

Low Latitude Plasma Blobs: A Review

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In recent years, there has been renewed activity in the study of local plasma density enhancements in the low latitude *F* region ionosphere (low latitude plasma blobs). Satellite, all-sky airglow imager, and radar measurements have identified the characteristics of these blobs, and their coupling to Equatorial Plasma Bubbles (EPBs). New information related to blobs has also been obtained from the Communication/Navigation Outage Forecasting System (C/NOFS) satellite. In this paper, we briefly review experimental, theoretical and modeling studies related to low latitude plasma blobs.

Keywords: plasma blobs, low latitude ionosphere, equatorial plasma bubbles

1. INTRODUCTION

There have been numerous observational and theoretical studies of magnetic field aligned plasma density depletions in the low latitude ionosphere, termed Equatorial Plasma Bubbles (EPBs) (Woodman 2009; Kelley et al. 2011; Kil 2015; and references therein). In addition to EPBs, plasma density enhancements (plasma blobs) have also been observed in the low latitude ionosphere as narrow positive spikes of plasma density along a satellite's orbit. Oya et al. (1986) were the first to report low latitude plasma blobs, using data from the Hinotori satellite. Subsequently, Le et al. (2003) and Park et al. (2003) analyzed data from the ROCSAT-1, KOMPSAT-1, and DMSP satellites. Pimenta et al. (2004) presented the first observations of low latitude plasma blobs using combined ground-based optical and radio techniques. Dashora & Pandey (2005) observed localized enhancements of Total Electron Content (TEC) in the nighttime low latitude ionosphere from Global Positioning System (GPS) data, which were interpreted as a manifestation of plasma blobs. New information about low latitude plasma blobs and their relation to EPBs, has been obtained from measurements using the Coupled Ion-Neutral Dynamics Investigation (CINDI) instrument onboard the Communication/

Navigation Outage Forecasting System (C/NOFS) satellite (e.g., Kil et al. 2011; Choi et al. 2012; Haaser et al. 2012).

The underlying mechanisms causing the plasma blob phenomenon remain under investigation. Three-dimensional simulations by the SAMI3 model demonstrated a creation of plasma blobs through a "super fountain effect" within EPBs (Huba et al. 2009; Krall et al. 2010). However, Kil et al. (2015) suggested that Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) may be a major source of plasma blobs during periods of solar minimum. The aim of this work is to review the observational evidence for low latitude plasma blobs, the interpretation of their physical characteristics, and their numerical simulation.

2. OBSERVATIONAL RESULTS

Examples of low latitude plasma blobs, observed *in situ* by the satellite DMSP F12 in the post-sunset sector of Local Time (LT), are illustrated in Fig. 1. Plasma blobs were present at an altitude of ~840 km on December 23, 1996, during low levels of solar activity (Fig. 1(a)), and at ~860 km on August 17, 2001, during high levels of solar activity (Fig. 1(b)). The plasma blobs are local, well formed, and are

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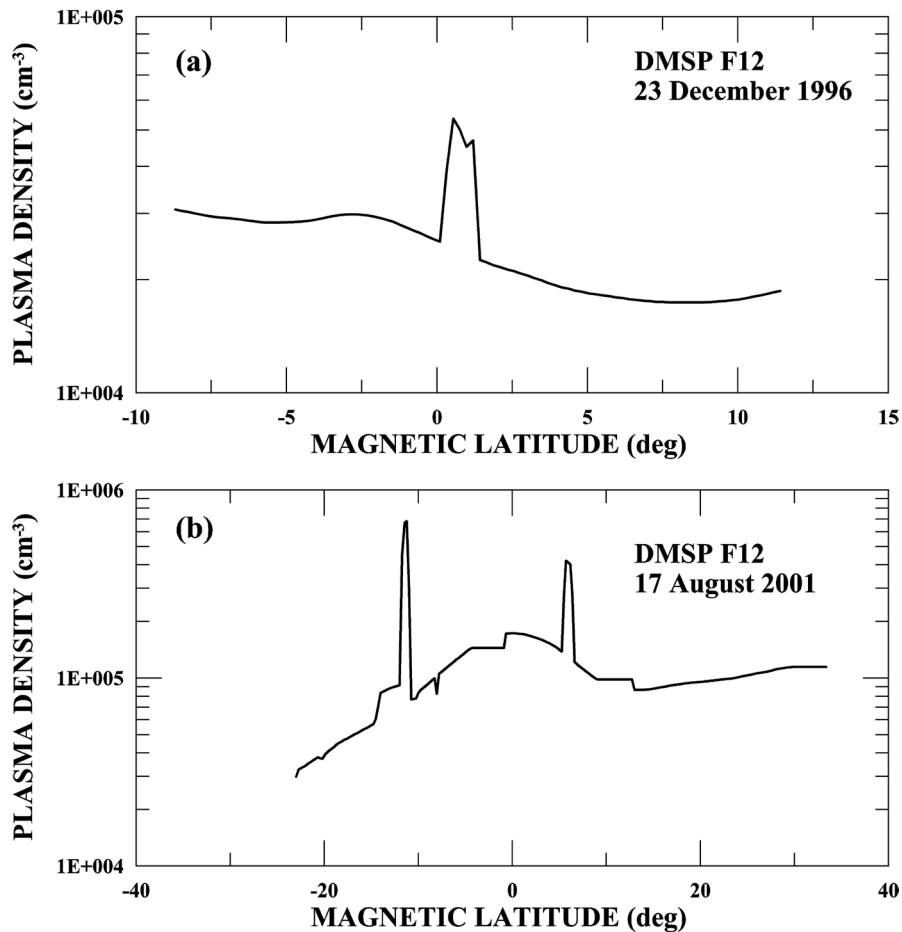


