A system science perspective of the drivers of equatorial plasma bubbles

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1 Abstract

The complex drivers of equatorial plasma bubbles and resulting scintillation requires a system science approach spanning the M-ITM disciplines. The current roadmap missions strongly support this approach, but gaps are identified in planned observations, with potential mission and solutions proposed.

Recommendations for the Heliophysics Roadmap:

1. **The complex drivers of equatorial plasma bubbles requires a system science approach spanning the M-ITM disciplines.**
2. **Currently planned missions including AWE, GDC, and DYNAMIC all contribute to this system science approach.**
3. **Measurements of the ions and neutral in the bubble seeding region (200-300 km altitude) are required to complete this approach, requiring the support of a mission concept like EN-LoTIS or EPIC in the Decadal Roadmap.**

2 Executive Summary / Condensed initial recommendations

Recommendations for the Heliophysics Roadmap:

1. **The complex drivers of equatorial plasma bubbles requires a system science approach spanning the M-ITM disciplines.**
2. **Currently planned missions including AWE, GDC, and DYNAMIC all contribute to this system science approach.**
3. **Measurements of the ions and neutral in the bubble seeding region (200-300 km altitude) are required to complete this approach, requiring the support of a mission concept like EN-LoTIS or EPIC in the Decadal Roadmap.**

3 Background

Equatorial Plasma Bubbles (EPBs) are known by many names, including ionospheric plumes and Equatorial Spread F (ESF) [1]. The varying nomenclature is associated with the different observational techniques used to study them, since the 4-dimensional morphology of the bubble structures is never fully revealed by any single measurement approach. Different techniques yield different insights into the structures, because each views only a small part of the phenomenon. For example, when observed with airglow imaging from high altitudes the depleted plasma structures are C-shaped wedges [2], but airglow images of the depletions in the plane perpendicular to the geomagnetic field show multiple tilted branches extending from a plume-like base [3]. These structures can extend hundreds of km in longitude and thousands of km in latitude. At low altitudes, the bubbles are initiated at the bottom side of the ionosphere by mesoscale undulations with horizontal wavelengths of several hundred kilometers. The appearance of these waves near 300 km altitude is a precursor to the formation of bubbles [4].

The problem of plasma bubble prediction has been outstanding for over 80 years [5] for several reasons:

- Global daily measurements of the existence / non-existence of bubbles is lacking.
- Global daily measurements of the variability of the drivers of bubbles is lacking.

In general, plasma bubbles form when mesoscale waves (such as Gravity Waves) create a perturbation in the bottomside ionosphere when the ionosphere is sufficiently unstable. If the Rayleigh-Taylor Instability growth rate is large and positive, the perturbation will grow into a large plume of depleted plasma that grows into the topside region [6, 7]. The growth rate is dependent on field-line integrated quantities, meaning that growth is not solely dependent on the local ionospheric conditions. Multiple paths and sources of energy conspire together to enhance or suppress the growth of plasma bubbles.

Neutral Wind Dynamo: The global scale neutral wind dynamo plays a large role in setting up the conditions necessary for the Rayleigh-Taylor instability. Electric fields generated by dynamo action of the thermospheric neutral winds in the E region causes a vertical E×B drift of the F region plasma at the magnetic equator. To first order, this drift is upward during the day and “reverses" downward at night. In the late afternoon, when the E region density decreases, the F region dynamo becomes more significant. The F region dynamo, in conjunction with the conductivity gradient across the terminator, causes a “pre-reversal" enhancement (PRE) of the eastward electric field and hence the upward vertical plasma drift. In the evening, in the absence of sunlight, the E region ionosphere rapidly decays and a steep density gradient develops on the bottomside of the raised F region, which is the condition under which the Rayleigh-Taylor (RT) instability forms [8].

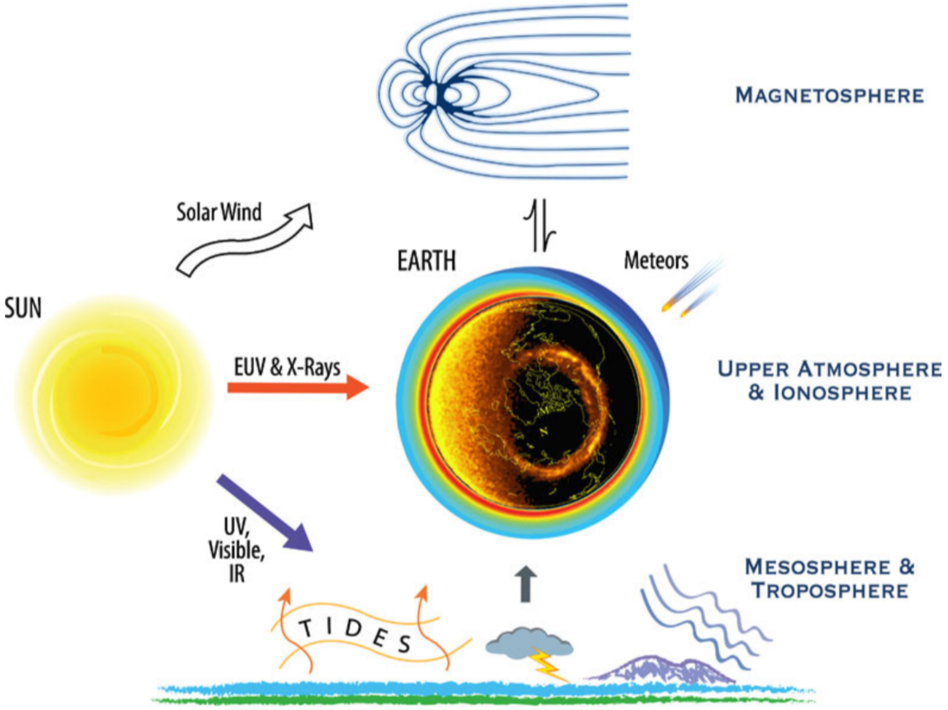

Figure 1: Ionospheric structure is modulated through multiple energy paths [9]

Solar Radiation: EUV radiation from the sun drives direct ionization of the ionosphere, as well as heating the thermosphere in which the ions form. This is an integrated effect, meaning that the energy deposited over the course of a day for a given location determines the ion distribution and loss at night.

