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The Equatorial Electrojet: A brief review

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RESUMEN

Se presenta un breve resumen del descubrimiento del electrochorro ecuatorial (EEJ) y de la importancia de América del Sur en la investigación del EEJ. Se discuten algunas cuestiones resueltas y no resueltas sobre el EEJ y el "contraelectrochorro" (CEJ) basado en una descripción de posibles peculiaridades del EEJ en Sudamérica. Se resume el trabajo observacional en Brasil y se incluye una versión breve de los programas de investigación del EEJ en Brasil y Perú. También se dan los lineamientos de un posible programa de cooperación latinoamericana sobre los efectos del EEJ durante el eclipse total de Sol del 11 de julio de 1991.

PALABRAS CLAVE: Electrochorro ecuatorial, magnetosfera.

ABSTRACT

A brief review of EEJ discovery, and the importance of South America on EEJ research are presented. Some solved and unsolved questions about EEJ and CEJ are discussed based on description of possible EEJ peculiarities in South America.

Observational work in Brazil is summarized and an abridged version of EEJ research programs in Brazil and Peru is related. The possibility of a cooperative Latin-American program on EEJ effects during the next Total Solar Eclipse of July, 11, 1991 is outlined.

KEYWORDS: Equatorial electrojet, magnetosphere.

1. INTRODUCTION

Pilar, Argentina (1905), and Vassouras, Brazil (1915) were the first magnetic observatories installed in South America. Their time series have been supplemented by some data from repeat stations, and it has been possible to obtain reasonable conclusions about regional secular variation (Gama, 1965; Barreto, 1987).

Regular geomagnetic observations at Huancayo, Peru, started in 1922, under a cooperative program with the Carnegie Institute of Washington. Geomagnetic variations at Huancayo, mainly of the horizontal component H, were found to be abnormally large in comparison to those at other latitudes. A crucial question arose as to whether there were points other than Huancayo with the same peculiarity.

Hirono (1950) reported that magnetic observations at Losop Island showed some analogy with Huancayo results. It was suggested that a line of maximum diurnal variation lies along the dip zero line. Chapman (1951) created the term "Equatorial Electrojet (EEJ)" designating a belt approximately 600 km wide centered on the dip equator. Ten years later, Forbush and Casaverde (1961) published an extensive paper, presenting a remarkable analysis of Huancayo data.

Subsequently, a great number of papers has been published. The EEJ turned out to be a subject of multidisciplinary interest, involving observational, physical and mathematical researches. EEJ observations spread out, and it became possible to consider a global study of its morphology and physical characteristics.

The EEJ could be understood as an enhanced overhead current system flowing normally eastward in daytime and westward in nighttime, in a belt centered at the dip equator, and in the ionospheric E region (90 to 130 km height), causing the ground-observed increase of H component.

However, in some days at a point in the EEJ region, the H value decreases rapidly during a period from one to three hours, suggesting a reversal of the current direction. Gouin and Mayaud (1967), based on African observations, suggested a plausible explanation of this unexpected event, named the "Counter-Electrojet (CEJ)". It has a predominant occurrence in early morning and early afternoon hours, and it is more frequent during quiet-sun years. A detailed review about the CEJ was published by Mayaud (1977).

Very clear reviews about EEJ and CEJ studies may be found in Richmond (1973), Kane (1976), Mayaud (1977), Fobes (1981), Reddy (1981 and 1989), Stening (1985), Rastogi (1989). On the other hand, important specific papers have been published where peculiar EEJ aspects are described, including their variability in time and geographical location, and some attempts to produce an acceptable EEJ physical model. Different observational methods have been used, such as ground, rocket and VHF radar measurements. Countries that are crossed by the EEJ are more involved in those publications, although the general interest on the subject has contributed to a truly planetary authorship list. Indian, African and South American authors are well represented on a list where they have a prominent place.

2. SOME EEJ CHARACTERISTICS

In spite of the comparatively recent date of EEJ discovery - about half a century ago- its problems are no longer a puzzle today, because we understand in a reasonable way its morphological characteristics and some of the physical processes related to observational data. However, many questions remain to be answered. Knowledge of the EEJ is mainly related to quiet day variations, since EEJ recorded during such days could be considered as a superimposed feature to Sq. On the other hand, there is no satisfactory model for the disturbed-day behavior of the EEJ.

