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DYNAMICS OF THE EQUATORIAL IONOSPHERE-THERMOSPHERE SYSTEM AS INVESTIGATED THROUGH NIGHT AIRGLOW TECHNIQUES

J. H. A. Sobral
PR/SCT - Instituto Nacional de Pesquisas Espaciais (INPE)
Caixa Postal 515
12201-970 - São José dos Campos, SP,
Brazil

ABSTRACT

The dynamics of the nocturnal equatorial F-region has been investigated to a substantial extent in the last few decades by means of airglow diagnostic tools such as photometers, optical imagers and Fabry-Perot interferometric systems. This paper concerns a concise review on those airglow studies.

1. INTRODUCTION

The presentation in the following sections on the relevant topics that have been studied in the past three decades utilizing airglow data, will follow the following order:

-Dynamics of the ionospheric plasma bubbles
  -Ve drifts
  -projections onto the equatorial plane
  -geometric studies

-Particle precipitation
  -atomic and molecular processes in the low-latitude aurorae
  -heating effects during storms

-Spread-F
  -range spread-F and ionospheric irregularities
  -neutral temperature enhancements

-Thermospheric winds and temperatures
  -meridional and zonal wind components
  -seasonal, solar cycle and local time variations
  -variations of the wind patterns with latitude

-The Equatorial Ionization Anomaly
  -the formation of the equatorial red arcs

Photometric data, that is, data on the spatial and temporal variations of just the airglow intensity have been used more extensively in the past few decades than optical interferometric wind and temperature data.

The locations of some of the presently well-known Fabry-Perot optical interferometric stations in operation at low latitudes which have been used in ionospheric studies are as follows:

1. Kwajalein Atoll, Marshall Islands (9.4°N, 167.5°E, 8.6° dip latitude)
2. Arequipa, Peru (16.5°S, 71.4°W, 3.5°S dip)
3. Arecibo, Puerto Rico (66.8°W, 18.6°N, 50°dip)
4. Mount Abu, India (24.6°N, 72.7°E)
5. São José dos Campos/Cachoeira Paulista, Brazil (23.0°S, 45.0°W, dip -30° for the epoch 1992)

2. DYNAMICS OF THE IONOSPHERIC PLASMA BUBBLES

2.1 The behavior of the eastward velocity, Ve, of the equatorial plasma depletions in the nocturnal F region over South America

In a recent study by Sobral et al., (1991; see also Sobral et al. 1985, 1990) on the eastward motion of ionospheric plasma depletions utilizing ground measurements of the atomic oxygen 630 nm airglow in the period of January 1988 to January 1990 at the low latitude station Cachoeira Paulista (23°S, 45°W), they concluded that:

1. The eastward velocity Ve of the postsunset ionospheric plasma depletions is seen to decrease, in average, from about 150 ms^{-1} at 2015 LT to 75 ms^{-1} at 0145 LT,

2. Both Ve and its latitude gradient tend to increase with increasing solar activity,

3. The magnitude of Ve tends to decrease with height, in the equatorial plane at the rate of 0.205 ms^{-1} and such height gradient tends to remain constant during the night.

Utilizing two nights of red line observations at the Haleakala Observatory, Hawaii, VanZandt and Peterson (1968) detected the Ve magnitudes of 175 km h^{-1} (49 ms^{-1}) and 400 km h^{-1} (111 ms^{-1}).

Mendillo and Baumgardner (1982) found Ve to decrease from 190 ms^{-1} at 2100 LT to 80 ms^{-1} at 0100 LT over Ascencion Island.

Weber et al. (1978), utilizing all-sky 630 nm imaging found Ve magnitudes in the range of 50-100 ms^{-1} along the Peruvian coast. They observed one case, after local midnight, in which the depletion drifted westward (see also Weber et al, 1982).

Sipler et al. (1983) observed Ve magnitudes in the range of 0 ms^{-1} to 240 ms^{-1} over the Kwajalein Atoll and compared those measurements with neutral wind measurements. They observed the Ve magnitudes for one given depletion to be smaller than the neutral wind speed. They found this fact somewhat surprising, considering that the zonal wind is the primary forcing mechanism for the generation of the downward polarization electric field that causes the **E**x**B** eastward drift of the depletion.