Fig. 1. DMSP F12 observations of plasma blobs at ~2130 LT under conditions of (a) solar minimum on December 23, 1996 at an altitude of ~840 km near 0235 UT and (b) solar maximum on August 17, 2001 at an altitude of ~860 km near 1720 and 1723 UT.

considerably denser than the background plasma.

2.1 Observations During High and Intermediate Levels of Solar Activity

Oya et al. (1986) and Watanabe & Oya (1986) were the first to recognize morphological patterns in low latitude plasma blobs. During the solar maximum from February 1981 to June 1982, electron density measurements were analyzed using the impedance probe onboard the Hinotori satellite, which operated at a 31.4° orbital inclination and an altitude of ~650 km. The blobs were clear electron density deviations (by a factor of approximately two) above background, stretching from several tens to hundreds of kilometers along the satellite track. The plasma blobs were only observable from +20° to +30°, and from -30° to -20°, magnetic dip latitude. They were commonly detected in the nighttime ionosphere (predominantly from 2200 to 0400 LT), though in very few cases the blobs were also seen in

the early morning hours of 0600 to 0800 LT. Plasma blobs were most likely to occur during solstices. Broader blobs (greater than a few hundred kilometers in size) have been observed only in the winter hemisphere. There were clear inverse correlations between blob occurrence and the level of geomagnetic activity as well as the value of the solar F10.7 cm index.

Le et al. (2003) elucidated plasma features within blobs during the 1999–2000 solar maximum, using measurements from the ROCSAT-1 satellite at 600 km altitude, and the DMSP F12, F14, and F15 satellites at ~850 km altitude. Within blobs, the zonal component of the electric field was oriented eastward, and the magnetic field-aligned plasma flow was generally poleward (comparable to that of EPBs). In addition, the blobs exhibited irregularities in size and density fluctuation spectra, as typically observed in EPBs. Therefore, these observations indicate a close association between plasma blobs and EPBs. Le et al. (2003) suggested that plasma blobs and EPBs share the same magnetic flux

tubes.

Additional statistical evidence of a link between plasma blobs and EPBs was suggested, using data obtained from the KOMPSAT-1 satellite (at an altitude of ~680 km) during 2000–2001 (Park et al. 2003, 2008a), the DMSP F15 satellite (at ~840 km) during 2000–2001 and 2003–2004 (Park et al. 2008a), and the CHAMP satellite (at ~350 km) during 2002–2004 (Park et al. 2008b). The global distribution of blob locations revealed a seasonal-longitudinal dependence, similar to that of EPBs, with the blobs predominantly observed in the winter ionosphere. In contrast to the results by Watanabe & Oya (1986), the KOMPSAT-1 observations of blob occurrence did not indicate a significant dependence on geomagnetic activity, or on the daily variation in the solar F10.7 cm index. In addition, blob occurrence frequency, as observed by the DMSP F15 satellite, was less sensitive to annual variation in the F10.7 index than EPBs.