The daily variation and its latitude dependence on a planetary scale could be interpreted on the basis of two current systems in the ionospheric E-region, one clockwise in the Northern Hemisphere and the other anti-clockwise in the Southern Hemisphere. Inside the polar regions, an enhanced ionization in E-ionospheric level and local fields caused by magnetospheric events are superimposed upon local dynamo processes, overshadowing the local dynamo effects which are the dominant Sq source at lower latitudes.

Away from the polar cap, the main source for the quiet day variations is a dynamo process in the ionospheric E-level, where local ionization is generated mainly by solar radiation. The ionospheric layers are subject to solar and lunar tidal forces and to thermospheric winds that cause their motions. In this region, electrons are relatively collision-free, but positive ions are subject to collisions with neutral particules. In consequence, a current of electrons is not neutralized by a positive ion current. At night hours, the solar radiation stops producing electrons and a recombination process removes E-level ionization, causing the observed flat appearence of the geomagnetic records, depending on the three directional conductivities. A residual ionization of the E-layer could be responsible for the low amplitude of Sq field.

At the equatorial region, the two hemispheric current systems reinforce each other, presenting a special behaviour at points near the dip equator, for a peculiar geometric arrangment of the electromagnetic forces. Exactly at the dip equator, the Z component is zero, and the geomagnetic field vector $\vec{B}$ coincides with its H component in the north-south (magnetic) direction, determining the orientation of the three directional conductivities. Under these conditions, in the ionospheric plasma with perpendicular electric $\vec{E}$ and magnetic $\vec{B}$ fields, Hall currents flow perpendicular to both fields ($\vec{E} \times \vec{B}$). If the flow of Hall currents is inhibited by boundaries, a polarization field is set up to oppose this flow. There is good evidence that the relatively low conducting layers above and below the region between 90-150 km enhance the effective east-west ionospheric conductivity near the dip equator, in a direction parallel to the boundaries and perpendicular to B. These brief considerations could be a synthetic explanation for the EEJ current flow.

The unexpected and evasive nature of CEJ events make a confident physical explanation of their behaviour more difficult. A well-confirmed aspect of CEJ, related to EEJ, is the reversal of H and Z profiles in geomagnetic records. This feature suggests the existence of a narrow band of westward currents in the opposite sense of EEJ electric currents. According to Matsushita (1977), CEJ mechanism could be a reversal of electric fields due to lunar tides, substorms and localized winds.

A concise list of solved and unsolved problems about EEJ and CEJ might be an useful supplement to the review papers quoted in the bibliography.

2.1 Some well-understood problems

(a) At points in the EEJ region, apart from a large H variation, there are also Z variations, mainly near the edges of the EEJ band.

(b) The strength of the EEJ is not the same all round the planet.

(c) The EEJ intensity is a function of longitude and has an inverse dependence to geomagnetic field intensity.

(d) The fluctuations in H and Z records at stations under EEJ influence have different aspects, if they are compared to similar variations of a disturbed field. Generally, fluctuation amplitudes are amplified by the EEJ and they follow its intensity.

(e) Sometimes a point with a southern magnetic latitude would be under the influence of the Sq current system from the Northern Hemisphere.

(f) The CEJ is a typical equatorial event. Its occurrence is unexpected and it has a short time and a variable intensity.

(g) Morning CEJ events are more frequent in equinoxes, and afternoon events in solstices.

(h) CEJ events do not occur at the same local time, in different longitudes.

(i) There is a modulation effect in CEJ events, due to the Moon.

2.2 Some unsolved problems

(a) What are the internal contributions to the geomagnetic variations observed at the Earth's surface, particularly at points under EEJ influence?

(b) Is the equatorial current system superimposed on the Sq system?

(c) What is the day-to-day variability of the EEJ and its response to the interaction with local ionospheric neutral winds?

(d) Are meridional currents present in the equatorial ionosphere?

(e) What is the latitudinal distribution of EEJ currents?

(f) Do the actual EEJ models have a sufficient accuracy to explain all the observed data?