Basu et al. (1991) compared zonal irregularity drifts and neutral winds measured near the magnetic equator in Peru.

More recently, Basu et al. (1991) compared zonal irregularity drifts and neutral winds measured near the magnetic equator in Peru.

Other early measurements of ionospheric drifts were described by Sipler et al (1981).

2.2 The geometry of the equatorial plasma depletions

Utilizing all-sky OI 630 nm images, Mendillo and Tyler (1983) found the depletions to be tilted about 40° towards the west in the upward direction or at a rate of 0.6° longitude west per 100 km height range over Ascencion Island (8.0°S, 14.4°W). The tilts were seen to increase with local time and they are possibly associated with poleward decreasing zonal thermospheric wind magnitudes (Anderson and Mendillo, 1983).

Weber et al. (1983) investigated plasma depletions at conjugate points utilizing data from the following instrumentations: all-sky imaging photometers at the wavelengths of 630 nm and 777.4 nm, ionosonde, in-situ density data from the AE-E satellite and scintillation data from the AFGL Airborne Ionospheric Laboratory. In a former observational campaign near the Peruvian coast, Weber et al. (1978) found that the depletions often extended themselves more than 1200 km in the north-south direction and 50-200 km in the east-west direction.

Rohrbaugh et al. (1989) studied the development of plasma bubbles at Mount Haleakala (Hawaii) utilizing 777.4 nm and 630.0 nm images.

3. PARTICLE PRECIPITATION

3.1 Optical Observations of particle precipitation:

Energetic atomic O, H and He, arising from charge transfer with trapped ions in the inner magnetosphere, were observed to precipitate at mid, low and equatorial latitudes with mean energy in the range of 1-100 keV (Tinsley, 1979, 1981; Tinsley et al. 1982, 1986, 1988; Rohrbaugh et al. 1983; Rassoul et al. 1992).

Rohrbaugh et al. (1983) found that the time variations of the emissions of H Balmer-beta emission at 486.1 nm and N_2^+ 1N at 428.1 nm indicate that there is more O precipitation than H precipitation during storms main phases and, on the other hand, H^+ loss is faster than O^+ and He^+ in the inner ring current during the whole duration of the precipitation event. They also found that precipitation increases with increasing latitude in the low to mid latitude range.

Tinsley et al. (1984, 1986, 1988) detected ring current particle precipitation at Cachoeira Paulista (22.7° S, 45.0° W, dip -30° for the epoch 1992) in Brazil during magnetic storms through ground measurements of the $N2^+$ emission.

Rohrbaugh et al. (1983) have detected particle precipitation increases of the OI ($3p^5P$-$3s^5S$) emission at 777.4 nm over the background OI 777.4 nm component due to radiative recombination, the latter being inferred from ionosonde data as equal to $.0018\ (f_0F_2)^4$.

3.2 Thermospheric heating resulting from particle precipitation:

Tinsley et al., (1988) reported evidence, based on particle precipitation data, that both mid-latitude ring current source and high-latitude Joule heating source are involved in the thermospheric heating observed above Arequipa during the storms of May 11-12, 1983, June

12-13, 1983 and August 7-8, 1983.

Rohrbaugh et al. (1983) reported a lower limit for energy deposition of about 0.05 mWm^{-2} during the storm events of April 1982 and July, 1982 which occurred at 12^o dip latitude.

4. SPREAD-F

4.1 Association of range spread-F events with plasma depletions:

Statistical studies of ionosonde and optical (630 nm) data from the low-latitude station Cachoeira Paulista (Sobral et al. 1980a,b, 1981) show that the plasma depletions signatures on the 630 nm airglow is always accompanied by range spread-F and that the range spread-F occurrence at the low-latitude station Cachoeira Paulista is caused by field-aligned plasma depletions.

Sahai et al. (1981) compared the behavior of the atomic oxygen 777.4 nm and 630 nm emissions during the occurrence of ionospheric plasma depletions over Cachoeira Paulista.

Meriwether et al. (1986) pointed out that the incidence of irregularities over Peru during winter is low due to the height of the F-layer that remains constant and because the zonal neutral wind is eastward during the night which tends to inhibit the growth of irregularities in the absence of upward drifts.

