Pi1B pulsations at the South American equatorial zone during the 29 October 1994 magnetic storm

Antonio L. Padilha*, M. Virginia Alves, Nalin B. Trivedi, INPE, Brazil
Tai-I. Kitamura, Manabu Shinohara, Kyushu University, Japan

This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

The effects of the great magnetic storm of 29 October 1994 on the daytime equatorial ionosphere have been studied by a ground-based array of fluxgate magnetometers in South America. The array covers around 2 h in magnetic local time and spans dip angles from 6.7°N to 10.8°S, with additional very-low latitude and nightside dip equator stations as reference. Following an abrupt increase in the AE index during the storm main phase, intense Pi1B activity is seen over a wide region around the prenoon dip equator. The pulsations are strongly attenuated not propagating outside the equatorial zone and have differences in time onset at different longitudes. It is proposed that they are associated with gradient-drift plasma instabilities triggered by prompt penetration of high latitude electric fields. Local ionospheric properties appear to control instability onset and growth rate along the dip equator.

Introduction

Pi1Bs are impulsive short-lasting broadband magnetic pulsations in frequencies higher than 25 mHz which have been associated with auroral particle precipitation during intense substorm onsets and intensifications. It is generally accepted that they represent the ground signature of overhead ionospheric currents created by enhanced conductivity due to the precipitation. Their properties have been derived from studies in space and along ground profiles at high and midlatitudes (e.g., Arnoldy et al., 1998, and references therein]. As it is not expected that they will be observed outside these regions, no detailed study with a dense chain of stations at equatorial latitudes has been reported so far.

A strong magnetic storm took place on 29 October 1994, with sudden commencement at 0025 UT. Unfortunately, the coverage of IMF data is not good and only a few observations from this event were published. Lui et al. (1996) reported ENA composition measurements from the GEOTAIL and found that at energy larger than 200 keV O^+ has the highest flow. Baishev et al. (1997) observed waves of diffuse luminosity propagating to the west at an auroral station. These waves were accompanied by intensification of the eastward electrojet, displacement of the electrojet center and auroral arc to the equator, and excitation of Pc4-5 geomagnetic pulsations.

This paper concerns bursty geomagnetic variations in the frequency range 25-100 mHz, as observed at equatorial ground-based stations during the 29 October 1994 magnetic storm. It uses data from temporary stations with latitudinal and longitudinal coverage of the equator in South America. To our knowledge this is the first experiment in which Pi1B pulsations have been detected by geomagnetic stations at these latitudes.

Available data

Figure 1 gives a map of South America with the locations of 11 stations. Also shown are relevant dip angles during the period of data acquisition indicating the dip equator (solid line) and the schematic extent of the equatorial electrojet effects (dashed lines). Three stations (BLM, ALC, and EUS) are located at the east-coast equatorial region, with ALC at the dip equator. Seven others (POV, ARI, PRM, VIL, COL, CUI, and SMA) lie roughly along the 10° magnetic meridian across the center of the continent, with PRM at the dip equator and SMA outside the equatorial region. ANC is positioned close to the dip equator at the West Coast. Station POH located in Micronesia equatorial region is not shown.

At each site a fluxgate magnetometer with a self-time calibration system was installed and provided digital data with a precision of 0.015 nT in H, D, and Z geomagnetic components (Tachihara et al., 1996). The signal was recorded as time differential with 3-s sampling and an upper limit around 0.7 nT/s was defined to ignore quick and huge variations. The clock of the data logger was calibrated automatically by global radio signals, which kept the time accuracy to within 100 ms during the acquisition.

The main morphological features of the ground-observed perturbations on 29 October 1994 are shown in Figure 2 through geomagnetic indices. For comparison, the figure also includes geomagnetic data in the two horizontal components at one of our equatorial stations (ALC). These data were band-pass-filtered using a zero-phase shift Butterworth function with unit response between 10 and 100 mHz.