(g) Are the CEJ events produced by some specific tidal modes in the atmosphere or are they connected with vertical drifts?

3. The Equatorial Electrojet in South America

Besides the historical fact that some of the first inferences of EEJ existence had been made at Huancayo, Peru, peculiar geomagnetic patterns are present in South America. It contains a major part of the EEJ and the South American Geomagnetic Anomaly (SAGA), a region where the geomagnetic field intensity has a minimum value. These features give to geomagneticians important opportunities of research.

The South American EEJ lineament presents interesting singularities that make its study a rewarding source of information. If we consider the dip equator track around the globe, it is noticed that the largest distance between geographic and dip equators occurs in South America, and a considerable angle is found between both lines. On the South American west coast, in Peru, the magnetic equator is parallel to the geographic equator, but they are separated in latitude by a distance of about 1400 km (≈13°). The dip equator traverses Brazilian territory from west to east but swerves northward to cut the geographic equator off the Continent, and both equators remain parallel in Africa. On the other hand, the EEJ has a Southern geographical position only in South America and in the Eastern part of the Pacific Ocean.

It might be concluded that geographically southern causes might be present in South American EEJ characteristics and, in opposition, northern characteristics might be found in the African EEJ. Among such effects, simultaneous but different seasonal effects, unequal lunar tidal results, and distinctive consequences of Coriolis action on neutral winds may be mentioned. Brazil is crossed by both equators, in an extension of more than 2500 km for each line. In Brazilian territory, as the dip equator swerves northward in such way that the distance between both lines decreases from 1200 km (near the western border) to 320 km (off the Atlantic coast), the angle between both lines is about 30° around the meridian of 45° W.

This parallax of the two equators creates a complex situation for the ionospheric dynamo. Kane and Trivedi (1980, 1982, 1985) discussed EEJ problems in Brazil and presented very important results. They found that EEJ has different aspects in Northeastern Brazil when compared to EEJ elsewhere. From comparisons between Eusebio (Brazil) and Huancayo (Peru), they found that EEJ currents are weaker at Eusebio and there are excursions of northern hemisphere Sq currents into the sourthern hemisphere and viceversa; also the events at the two stations do not occur at the same local time.

Another interesting aspect of the South American EEJ refers to its remarkable secular motion. Based on old (Rijkevorsel, 1890; Costa, 1935) and new (Gama, 1969a; Motta and Barreto, 1986) repeat station observations, it was possible to outline the motion of the dip equator in Brazil (Barreto, 1988). A similar study was made by Casaverde and Giesecke (1988) for Peru, and good agreement was found. Apparently there is an acceleration in the westward motion of I-isoporics in Brazil. The difference between maximum (eastern region) and minimum (western region) annual variation values increased from 19'/year to 28'/year in the period 1967/1985. In accordance with the statement of a northwestern displacement of the excentric dipole field (Nagata, 1965), a sliding westward movement of isoclinic lines (and, in consequence, of the dip equator) is more acceptable than an apparent rotation of the dip equator, that could be misinterpreted from a glance at the graphical aspect of the dip equator in different epochs.

4. Experimental work on EEJ in Brazil

At the 1987 IAGA Assembly, the IDCDC (Interdivisional Comission for Developing Countries) proposed to intensify studies of the EEJ on a global scale, buy means of an effort named International Equatorial Electrojet Year (IEEY). After some postponements, it was settled for the period 1991/1992.

During the early sixties, Hesse (1982) performed an experiment using mobile magnetometers along the dip equator. The data from the various sites allowed an interpretation of the EEJ morphology and of the sources of Sq variations.

Gama (1972) obtained EEJ data using an old-fashioned magnetometer and performing a careful comparison with Tatuoca and Vassouras observatories for the same days. From those experiments it was possible to establish practical rules for correcting the data from repeat stations under EEJ influence. These corrections were used in Gama's work on normal field modeling (Gama, 1965; Gama, 1969a) and they have been proposed to be adopted in all South American field work (Gama, 1969b).

After this initial phase of EEJ study, researchers from the Instituto de Pesquisas Espaciais (INPE), mainly Kane and Trivedi, have published a long and important series of papers about the EEJ, using Huancayo, Tatuoca, Eusebio and Alcantara magnetic stations (Kane & Trivedi, 1980, Kane & Trivedi, 1982; Kane & Trivedi, 1985; Trivedi *et al.*, 1989).