Park et al. (2008b), using simultaneous satellite observations of plasma blobs with CHAMP, ROCSAT-1, STSAT-1 (at ~680 km), and DMSP F15, deduced that the blobs are magnetic field-aligned structures extending over several hundred kilometers of altitude. The CHAMP satellite measured magnetic field perturbations associated with the plasma blobs, which were attributed to the field-aligned currents flowing on the surface of the blob flux tube. The magnetic signatures of the blobs were consistent with those of EPBs, which further supports their close relationship.

Pimenta et al. (2004) performed ground-based observations of plasma blobs in the nighttime *F* region ionosphere using concurrent measurements with the OI 630.0 nm emission all-sky imager, a photometer, and a digisonde. The observations were carried out at Cachoeira Paulista, Brazil (magnetic latitude 13.25° S), from October 1998 to September 2000, under conditions of low geomagnetic activity. The occurrence of plasma blobs was associated with EPBs. Typical east-west and north-south dimensions of the blobs were 150–180 km and 190–240 km, respectively. The same OI 630.0 nm emission all-sky imager detected a plasma blob associated with a large-scale EPB during the severe geomagnetic storm of April 6–7, 2000, with a $Dst_{\min} \sim -288$ nT (Pimenta et al. 2007). As expected, the plasma blob moved westward at a velocity of ~30 m/s.

Ground-based observations of enhancements in the nighttime low latitude *F* region airglow (attributed to plasma blobs), using the OI 630.0 nm emission all-sky imager, have also been made at Arecibo, Puerto Rico (magnetic latitude 28° N), on three December solstice nights during 2002–2004 (Martinis et al. 2009). The all-sky imager observations were supplemented by data from the Arecibo incoherent scatter radar and ROCSAT-1 satellite. The airglow enhancements

occurred in regions of originally depleted airglow associated with EPBs. The radar data indicated that the airglow enhancements were accompanied by the reversal of the background zonal and meridional plasma motions, to westward and southward, respectively. Above the airglow enhancement, ROCSAT-1 observed that plasma drifted poleward and downward within the plasma blob, and in the opposite direction outside the blob.

On March 8, 2004, Yokoyama et al. (2007) detected plasma blobs and EPBs along a common magnetic flux tube, using concurrent observations with the ROCSAT-1 satellite and the 47 MHz backscatter radar located in West Sumatra, Indonesia (magnetic latitude 10.36° N). The blobs were seen from ROCSAT-1 at a dip latitude of ~9° N. However, EPBs were observed by the backscatter radar at a dip latitude of ~13° S. The plasma drift velocities within the blobs and EPBs were consistent in amplitude and direction, and they had similar zonal structures.

During October, 2004, and February, 2005 (periods of low geomagnetic activity), Dashora & Pandey (2005) reported observations of isolated and localized TEC enhancements near the crest of the Appleton anomaly, using the GPS receiver at Udaipur, India (magnetic latitude 15.6° N). It was suggested that these TEC enhancements were due to plasma blobs in the *F* region. On October 5, 2004, consecutive TEC enhancements and depletions (related to EPBs) were observed, which indicated a close relationship between plasma blobs and EPBs.

2.2 Observations During the Solar Minimum

The C/NOFS satellite provides a new opportunity to study low latitude plasma blobs and their relation to EPBs. C/NOFS supports an Air Force mission to predict background plasma densities and irregularities in the equatorial ionosphere (de La Beaujardière et al. 2004). The satellite was launched in April 2008, into a 13° inclined elliptical orbit, with its perigee at ~400 km and apogee at ~850 km. The payload on C/NOFS measures several ionospheric parameters: electron density, ion and electron temperatures, ion composition, electric fields and ion drifts, magnetic fields, neutral winds, and ionospheric scintillations.

Using C/NOFS measurements, on March 2, 2009, Kil et al. (2011) did not observe EPBs at the longitudes where blobs were detected, and suggested that EPBs need not be a precondition for the appearance of blobs. This observation was supported by a further study using simultaneous C/NOFS and CHAMP measurements on three nights during June 2008 and two nights during April 2009 (Kil et al. 2015). Blobs were observed at any longitude, with or without EPBs,

and many blob events were not associated with EPBs. Blobs were detected during global disturbance of the ionosphere. Kil et al. (2015) concluded that blobs are not exclusively connected with EPBs, and that MSTIDs can be an important source of blobs. Miller et al. (2014) supported this analysis by reporting concurrent observations from the OI 630.0 nm emission all-sky imager on the Caribbean island of Bonaire (magnetic latitude 22.46° N), and the C/NOFS satellite on January 17 and 21, 2010.

