at the appropriate altitudes.

It is easy to find that the He^+ ions recombine at the altitude of ~400 km with the characteristic time $T \cong 7 \times 10^2\ s \sim 12$ min (He^+–N_2 reaction) and $T \cong 2 \times 10^4\ s \sim 6$ h (He^+–O_2 reaction). $n(N_2)$, $n(O_2)$ densities taken at the altitudes of ~400 km are equal to 10^6 and $5 \times 10^4\ cm^{-3}$, respectively (Fatkullin et al., 1981).

If the plasma bubbles reach the topside ionosphere altitudes (~700 km), the loss reaction effect becomes insignificant for the He^+ density variations in the bubble ion composition. The characteristic times are $T \cong 7 \times 10^7\ s \sim 2$ years (He^+–N_2 reaction) and $T \cong 10^9\ s \sim 31$ years (!) (He^+–O_2 reaction), where $n(N_2)$, $n(O_2)$ are equal to $5 \times 10\ cm^{-3}$ and $1\ cm^{-3}$, respectively (Fatkullin et al., 1981).

Hence, the loss reactions of He^+ are the fastest (He^+–N_2 reaction) at the bottomside of F-region and they are extremely slow in the topside ionosphere (years!). That is why they may be disregarded in this region.

Thus, the problem of the He^+ survival in the plasma bubble ion content depends on (1) how fast the initial perturbations flow up, when the plasma bubbles form, and (2) how fast the plasma bubbles reach the topside ionosphere altitudes.