With regard to the IEEY in Brazil, INPE researchers took steps to arrange for successful experiments. The permanent program, besides using data from INPE permanent variation stations at Eusebio and Alcantara, includes recordings from new provisional stations under EEJ influence. Some cooperative efforts from the Observatorio Nacional (O.N.) were added to INPE activities, including data from its magnetic observatories at Tatuoca and Vassouras, and from the repeat station network. Tatuoca is now very near the northern edge of the EEJ, and Vassouras is a middle-latitude observatory, that could be used as a comparison station.

After some initial trials, prototype flux-gate magnetometers were built at INPE, with good results. During a couple of weeks, the first experiment was conducted in September, 1989 in the northwestern region of Brazil (State of Maranhão).

Later, more sophisticated automatic flux-gates were built at INPE, to be installed in perpendicular profiles to the dip equator. In the beginning of 1991, eight instruments were ready to work. It is planned to install them along a profile in the western Brazilian region, near the Peru border. In cooperation with colleagues from Flinders University, South Australia, an array of about 28 automatic sensitive ringcore flux-gate magnetometers were installed in the Maranhão-EEJ region.

A magnetometer array is useful for studying simultaneously both internal and external geomagnetic fields in a single experiment. It can furnish important data to interpret electrical properties of the Earth crust and the upper mantle and their relationships to geological features.

A combination of MT and GDS methods is an effective way to study electrical properties of the lower crust and the upper mantle. MT data provide vertical profiles of electrical conductivity and GDS yields lateral distribution of conductivity. A joint interpretation of MT and GDS results may provide insights into the induction problems.

The current assumption that the vertical geomagnetic field is uniform in the vicinity of the MT site could be verified by a magnetometer array, mainly in the EEJ region, where electrojet fields are non-uniform. However, MT results could be satisfactory, up to periods of five hours.

In spite of the encouraging operation of MT and GDS arrays in EEJ region, for logistic and financial reasons an array of only magnetometers will be installed and MT measurements will be conducted separately at some station in the region of the array.

Some findings may be summarized for the preliminary measurements performed in September, 1989:

(1) IGRF mathematical model had indicated that Santa Rita station was north of dip equator, but it is actually slightly south of it.

(2) The rate of change of magnetic dip angle with latitude was found to be of 1.37°/degree of latitude. This change is know to be 1.9° in Peru and around 2.5° in India.

(3) Previous studies have shown that the range of daily variation of H in NE-Brazil was seldom close to 200 nT, but in Santa Rita it is common to find the daily range of H close to 200 nT or more.

(4) Some day-to-today variability of EEJ could be detected, but the data are not sufficient to understand its response to interaction with local neutral winds.

In addition to the Brazilian program, there is a good scientific effort performed by Peruvian geomagnetists from the Instituto Geofísico del Peru, the Universidad Nacional de San Agustín, and the Universidad de Piura. Under the sponsorship of the Consejo Nacional de Ciencia y Tecnología an extensive program of geomagnetic measurements was planned, that may be summarized as follows.

(a) Objective. To study EEJ morphology in Peru and irregularities at ionospheric E-region.

(b) Operation of Askania variographs (H,D,Z) at Guadalupe (near the dip equator), Jicamara (at the same latitude of Huancayo, but outside of the Andean Anomaly), and Piura (outside of EEJ influence).

(c) Operation of temporary stations at Yuca, Nazca, Cañete, Casma and Trujillo. These stations are situated along a profile perpendicular to the dip equator. They are separated by distances around 150 km. It is planned to use digital magnetometers at those stations.

(d) To use Huancayo, Jicamara and Ancón observatories as reference stations.

(e) To study ionospheric irregulaties with simultaneous radar observations at Jicamara and Piura.