Using measurements made by the C/NOFS satellite on June 20, 26 and 27, 2009, and September 15, 2009, Klenzing et al. (2011) suggested that plasma makes $E \times B$ drifts inside blobs. This is comparable with typical observations of EPBs. However, there was a longitude offset between peak $E \times B$ and parallel plasma drifts associated with blobs.

Choi et al. (2012), using C/NOFS data, investigated the morphological features of blob events during a solar minimum (August 2008, to April 2010) and compared them with those of EPBs. Most blobs were observed near midnight within an altitude range of 400–450 km and at approximately $\pm 25^\circ$ magnetic latitude. Blobs were also most frequently detected at the June solstice. The blob occurrence rate peaked near a magnetic apex height of 1,700 km, where EPBs are rare. The morphological differences between blobs and EPBs imply that they may not be causally linked.

Using C/NOFS data, Haaser et al. (2012) also performed a statistical analysis of the relationship between blobs and EPBs during 2009 and 2010. They focused on the characteristics of plasma drift velocities within EPBs and blobs observed at altitudes of 400–550 km, between 2100–0300 LT, when plasma density perturbation was greater than 50% relative to background, at scales of 50–500 km. Overall, the morphological results were consistent with those of Choi et al. (2012). Blobs and EPBs were not systematically observed at the same longitudes. During December, solstice blobs were observed between longitudes 180° and 240°, where the EPB occurrence rate was low. However, many small magnitude blobs were detected closer to the geomagnetic equator where EPBs did occur. Within blobs, the perturbation plasma drifts often corresponded to plasma motions termed the “plasma fountain effect”. At apex altitudes above 800 km, blob plasma moved upward. However, upward drifting plasma was not detected within EPBs. Haaser et al. (2012) suggested that there are several types of plasma blobs driven by different mechanisms.

Huang et al. (2014) presented evidence of the association of plasma blobs with EPBs using C/NOFS observations of plasma densities and drift velocities throughout several days in 2008 and 2009. They found that blobs could occur over the geomagnetic equator. Blobs were accompanied with

enhanced upward plasma drift, compared with background values. Occasionally, C/NOFS encountered EPBs near the geomagnetic equator and plasma blobs were subsequently recorded at the same longitudes approximately 10° from the equator. During other passes, C/NOFS first observed blobs about 10° from the equator, and then EPBs near the magnetic equator at the same longitudes. These observations suggest that blobs can exist just above EPBs and that they are closely related.

3. FORMATION MECHANISMS OF LOW LATITUDE BLOBS

Different explanations of low latitude blob phenomenon have been proposed, based on quantitative analyses. The earliest and simplest explanation was developed using the simulations of equatorial bubble development undertaken by Anderson & Haerendel (1979). It has been established that local parts of EPBs can be plasma density enhancements compared with the background. While an EPB is a flux tube integrated depletion, local plasma density inside the EPB may not necessarily be less than the background plasma density along the entire flux tube. Example calculations demonstrated that when the EPB originates with a density just below that of the F2 layer peak, the local plasma density inside the EPB at the geomagnetic equator can be weakly enhanced over the background value when the EPB apex height exceeds the F2 layer peak (Fig. 2). This mechanism may be responsible for the weak blobs observed in association with EPBs at the geomagnetic equator (Haaser et al. 2012).

The second explanation of blob creation relates to the “plasma fountain effect” that occurs in the equatorial ionosphere and causes Equatorial Ionization Anomaly (EIA) crests (e.g., Hanson & Moffett 1966). Numerical modeling with NRL SAMI3/ESF three-dimensional simulation code (Krall et al. 2010) indicated that this mechanism (termed the “super fountain effect”) can produce plasma density crests within EPBs (Fig. 3). Further, the plasma density at or above the EPB density crests can appear as a blob if the super fountain inside an EPB is relatively weak. During a mild northward neutral wind, the northern EPB crest can become a plasma blob within an EPB (Krall et al. 2009). The simulated plasma blobs demonstrated characteristics consistent with those of blobs observed during the solar maximum.