Tides and Planetary Waves: Global-scale waves in the neutral atmosphere known as tides have a strong effect on the longitudinal distribution of ions [10]. Waves with multi-day periodicities are a strong candidate for the day-to-day variability of bubble formation, as these could enhance the likelihood one night and suppress it the following night [11, 12].

Geomagnetic Storms: Rapid changes in the high-latitude regions can drive the global ion and neutral distribution through Travelling Atmospheric Disturbances and Penetrating Electric Fields [13, 14]. Simulations have shown that the same storm can enhance the likelihood of bubbles in one longitudinal sector and suppress them elsewhere [15]. Additionally, changes in geomagnetic activity earlier in the day can affect the growth of bubbles in the evening [16].

Metal Ions: The presence of heavy metallic ions from smoke and meteoric debris in the E-region has been shown to suppress the likelihood of bubbles [17].

Natural Hazards: Volcanic activity and other impulsive events can have a strong effect on space weather. The 2022 Hunga-Tonga eruption showed a strong effect on thermospheric winds and currents [18, 19], and left behind an ionospheric hole near the eruption and a trail of plasma bubbles after the shock wave passed [20].

All of these effects work together to alter the structure of the ionosphere and thermosphere, which in turn determines whether an atmospheric seed will grow and form into a bubble. Untangling the effects of these competing drivers is the key challenge.

4 Outstanding Problems

Due to the scale size of the bubbles themselves, the dynamics across altitudes, and temporal range of the drivers, single point measurements are unlikely to capture some events, and miss important dynamics, spatial structures, and the evolution of plasma bubbles. Multiple missions and ground-based observatories are often used to better capture the influence of the various contributions to bubble formation. This lack of adequate data coverage has limited the field's ability to make substantial progress in determine the drivers and their relative contributions to bubble formation and evolution. While single satellite studies provide important insights, they inherently miss many events. In fact, by capturing these limited glimpses of plasma bubbles, misinterpretations of their characteristics, and thus their relationship to the different drivers are expected.

In order to accurately validate models and understand the drivers of plasma bubbles, constellation missions are necessary. Opportunistic studies and events which can make use of *ad hoc* constellations can help us push forward on this compelling and long unanswered science question. In addition to thinking about a constellation flying at a single altitude, satellites and/or remote sensing instruments that can probe other altitudes is necessary. As plasma bubble dynamics change significantly with altitude, it is important that we ensure missions can capture the 3-D spatial and temporal structure of these dynamics across a wide variety of scale sizes.

The orbital geometry of a single spacecraft limits *in situ* observations of bubbles from space. Single point measurements increase the likelihood of missing events, and orbital precession changes where events can be observed. This has led many space-based studies to focus on climatology rather than day-to-day variability.

Some Questions:

- What is the role of global-scale neutral waves in forming EPBs and/or determining their global distribution?
- What is the role of electric fields produced by magnetospheric forcing in the formation of EPBs?

4.1 Existing Measurements

- The GOLD mission is currently providing daily measurements of the ionosphere over the American sector, including bubble activity.

- The ICON mission is currently detecting bubbles from *in situ* plasma measurements and from remote far ultraviolet measurements. Additionally, it provides remote wind profiles, allowing for the the variability of the thermospheric drivers of the ionospheric dynamo.
- COSMIC-2 provides both *in situ* measurements of plasma bubbles as well as Radio Occultation measurements of the resulting scintillations from six platforms.
- DMSP (F17, F18) SSUSI observes plasma bubbles in near real time.

5 Recommendations

5.1 New Measurements

A number of missions in operation and on the current roadmap will provide new and exciting insights into some of the drivers discussed here.

- The AWE mission (launching in 2023) will provide measurements of the Gravity Waves that can act as the seeds for plasma bubbles.
- The Geospace Dynamics Constellation (GDC) will provide into how the drivers from high latitudes control the distribution and motion of ions and neutrals at lower latitudes. In later phases, the spacecraft will be separated in longitude, providing more global context.
- DYNAMIC will provide low altitude thermospheric winds that drive the dynamo. Polar orbiting measurements will allow the derivation of daily tides.

However, there are key gaps in this existing roadmap when looking at the system science approach discussed here. In particular, low altitude *in situ* measurements of ions and neutrals would capture the bottomside formation of bubbles. Future mission concepts such as EN-LoTIS (ESA/NASA Lower Thermosphere-Ionosphere Science) could fill in the gap.

Another concept that could fill in this gap would be the Equatorial Plasma Ionospheric Coupler (EPIC) mission, which would provide two equatorial elliptical spacecraft with it in situ instrumentation with a third spacecraft focused on remote measurements. This combination would provide comprehensive measurements of bubbles and their drivers.

Where large missions are not planned to make required measurements, small satellites can also be used to fill in the gaps [21]. The reduced development time could mean that the community should be planning these missions now to provide maximum impact alongside their larger counterparts.

5.2 Systematic modeling

Modeling techniques that incorporate growth rate analysis from a global perspective can be used to determine the relative importance of each energy path that modifies the equatorial regions.

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