The storm main phase started around 9 UT, with a depression in Dst and increase up to 7 in Kp. It had a two-step development, an indicative that a second particle injection took place before the ring current had decayed to the prestorm level (Kamide et al., 1998). Dst reached its first minimum of –102 nT at 11-12 UT, with AE around 500 nT. At 13 UT, AE showed an abrupt increase of 600 nT, probably related to a major substorm onset resulting from another energy deposition in the auroral region. For the next three hours, AE remained very high with peaks larger than 2000 nT. Dst reached its second minimum of

–123 nT at 15-16 UT, recovering substantially near the end of the day.

Data from station ALC show that the activity enhanced considerably since 6 LT (dawn sector), in accordance with the beginning of the storm main phase. An additional amplification occurred after 10 LT (prenoon), coincident with the sharp increasing of the AE curve. Amplitude of D-component is much smaller than that of H-component, an indicative of enhanced E-W ionospheric currents.

Pi1B activity

Preliminary data analysis was undertaken using FFT spectral estimates. Spectrograms were calculated at each station and inspected to identify signatures of high power and high coherency across the array. Figure 3 contains 10- to 100-mHz spectrograms from the 12 stations for the time interval in which the maximum geomagnetic activity was observed. Regarding local time, the beginning of the period (1300 UT) corresponds to the prenoon sector at South American stations, ranging from 0812 LT (site ANC) to 1013 LT (site EUS), and nighttime at POH (2305 LT).

Starting just after 1300 UT, broadband bursts (Pi1B) are observed in irregular intervals at the South American sites closest to the dip equator. Some of these bursts have intense power in the whole frequency band (up to 100 mHz) and show a dependence on distance from the dip equator with increased power at stations ANC, PRM, and ALC. From Pi1B studies at mid and high latitudes, the source region of these pulsations may not have been far away from the dip equator (Bösinger and Wedeken, 1987). Unfortunately, the low sampling rate of data acquisition prevents observation of the power enhancements frequently seen in frequencies higher than 100 mHz (Heacock and Hunsucker, 1981). Also, some of the events have intervals with quick variations of very large amplitude that sometimes exceed the time differential limit of the recording system. These intervals appear in our graphics as data gaps.

Along the dip equator, the Pi1B signal is only observed at daytime sector, an indicative of its close connection with the influence of Cowling conductivity effects. Some isolated events of very short duration have variable time delay between the stations ALC, PRM, and ANC. Also, no clear direction of propagation is discernible for these events. Accordingly, they can not be associated with the passage of an east-west traveling surge or to any model of oppositely directed electric fields, as proposed by Kikuchi et al. (2000) to explain a delay in substorm events at two equatorial stations. Here, a model including isolated ionospheric sources seems more appropriate.

Within the time interval of Figure 3, the event commencing around 1330 UT was the most intense recorded and was selected to be examined more closely at the sites along the meridian 10^{o}. To isolate the Pi1 most prominent band, the data were band-pass-filtered between 25 and 100 mHz. Figure 4 shows stacked plots of the filtered data in the H-component for the interval 1325-1340 UT, when the pulsation train was well developed.

The event is observed simultaneously at all stations from POV to COL, covering distances of at least 350 km north and south from the dip equator (site PRM), an indicative that the ionospheric activity must be of large dimensions and/or the occurrence of an efficient propagation along geomagnetic field lines. It is not seen at CUI (770 km south from PRM), which has the same geomagnetic signature of SMA. This is corroborated by cross-correlation analysis that shows that CUI has stronger correlation with SMA than with their neighboring equatorial stations. Moreover, it can not be attributed to the well known equatorial amplification experienced by geomagnetic variations at daytime because it has been reported that for the typical periods of Pi1 (less than about 30 s) the daytime equatorial signals suffer attenuation rather than amplification (Sarma and Sastri, 1995).

Taken into account the time resolution of 3 s of our data, this disturbance has an apparent velocity larger than 120 km/s and an effective damping lesser than 750 km. However, these quantitative results must be regarded with caution because ground-based magnetometers integrate the effects of ionospheric currents up to 150-200 km distant (Engebretson et al., 1995).

It can be then concluded that these Pi1B pulsations are locally generated close to the dip equator but are also strongly attenuated at the equatorial zone, similar to what is observed at higher latitudes (Bösinger and Wedeken, 1987). On the other hand, the stations are located over very different geologic structures, which generates different induction effects avoiding the comparison of pulsation amplitudes.