Additional explanations for blob occurrence in the low latitude ionosphere are qualitative. Le et al. (2003) suggested that the eastward electric field inside an EPB would push up

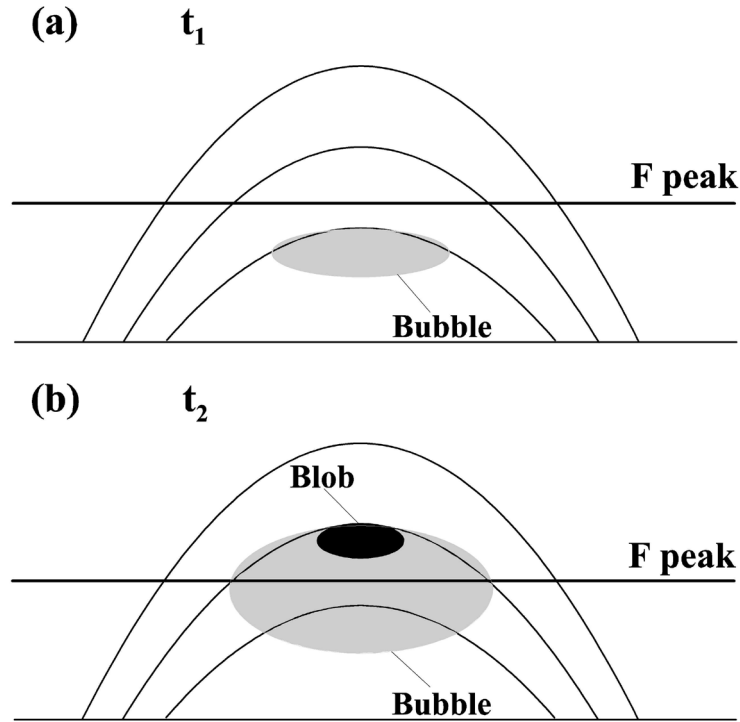


Fig. 2. Schematic illustration of the creation of blob based on the mechanism by Anderson & Haerendel (1979): (a) the initial stage of bubble formation at the geomagnetic equator just below the F peak at $t=t_1$; (b) the situation at $t=t_2$ when the bubble rises above the F peak and a blob forms near the bubble flux tube apex. The thick line represents the F peak. The grey shadings indicate plasma depletions, and the black shading indicates a plasma blob.

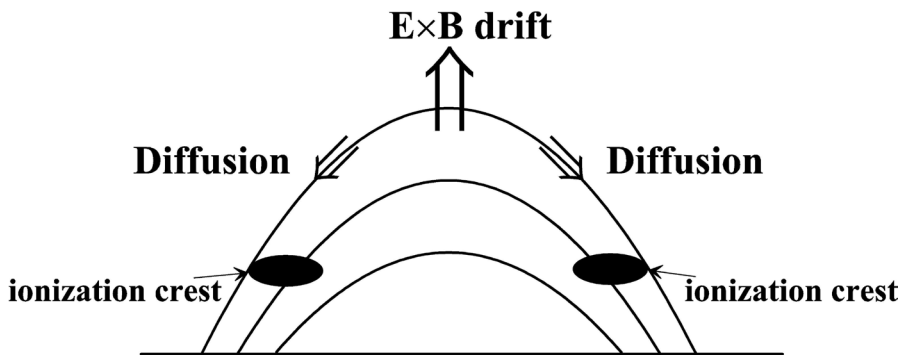


Fig. 3. Schematic illustration of the 'super fountain effect' within a bubble examined by Krall et al. (2010). The large and small arrows denote plasma transport due to $E \times B$ drift and ambipolar diffusion, respectively. The black shadings indicate ionization crests formed inside the bubble.

high-density plasma at the EIA crest plasma density peak when the EPB flux tube reaches EIA latitudes. This would result in the occurrence of a blob just above the EPB flux tube. However, the eastward electric field associated with an EPB is embedded into the EPB flux tube, preventing the raising of plasma above the flux tube. EPBs percolate through the surrounding plasma, and plasma flows around an EPB.

Huang et al. (2014) proposed that the hypothetical scenario

of blob formation is closely related to different stages of EPB development. This theory combines the different formation mechanisms to explain blob appearance at early, intermediate, and fully developed stages of EPB evolution. The mechanism corresponding to the early and intermediate stages is similar to that of Le et al. (2003), related to the F peak high-density plasma at the geomagnetic equator. Krall et al. (2010) suggested a mechanism corresponding to a fully developed EPB. On the other hand, Miller et al. (2014) and

Kil et al. (2015) suggested that during the solar minimum, localized positive perturbations in plasma density associated with MSTIDs may occur as blobs that have no relation to EPBs.