Some attempts are been made by the Working Group on Geophysical Maps of the Pan-American Institute of Geography and History (PAIGH) to involve other Latin American countries in EEJ reasearch activities. Besides Brazil and Peru, only Bolivia is crossed by EEJ and, for this reason, a Bolivian significant participation in the IEEY will be very important. Patacamaya Magnetic Observatory is under the influence of EEJ and its results will be very valuable. While the other Latin American magnetic observatories are outside the EEJ influence, it might be possible to enroll some of them in an experiment that has the EEJ phenomena as one of its investigation purposes.

Chapman and Bartels in their classical book (Chapman and Bartels, 1940) discussed the effect of a solar eclipse on the EEJ features. Gama (1948) published the analysis of Vassouras data during the 1947 Solar Eclipse. According to Rastogi (1989), solar eclipse effects at low latitudes are different on the EEJ when the tracks of totality are parallel to the dip equator. Roughly, this was the condition of the 1947 eclipse.

Though Vassouras was outside the 1947 eclipse totality, Gama (1948) did his research with good results.

The eclipse of November 12, 1966 was a very important event in South America. Significant aeronomic observations were made by INPE and other international organizations, mainly about the SAGA. Very intensive observations of the effects of an eclipse on the EEJ were made in Peru, due to good eclipse conditions. The eclipse track was practically normal to the dip equator. Magnetic observations were taken at six stations where the inclination varied from 2°N to 5°S. One of the conclusions was that the H changes during eclipses were proportional to the reduction in ionospheric E-region electron density.

Another total solar eclipse may give us an opportunity of investigating EEJ effects. On July 11, 1991, a total solar eclipse will occur, presenting very interesting aspects. The 1991 eclipse is an exciting event for astronomers, for its long duration (almost 7 minutes, the longest of all remaining total eclipses in this century), and for the places crossed by its track (Bangert *et al*, 1989). Important astrophysical observatories (Hawaii, Mexico) are close to the eclipse central line.

However, magnetic observatories have not been forgotten by the 1991 Eclipse Designer, because three Latin American stations will be in the lunar shadow: Teoloyucan (Mexico), Chiripa (Costa Rica), and Fúquene (Colombia). In addition, at many other magnetic observatories a partial eclipse will be observed, some under EEJ influence.

The PAIGH Working Group on Geophysical Maps is planning an inexpensive program for the 1991 eclipse. Some previous contacts have been made, in order to coordinate possible geomagnetic measurements. From a general standpoint, the observing stations could be divided into four classes:

(a) Stations in the totality or near it, but far off the EEJ. Such are the cases of Teoloyucan, Chiripa and Fúquene magnetic observatories.

(b) Stations in the totality, and located near the EEJ. A provisional station in the Brazilian Amazonic region (for instance, the cities of Tefé of Manicoré), where a portable flux-gate magnetometer could be installed.

(c) Stations at points where a partial eclipse is observable and located in the EEJ, or near it. Such are the cases of Huancayo, Tatuoca, Patacamaya observatories, and Alcantara station.

(d) Stations outside both the EEJ and the eclipse zone. Such are the cases of Vassouras, Pilar, Las Acacias observatories.

Data from (a), (b) and (c) stations must be correlated and compared with those from (d) stations. Comparisons between (a) stations and (b), (c) and (d) stations could be useful.

Even if no major scientific conclusions were obtained from such extensive observations and data analysis, we must make sure that an ultimate result be acquired: an ample exercise of scientific cooperation among Latin American countries.

A cooperation among Third World nations is the only way to overcome the circumstantial problems that involve our countries.

BIBLIOGRAPHY

BANGERT, J.A., A.D. FLALA and W.T. HARRIS, 1989. Total Solar Eclipse of 11 July, 1991. U.S. Naval Observatory, Circular No. 174.

BARRETO, L.M., 1987. Considerações sobre a variação secular e o modelamento do campo geomagnético no Brasil. Publ.Espec. No. 5, Observatorio Nacional.

BARRETO, L.M., 1988. Secular Variation and Geomagnetic Normal field modelling in Brazil. *Deutsch. Hydrograph. Zeitsch.*, 41.

CASAVERDE, M. and A. GIESECKE, 1989. Variación del Ecuador Magnético en el Perú. *Revista Geofísica del IPGH*, 29.

CHAPMAN, S., 1951. The Equatorial Electrojet as detected from the abnormal electric current distribution about Huancayo, Peru and elsewhere. *Arch. Meteorol. Geophys. Bioklismat.* Serv. A, 4.