Discussion and conclusions

It is known that the equatorial ionosphere disturbances are the extensions of the very complex electrodynamic changes in the magnetosphere-ionosphere system resulting from solar wind-magnetosphere interactions. In particular, ground-based magnetometers respond mainly to changes in E-region currents and can be used to record the ionospheric signatures of the magnetospheric energy transfer process.

Theoretical models have shown that this energy transfer to low latitude can be explained by the effect of short-lived (1-2 h) penetration of the primary convective electric field which is regulated by shielding effects associated with field-aligned currents and/or storm-time thermospheric winds from high latitudes which lead to the generation of dynamo electric fields that propagates equatorward with latitude-dependent time delays. The timing between the substorm onset in the auroral zone and the maximum Pi1B across the equatorial array favors the mechanism of prompt penetration of electric fields from high latitudes (e.g., Kikuchi and Araki, 1979). In fact, many features of our results are in good agreement with the general empirical model proposed by Fejer and Scherliess (1997) for storm-time equatorial electric fields. In this model, following a sudden increase in the AE index, high latitude electric fields penetrate nearly instantaneously into the low latitude ionosphere since the region 2 field-aligned current lags behind the change in the polar cap potential drop. Under these undershielding conditions the equatorial perturbation vertical drifts will generate eastward electric fields during the day. Less than 2 h after the increase in the AE index, these prompt penetration drifts essentially vanish, as the shielding is re-established.

It is speculated here that the penetration of these high latitude electric fields produces strong irregularities in the daytime equatorial ionosphere through plasma instabilities. There are basically two processes that generate the primary irregularity: the meter-scale two-stream instability and the kilometer-scale gradient-drift instability (Kelley, 1989). The extension and magnitude of the geomagnetic variations (simultaneity to within 3~s at distances of hundreds of kilometers and amplitude of about 0.5 nT) point to gradient-drift instability as the most likely source of the Pi1B activity. This instability will produce irregularities whenever the gradient in the electron density has a component parallel to the ambient electric field and will drive currents parallel to the E-W Pederson currents in the ionospheric E-region.

Time differences in activity onset along the dip equator can be ascribed to differences in local ionospheric properties. It is known that the South American equatorial sector presents large longitudinal differences in many of its ionospheric parameters (e.g., Kane, 1984; Abdu et al., 1992). To the proposed model of gradient-drift instabilities be valid, such differences would have to affect significantly the magnitude of the plasma dip velocity and the size of the background gradient, two of the most important parameters that define the onset and growth rate of the instability process, in distances of less than 1600 km (ANC to PRM).

Acknowledgments

This study was partially supported by grants from FAPESP (93/0652-2) and CNPq (350683/94-8). We acknowledge the WDC-2, Kyoto, for Dst and provisional AE indices, and GFZ Potsdam, for Kp index.

References

Abdu, M.A., Fejer, B.G., Batista, I.S., Sobral, J.H.A., and Szuszczewicz, E.P., 1993, Equatorial ionosphere sunset electrodynamics in the American sector from SUNDIAL December 1988 campaign results, Geomagn. Aeron., 33, 13-19.

Arnoldy, R.L., Posch, J.L., Engebretson, M.J., Fukunishi, H., and Singer, H.J., 1998, Pi1 magnetic pulsations in space and at high latitudes on the ground, J. Geophys. Res., 103, 23581-23591.

Baishev, D.G., Yumoto, K., Solovyev, S.I., Molochushkin, N.E., and Barkova, E.S., 1997, Variations of magnetic fields during appearance of large-scale waves of diffuse aurora in the evening sector during magnetic storms (in Russian), Geomagn. Aeron., 37, 39-46*.*

Bösinger, T. and Wedeken, U., 1987, Pi1B type magnetic pulsations simultaneously observed at mid and high latitudes, J. Atmos. Terr. Phys., 49, 573-598.