4. CONCLUSION

Different aspects of low latitude plasma blobs have been reviewed in this paper. Blobs appear at low latitudes from the geomagnetic equator to $\pm 30^\circ$ magnetic latitude, in the local time sector from evening to early morning, during any season and level of solar activity, and at 250–840 km altitude. The occurrence frequency of blobs is dependent on local time, the magnetic latitude, the season, and the level of solar activity. During the solar maximum, blobs accompany EPBs. However, frequently during the solar minimum, they do not appear to be associated with EPBs. During the last decade, coordinated studies using *in situ* measurements at different altitudes with several satellites, radar and all-sky airglow imager data, have significantly increased our knowledge of blobs under various geophysical conditions. However, there are still unresolved questions on the mechanisms responsible for blob formation. It is possible that different mechanisms can coexist, or one predominates depending on the level of solar activity. Therefore, in order to better understand low latitude ionospheric plasma behavior, it is important to develop a comprehensive theory about blob generation based on further observational, theoretical and modeling studies.

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REFERENCES

Anderson DN, Haerendel G, The motion of depleted plasma regions in the equatorial ionosphere. *J. Geophys. Res.* 84, 9A0050 (1979). <http://dx.doi.org/10.1029/JA084iA08p04251>

Choi HS, Kil H, Kwak YS, Park YD, Cho KS, Comparison of the bubble and blob distributions during the solar minimum, *J. Geophys. Res.* 117, A04314 (2012). <http://dx.doi.org/10.1029/2011JA017292>

Dashora N, Pandey R, Observations in equatorial anomaly region of total electron content enhancements and depletions, *Ann. Geophys.* 23, 2449–2456 (2005). <http://dx.doi.org/10.5194/angeo-23-2449-2005>

de La Beaujardière O, the C/NOFS Science Definition Team, C/NOFS: a mission to forecast scintillations, *J. Atmos. Sol.-Terr. Phys.* 66, 1573–1591 (2004). <http://dx.doi.org/10.1016/j.jastp.2004.07.030>

Haaser RA, Earle GD, Heelis RA, Klenzing J, Stoneback R, et al., Characteristics of low-latitude ionospheric depletions and enhancements during solar minimum, *J. Geophys. Res.* 117, A10305 (2012). <http://dx.doi.org/10.1029/2012JA017814>

Hanson WB, Moffett RJ, Ionization Transport Effects in the Equatorial *F* Region, *J. Geophys. Res.* 71, 5559–5572 (1966). <http://dx.doi.org/10.1029/JZ071i023p05559>

Huang CS, Le G, de La Beaujardière O, Roddy PA, Hunton DE, et al., Relationship between plasma bubbles and density enhancements: Observations and interpretation, *J. Geophys. Res.* 119, 1325–1336 (2014). <http://dx.doi.org/10.1002/2013JA019579>

Huba JD, Krall J, Joyce G, Atomic and molecular ion dynamics during equatorial spread *F*, *Geophys. Res. Lett.*, 36, L10106 (2009). <http://10.1029/2009GL037675>

Kelley MC, Makela JJ, de La Beaujardière O, Retterer J, Convective ionospheric storms: A review, *Rev. Geophys.* 49, RG2003 (2011). <http://dx.doi.org/10.1029/2010RG000340>

Kil H, The Morphology of Equatorial Plasma Bubbles – a review, *J. Astron. Space Sci.* 32, 13–19 (2015). <http://dx.doi.org/10.5140/JASS.2015.32.1.13>

Kil H, Choi HS, Heelis RA, Paxton LJ, Coley WR, et al., Onset conditions of bubbles and blobs: A case study on 2 March 2009, *Geophys. Res. Lett.* 38, L06101 (2011). <http://dx.doi.org/10.1029/2011GL046885>

Kil H, Kwak YS, Lee WK, Miller ES, Oh SJ, et al., The causal relationship between plasma bubbles and blobs in the low-latitude *F* region during a solar minimum, *J. Geophys. Res.* 120, 3961–3969 (2015). <http://dx.doi.org/10.1002/2014JA020847>