In a more recent work Mendillo et al. (1992) suggest that the equatorward winds observed at Kwajalein (Marshall Islands) can alter the airglow pattern over that site. The forcing effects of equatorial winds on the ionospheric plasma, they claim, can cause a stabilizing effect on the irregularity growth rates.

The OI 630 nm airglow intensity variation with solar cycle has been monitored by Sahai et al. (1988a). During higher solar activity period, as expected, they found more intense airglow. Storm effects in the nocturnal F-region over Cachoeira Paulista have been reported by Sahai et al. (1988b).

4.2 Spread-F and thermospheric neutral temperature:

Fabry-Perot data on the F-region temperature at Mount Abu (24.6^o N, 72.7^o E) (Rajaraman et al., 1978, 1979) show thermospheric temperature increases of up to 200^oK during sunset in the presence of spread-F and no temperature increase in the absence of spread-F.

5. THERMOSPHERIC WINDS AND TEMPERATURES

5.1 Winds:

The neutral wind speed measurements discussed below concern separate data on the meridional and zonal components of the neutral wind in the nocturnal F-region.

Wind velocities observations over Arequipa by Biondi et al., (1991; se also Biondi et al., 1990a, b) over 2/3 of a solar cycle (1983-1990) led to the following conclusions:

1. The wind patterns vary more markedly with season than with solar cycle.

2. The zonal flows are predominantly eastward throughout the night (westward flows briefly appeared in 1986), except for solar minimum equinoxes when weak westward flows occur in early and late night. The peak eastward velocity increases toward solar maximum; at solar minimum winter solstice they are 100-130 ms^{-1} (1983, 1984 and 1986) and at solar maximum they reach up to 200 m^{-1} (1988, 1989 and 1990).

3. The authors compare the remarkable solar cycle variations that they observed at Arequipa with the opposite conclusion stated by Burnside and Tepley (1989) for the winds over Arecibo: "nocturnal and seasonal variations in the neutral wind field...are remarkably unaffected by changes in the solar cycle".

4. The increases in the pressure gradients in the vicinity of the subsolar point might be expected to lead to higher wind velocities at solar maximum; however, the observed increases with increasing solar cycle are small, suggesting that increased ion drags plays a role in slowing down the wind speeds.

5. The meridional winds over Arequipa present small velocity magnitudes throughout the solar cycle and are much smaller in magnitude than the zonal winds.

6. At the equinoxes, the early-night southward (poleward) flow that appears during solar minimum is changed to equatorward flow at solar maximum.

7. A weak transequatorial flow from the summer to the winter hemisphere early and late in the night, and nearly-null velocities otherwise are observed in most of the years of their observation period (1983-1990). During solar minimum and solar maximum equinoxes the meridional flow is poleward and equatorward, respectively.

Herrero and Meriwether (1980) studied the meridional gradients of the atomic oxygen 630 nm airglow over Arecibo, relating them to the dynamics of the ionosphere-thermosphere system over Arecibo.

Burnside and Tepley (1989) observed following features of the wind field over Arecibo:

1. Well-defined seasonal and nocturnal variations of the zonal flows over Arecibo.

2. The nocturnal zonal winds are predominantly eastward throughout the solar cycle except during summer, when a reversal to westward frequently occurred after local midnight during the second and third quarters of the years 1980-1985.

3. Over Arecibo, the largest equatorward velocities are observed in summer and either a reduction of the wind velocity or a reversal is observed after midnight during summer and equinoctial months, causing the so-called "midnight collapse" of the ionosphere over Arecibo (see also Sobral et al, 1978).

Burrage et al. (1990) measured nocturnal thermospheric winds at low latitudes utilizing Atmosphere Explorer (AE-E) satellite measurements of the $O(^1D)$ 630-nm.

Biondi and Sipler (1985) analysed horizontal and vertical winds and temperatures in the equatorial station Natal, Brazil during the period of August-September, 1982 (see also Biondi and Sipler, 1984).

Bittencourt et al. (1976) studied height gradients of the tropical F-region winds utilizing OGO-4 data on the OI 135.6 nm and OI 630 nm emissions.