Engebretson, M.J., Hughes, W.J., Alford, J.L., Zesta, E., Cahill Jr, L.J., Arnoldy, R.L., and Reeves, G.D., 1995, Magnetometer array for cusp and cleft studies observations of the spatial extent of broadband ULF magnetic pulsations at cusp/cleft latitudes, J. Geophys. Res., 100, 19371-19386.

Fejer, B.G. and Scherliess, L., 1997, Empirical models of storm time equatorial zonal electric fields, J. Geophys. Res., 102, 24047-24056.

Heacock, R.R. and Hunsucker, R.D., 1981, Type Pi 1-2 magnetic-field pulsations, Space Sci. Rev., 28, 191-221.

Kamide, Y., Yokoyama, N., Gonzalez, W., Tsurutani, B.T., Daglis, I.A., Brekke, A., and Masuda, S., 1998, Two-step development of magnetic storms, J. Geophys. Res., 103, 6917-6921.

Kane, R.P., 1984, Differential behavior of the equatorial ionosphere on the eastern and western coasts of the South-American continent, J. Geomagn. Geoelectr., 36, 197-201.

Kelley, M.C., 1989, The Earth's ionosphere: Plasma physics and electrodynamics, Academic Press, San Diego.

Kikuchi, T. and Araki, T., 1979, Horizontal transmission of polar electric-field to the equator, J. Atmos. Terr. Phys., 41, 927-936.

Kikuchi, T., Lühr, H., Schlegel, K., Tachihara, H., Shinohara, M., and Kitamura, T.-I., 2000, Penetration of auroral electric fields to the equator during a substorm, J. Geophys. Res., 105, 23251-23261.

Lui, A.T.Y., Williams, D.G., Roelof, E.C., McEntire, R.W., and Mitchell, D.G., 1996, First composition measurements of energetic neutral atoms, Geophys. Res. Lett., 23, 2641-2644.

Sarma, S.V.S., and Sastry, T.S., 1995, On the equatorial electrojet influence on geomagnetic pulsation amplitude, J. Atmos. Terr. Phys., 57, 749-754.

Tachihara, H., Shinohara, M., Shimoizumi, M., Saka, O., and Kitamura, T., 1996, Magnetometer system for studies of the equatorial electrojet and micropulsations in equatorial regions, J. Geomagn. Geoelectr., 48, 1311-1319.

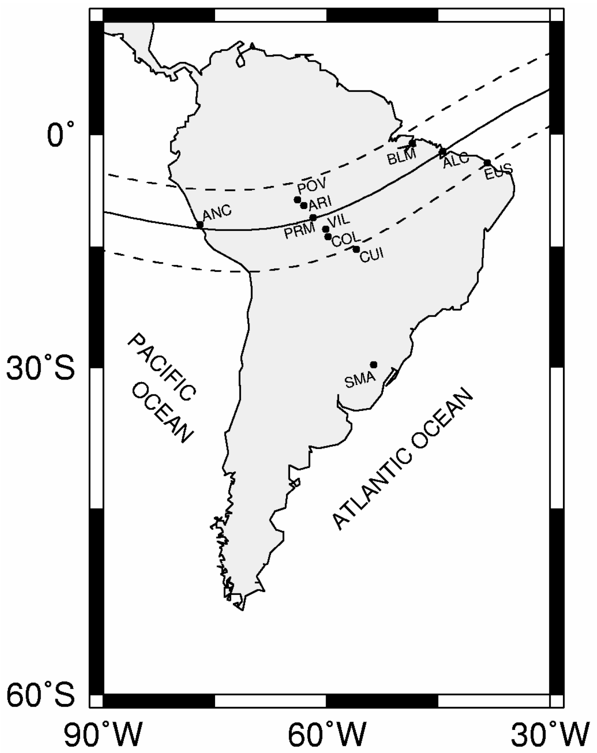

Figure 1 - Map of South America showing the sites from which data are used in this study. Solid line is a schematic representation of dip equator in October 1994 and dashed lines are ±10° dip angles at the same time.

