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A system science perspective of the drivers of equatorial plasma bubbles

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

KEYWORDS
ionosphere, thermosphere, plasma bubble, system science, plasma irregularities, space physics

Introduction

Equatorial Plasma Bubbles (EPBs) are known by many names, including ionospheric plumes and Equatorial Spread F (ESF) (Kelley et al., 2011). 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 (Kil et al., 2009), but airglow images of the depletions in the plane perpendicular to the geomagnetic field show multiple tilted branches extending from a plume-like base (Makela and Otsuka, 2011). 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 (Hysell, 2000).

Bubble structure observation is further complicated due to the range of scale-sizes of density variations associated with EPBs, such as scintillation structures (e.g., (Magdaleno et al., 2017)). Scintillation has often been used to determine the presence or boundaries of EPBs (Cervera and Thomas, 2006), but the relationship between scintillation intensity and EPBs is not understood. Scintillation observations offer unique challenges. While *in-situ* observations provide very detailed and accurate information of small-scale structures, observations utilizing remote sensing are highly dependent of the orientation of the signal path to the scintillation region, thus limiting their ability to fully ascertain the scintillated structure size and intensity. Further, intense scintillation can result in loss-of-lock of signals, limiting observations of strong scintillation regions.

The problem of plasma bubble prediction has been outstanding for over 80 years (Booker and Wells, 1938) 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.

Drivers of plasma bubbles

In this framework, we will separate the drivers in terms of both mesoscale (100 s of km) and large-scale (1,000 s of km) features. 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. The definition of "sufficiently" here depends largely on the amplitude of this seed wave (Retterer and Roddy, 2014). A mesoscale seed with a sufficiently large amplitude could amplify the instability of the ionosphere in a region. The mesoscale waves as a seeding mechanism is strongly supported by observations of bubbles with a periodic spacing (e.g., Aa et al., 2020) The variability of Gravity Waves and their contributions to ionospheric structure is reviewed in Zawdie et al. (2022).

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 (Ossakow, 1981; Sultan, 1996). Likewise, if the growth rate is large and negative, bubbles can be suppressed. 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 condit`ions 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 (Abdu, 2019).

Solar radiation

EUV radiation from the Sun drives direct ionization of the ionosphere, as well as heating the thermosphere in which the ions form (Schunk and Nagy, 2009). 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. The changes in the ionospheric profile can affect the formation of bubbles over long terms (Huang, 2002).

Tides and planetary waves

Global-scale waves in the neutral atmosphere known as tides have a strong effect on the longitudinal distribution of ions (Heelis and Maute, 2020). 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 (Liu et al., 2013, 2021).

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 (Kelley et al., 1979; Abdu, 2012). Simulations have shown that the same storm can enhance the likelihood of bubbles in one longitudinal sector and suppress them elsewhere (Carter et al., 2016). Additionally, changes in geomagnetic activity earlier in the day can affect the growth of bubbles in the evening (Carter et al., 2014a).

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 (Huba et al., 2020).

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 (Harding et al., 2022; Le et al., 2022), and left behind an ionospheric hole near the eruption and a trail of plasma bubbles after the shock wave passed (Aa et al., 2022).

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 for Space Weather prediction.

Additionally, bubbles take time to grow, can last for a long time, and drift in east-west direction (including co-rotation with the Earth). While understanding the conditions for bubble growth is critical, it may be equally important to understand the decay of bubbles and its dependence on geospace conditions.

Challenges

Due to the scale size of the bubbles themselves, the smaller scale size of density structures associated with bubbles (i.e., scintillation), 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 addition, capturing low-altitude measurements where bubbles are first formed increases satellite drag, which limits the lifetime of the spacecraft. 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.

Open 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?

Current roadmap

Key observables

The first key observable is the identification of the existence of plasma bubbles, along with any accompanying scintillation. This can be achieved on the ground *via* All-Sky Imagers, radar, GPS Total Electron Content (TEC) measurements, and from space *via in situ* plasma density measurements and remote imaging. Both types of measurements are needed, as ground-based gives near-constant monitoring for a fixed location and space-based can give global sampling. Combined observations from ground-based and space-based measurements can fill in the gaps in detection (e.g., Ngwira et al., 2013; Aa et al., 2020).

One of the key measurements needed for many of the forcing mechanisms here is that of the neutral atmosphere. This includes both neutral density and wind information over multiple longitudes to extract tides and planetary waves, as well as changes to the neutral wind dynamo and traveling atmospheric disturbances. It is important to note that changes in the neutral atmosphere can affect both the seeding mechanisms and the large-scale forcing mechanisms.