5.2 Temperatures (Tn):

Gupta et al. (1986) measured the equatorial thermospheric temperatures through spectroscopic methods utilizing rocket released atomic sodium. The experiments were carried out over the near equatorial station at Srihatoka (13^o 41' N, 80^o 14' E, dip lat. 5.5^o N). They found enhanced thermospheric temperatures during a storm sudden commencement.

Biondi and Meriwether (1985) studied the thermospheric temperature variations over Arequipa utilizing 62 nights of Tn data obtained by a Fabry-Perot interferometer. The measurements were found to be larger than the MSIS 1 (Hedin 1977) by 180^oK and such a discrepancy increased to about $400\text{-}500^oK$ during strong geomagnetic activity. They concluded that enhanced temperature may result from energetic neutral particles from the ring current or from auroral sources such as gravity waves or neutral winds. Measurements carried out over the Kwajalein Atoll in the Pacific zone also showed higher values than those of MSIS 1 by about 330^oK.

There are less discrepancies, however, between Fabry-Perot Tn and incoherent scatter Tn data (Cogger et al., 1970; Hernandez et al., 1975).

Hernandez and Killeen (1988) studied kinectic temperatures in the upper atmosphere.

Biondi et al. (1988) studied in detail the dynamics and coupling of the equatorial thermosphere and the F-region ionosphere in Peru, utilizing simultaneous Fabry-Perot interferometer and incoherent scatter radar observations on the magnetically disturbed days 24 and 25 September 1986. They compared zonal plasma drift measurements with zonal neutral wind measurements obtained by the incoherent scatter radar and the Fabry-Perot interferomter, respectively. They found that the two motions were not correlated during evening twilight but they became correlated later in the night. They attributed the increasing correlation between those two velocities to a decreasing Pedersen conductivity which leaded to a subsequent control of the F-region dynamo over the F-region ionospheric zonal drift.

Note: Michelson interferometers have also been used for measuring thermospheric winds and temperatures but since they have been used only at high latitudes their results are out of scope here (for information on those studies the reader is suggested to see Wiens et al., 1988 ; Thuillier et al., 1990).

Sobral (1978) used artificially induced HF heating effects on the OI 630 nm airglow intensity during ionospheric heating experiments at Arecibo in order to determine the collisional quenching rate of the metastable atomic oxygen. Sobral et al. (1992) has studied the atomic processes which lead to the quantum yields of the $O(^1D)$ and $O(^1S)$. And more recently, Sobral et al. (1993) has utilized the OI 557.7 nm and 630 nm from rocketborne measurements to estimate the quenching effects of the $O(^1D)$ by $O(^3P)$.

6. THE EQUATORIAL ANOMALY

The equatorial ionization anomaly (EIA) consists of two bands of enhanced electron concentration which run $\pm$ 20^o parallel to the magnetic equator. Associated with it are two bands of enhanced OI 630 nm which have been studied through OI 557.7 nm and 630 nm airglow (Barbier, 1958, 1961; Barbier et al., 1961, 1962; Weill, 1967; Kulkarni, 1974).

The optical studies of the EIA have not gained much attention since those early studies.

Sridharan et al. (1991) measured electron density biteouts that are possibly related to the upward drifts that lead to the fountain effect and the subsequent creation of the EIA. Their measurements were performed at the equatorial station Sriharitoka (5.5^o dip latitude) in India utilizing OI 630 nm dayglow measurements.

7. CONCLUSIONS

Summarizing, in the author's view the relevant contributions of the airglow studies to the improvement of the knowledge of the dynamics of the ionosphere-thermosphere system at equatorial and low latitudes may be stated as follows:

1) Extensive measurements of the variations of the zonal velocity Ve, geometry and dynamics of equatorial plasma depletions in the nocturnal F region. Determination of Ve variations with season, solar cycle and local time.
2) Measurements of the low latitude aurorae caused by precipitating ring current particles and their thermal effects in the thermosphere.
3) Verification of the simultaneous occurrence of spread-F with ionospheric plasma depletions; of neutral winds as an spread-F inhibiting factor and temperature enhancements during spread-F occurrence.
4) Measurements of thermospheric wind velocities and temperatures.
5) The development of postsunset Equatorial Ionization Anomaly.

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