COSTA, D.F., 1935. Anuário do Observatório Nacional. Observatório Nacional.

FORBES, J.M., 1981. The Equatorial Electrojet. *Reviews of Geophysics and Space Physics, 19*, 3.

FORBUSH, S.E. and M. CASAVERDE, 1961. Equatorial Electrojet in Peru. Carnegie Inst. of Washington Publ. No. 620.

GAMA, L.I., 1948. Magnetic effects observed at Vassouras, Brazil, during the Solar Eclipse of May 20, 1947. *J. Terrestrial Magnetism and Atmospheric Electricity, 53*, 3.

GAMA, L.I., 1965. Campo magnético normal e sua variação secular no Brasil em 1960. Publ. Serv. Magn. No. 9. Observatório Nacional.

GAMA, L.I., 1969a. Campo magnético normal e sua variação secular no Brasil em 1965.0. Publ. Serv. Magn. No. 13. Observatório Nacional.

GAMA, L.I., 1969b. Recommendations from the South American Meeting on Geomagnetism. *IAGA News* , 8.

GAMA, L.I., 1972. Sobre a variaçao diurna do campo magnético no Brasil. Publ. de Geomagn. No. 15. Observatório Nacional.

GOUIN, P. and P.N. MAYAUD, 1967. A propos de l'existence possible d'un "contre-electrojet" aux latitudes magnétiques equatoriales. *Ann. Geophys.* 23.

HIRONO, M., 1950. *Journal of Geomagnetism and Geoelectricity*, 2.

HESSE, D., 1982. An investigation of the Equatorial Electrojet by means of ground base measurements in Brazil. *Ann Geophys.*, 38.

KANE, R.P., 1976. Geomagnetic field variations. *Space Science Rev*,. 18.

KANE, R.P. and N.B. TRIVEDI., 1980. Influence of Northern and Southern Hemisphere Sq current system on equatorial magnetic variations. *J. Atmosph. Terres. Physics*, 42.

KANE, R.P. and N.B. TRIVEDI, 1982. Comparison of Equatorial Electrojet characteristics at Huancayo and Eusebio (Fortaleza) in the South American region. *J. Atmosph. Terres. Physics*, 44.

KANE, R.P. and N.B. TRIVEDI, 1985. Equatorial Electrojet movements at Huancayo and Eusebio. *J. Geomagn. and Geoelectricity*, 37.

MAYAUD, P.N., 1977. The equatorial counter-electrojet a review of its geomagnetic aspects. *J. Atmosph. Terres. Physics*, 39.

MOTTA, C.M. and L.M. BARRETO, 1986. Campo Geomagnético Normal e sua variação secular no Brasil em 1985.0. Observatorio Nacional.

NAGATA, T., 1965. Main characteristics of recent secular variation. *Journal of Geomagnetism and Geoelectricity*, 17.

RASTOGI, R.G., 1989. The Equatorial Electrojet: magnetic and ionospheric effects in Geomagnetism, Vol. 3, J.A. Jacobs, Ed,.. Academ. Press.

REDDY, C.A., 1981. The Equatorial Electrojet: a review of the ionospheric and geomagnetic aspects. *J. Atmosph. Terres. Physics*, 43.

REDDY, C.A., 1989. The Equatorial Electrojet. *PAGEOPH*, *131*, 3.

RICHMOND, A.D., 1973. Equatorial Electrojet development of a model including winds and instabilities. *J. Atmosph. Terres. Physics*, 35.

RIJKEVORSEL, V. and ENGELENBURG, 1890. Magnetic survey of the Eastern part of Brazil. Royal Academy of Sciences at Amsterdam.

STENING, R.J., 1985. Modelling the Equatorial Electrojet. *Journal of Geophys. Res.*, 90.

TRIVEDI, N.B., J.M. da COSTA, I. VITORELLO, A.L. PADILHA, L.M. BARRETO, 1989. Recent geomagnetic measurements in the Equatorial Electrojet Region NE, Brazil. Presented at the VIII International Symposium on Equatorial Aeronomy, Tucumán, Argentina. (Unpublished.)

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