Another key component that needs longitudinally distinct measurements is that of electric fields and ion drifts. These can arise from Penetrating Electric Fields from storms, as well as the Neutral Wind Dynamo.

Finally, E-region measurements, including plasma density and metallic ions, have a significant effect on the ionospheric conductivities in the growth rate. Measurements from ionosondes and lidar can help shed light on this variability.

Existing measurements

- The GOLD mission is currently providing daily measurements of the ionosphere over the American

and Atlantic sectors, including bubble activity (Eastes et al., 2020; Martinis et al., 2021).
- The ICON mission is currently detecting bubbles from *in situ* plasma measurements and from remote far ultraviolet measurements (Mende et al., 2017; Immel et al., 2018). Additionally, it provides remote wind profiles, allowing for the variability of the thermospheric drivers of the ionospheric dynamo (Harding et al., 2017).
- COSMIC-2 provides both *in situ* measurements of plasma bubbles as well as Radio Occultation measurements of the resulting scintillations from six platforms (Schreiner et al., 2020).
- DMSP (F17, F18) SSUSI observes plasma bubbles in near real time (Comberiate et al., 2010; Paxton et al., 2018).
- All-Sky Imagers around the world (e.g., Pimenta et al., 2003; Martinis and Mendillo, 2007; Shiokawa et al., 2015; Sharma et al., 2017) provide monitoring of bubbles.
- Ground-based TEC networks (e.g., Pi et al., 1997; Valladares and Chau, 2012; Olwendo et al., 2013) and ionsonde networks (e.g., Bullett et al., 2010; Reinisch and Galkin, 2011) can provide detection of bubbles and scintillation.

Upcoming 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 (Taylor et al., 2020).
- 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 (Jaynes et al., 2019). 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 (National Research Council, 2013). Polar orbiting measurements will allow the derivation of daily tides.

Discussion

However, there are key gaps in this existing roadmap when looking at the system science approach discussed here. Identifying the nightly existence/non-existence of bubbles globally requires a spacecraft approach, but this could take an *in situ* or remote approach. The GOLD spacecraft images the American and Atlantic sector nightly from a geostationary orbit at a relatively high sample rate, allowing for the identification of bubble onset times (Martinis et al., 2021). The images could be extended to multiple longitudes either through a different orbit (sacrificing revisit time for coverage) or by additional geostationary platforms.

From a satellite perspective, a very low inclination orbit (~15^o) would be desired. This allows for full coverage of the geomagnetic equator region. Pairing *situ* measurements with remote measurements would fill in the holes and provide information on the large-scale forcing that can enhance or suppress the growth of bubbles. A concept that implements this approach is the Geospace Observing System (listed as "FMT-4" in the LWSAC final report), which would provide two equatorial elliptical spacecraft with *in situ* instrumentation with a third spacecraft focused on remote measurements (Cohen et al., 2022). By pairing two elliptical orbits such that the apogee and perigee are in sync, the total satellite drag is reduced while low-altitude measurements are not compromised. This combination would provide comprehensive measurements of bubbles and their drivers.

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.

Where large missions are not planned to make required measurements, small satellites can also be used to fill in the gaps (Verkhoglyadova et al., 2021). The reduced development time could mean that the community should be planning these missions now to provide maximum impact alongside their larger counterparts.

As mentioned earlier, scintillation observations by remote sensing alone such as GNSS radio occultation (RO) may not provide accurate or spatially complete information regarding these structures. It is important that the number and orientation of RO line-of-sights through a given scintillation region be maximized. While the existing roadmap takes advantage of RO for EPB system science, the planned RO combined with *in-situ* observations will not adequately address the scintillation aspect of the system. However, taking advantage of commercial data buys for ionospheric RO data, small satellite hosting RO sensors, and RO sensors utilizing multiple GNSS constellations (e.g., GLONASS, Galileo), will enable EPB system science to include the generation and coupling of the smallest density structures associated with the phenomenon.

Numerical models of equatorial plasma bubbles have advanced significantly in the last 40 years (Yokoyama, 2017). One current divide is the scale sizes in the model required to capture global forcing vs. a high resolution localized model to capture bubbles development. 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 (e.g., Carter et al., 2014b;

Hysell et al., 2022; Smith and Klenzing, 2022). Another path forward is to incorporate variable grid scale ionosphere in a global model (Huba and Liu, 2020).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JK wrote the first draft of the manuscript. All authors contributed to manuscript concept and revision, including reading and approving the submitted version.

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Conflict of interest

Author RB was employed by The Aerospace Corporation.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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