Klenzing JH, Rowland DE, Pfaff RF, Le G, Freudenreich H, et al., Observations of low-latitude plasma density enhancements and their associated plasma drifts, *J. Geophys. Res.* 116, A09324 (2011). <http://dx.doi.org/10.1029/2011JA016711>

Krall J, Huba JD, Martinis CR, Three-dimensional modeling of equatorial spread *F* airglow enhancements, *Geophys. Res. Lett.* 36, L10103 (2009). <http://dx.doi.org/10.1029/2009GL038441>

Krall J, Huba JD, Joyce G, Yokoyama T, Density enhancements associated with equatorial spread *F*, *Ann. Geophys.* 28, 327–

- 337 (2010). <http://dx.doi.org/10.5194/angeo-28-327-2010>
- Le G, Huang CS, Pfaff RF, Su SY, Yeh HC, et al., Plasma density enhancements associated with equatorial spread *F*: ROCSAT-1 and DMSP observations, *J. Geophys. Res.* 108, 1318 (2003). <http://dx.doi.org/10.1029/2002JA009592>
- Martinis C, Baumgardner J, Mendillo M, Su SY, Aponte N, Brightening of 630.0 nm equatorial spread-*F* airglow depletions, *J. Geophys. Res.* 114, A06318 (2009). <http://dx.doi.org/10.1029/2008JA013931>
- Miller ES, Kil H, Makela JJ, Heelis RA, Talaat ER, et al., Topside signature of medium-scale traveling ionospheric disturbances, *Ann. Geophys.* 32, 959–965 (2014). <http://dx.doi.org/10.5194/angeo-32-959-2014>
- Oya H, Takahashi T, Watanabe S, Observation of Low Latitude Ionosphere by the Impedance Probe on Board the Hinotori Satellite, *J. Geomagn. Geoelectr.* 38, 111–123 (1986). <http://dx.doi.org/10.5636/jgg.38.111>
- Park J, Min KW, Lee JJ, Kil H, Kim VP, et al., Plasma blob events observed by KOMPSAT-1 and DMSP F15 in the low latitude nighttime upper ionosphere, *Geophys. Rev. Lett.* 30, 2114 (2003). <http://dx.doi.org/10.1029/2003GL018249>
- Park J, Min KW, Kim VP, Kil H, Kim HJ, et al., Statistical description of low-latitude plasma blobs as observed by DMSP F15 and KOMPSAT-1, *Adv. Space Res.* 41, 650–654 (2008a). <http://dx.doi.org/10.1016/j.asr.2007.04.089>
- Park J, Stolle C, Lühr H, Rother M, Su SY, et al., Magnetic signatures and conjugate features of low-latitude plasma blobs as observed by the CHAMP satellite, *J. Geophys. Res.* 113, A09313 (2008b). <http://dx.doi.org/10.1029/2008JA013211>
- Pimenta AA, Sahai Y, Bittencourt JA, Abdu MA, Takahashi H, et al., Plasma blobs observed by ground-based optical and radio techniques in the Brazilian tropical sector, *Geophys. Rev. Lett.* 31, L12810 (2004). <http://dx.doi.org/10.1029/2004GL020233>
- Pimenta AA, Sahai Y, Bittencourt JA, Rich FJ, Ionospheric plasma blobs observed by OI 630 nm all-sky imaging in the Brazilian tropical sector during the major geomagnetic storm of April 6–7, 2000, *Geophys. Rev. Lett.* 34, L02820 (2007). <http://dx.doi.org/10.1029/2006GL028529>
- Watanabe S, Oya H, Occurrence Characteristics of Low Latitude Ionosphere Irregularities Observed by Impedance Probe on Board the Hinotori Satellite, *J. Geomagn. Geoelectr.* 38, 125–149 (1986). <http://dx.doi.org/10.5636/jgg.38.125>
- Woodman RF, Spread *F* – an old equatorial aeronomy problem finally resolved?, *Ann. Geophys.* 27, 1915–1934 (2009). <http://dx.doi.org/10.5194/angeo-27-1915-2009>
- Yokoyama T, Su SY, Fukao S, Plasma blobs and irregularities concurrently observed by ROCSAT-1 and Equatorial Atmosphere Radar, *J. Geophys. Res.* 112, A05311 (2007). <http://dx.doi.org/10.1029/2006JA012044>