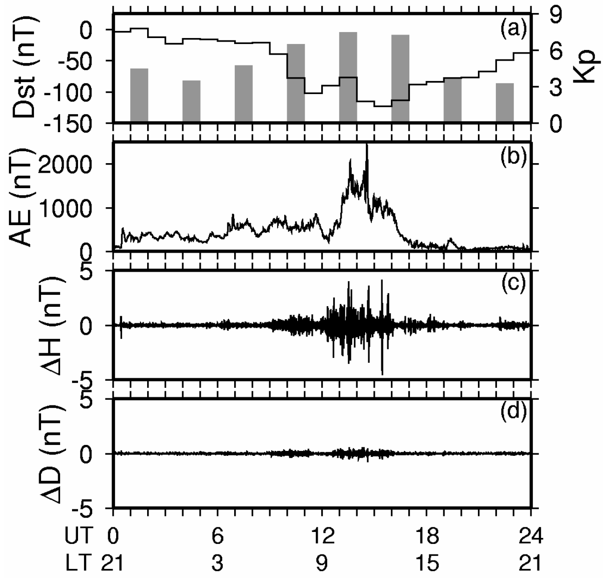

Figure 2 - Indices of global geomagnetic activity compared to equatorial ground magnetometer data on 29 October 1994. (a) Dst (solid line) and Kp (bars) indices; (b) AE index; (c) band-pass-filtered H-component for site ALC; (d) band-pass-filtered D-component for site ALC.

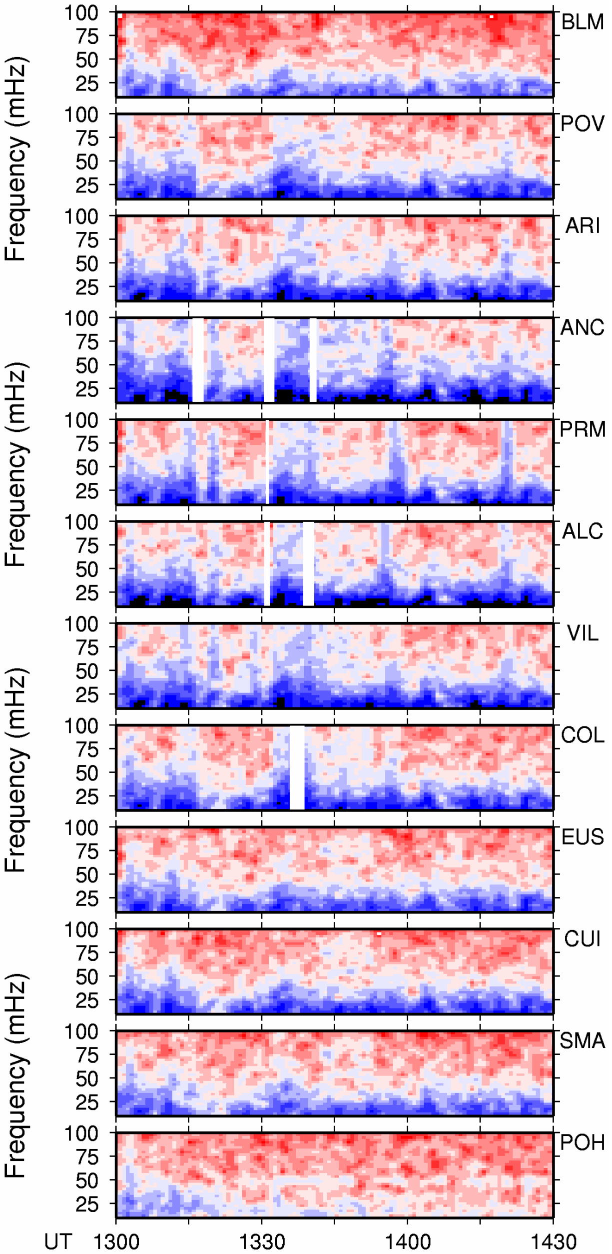

Figure 3 - Spectrograms of band-pass-filtered H-component data from sites identified on the right for the 29 October 1994 event. The white vertical bands are data gaps. The scale of the spectrograms is logarithmic between 10^{-1} (blue) and 10^{-4} (red) in units of nT^2/Hz.

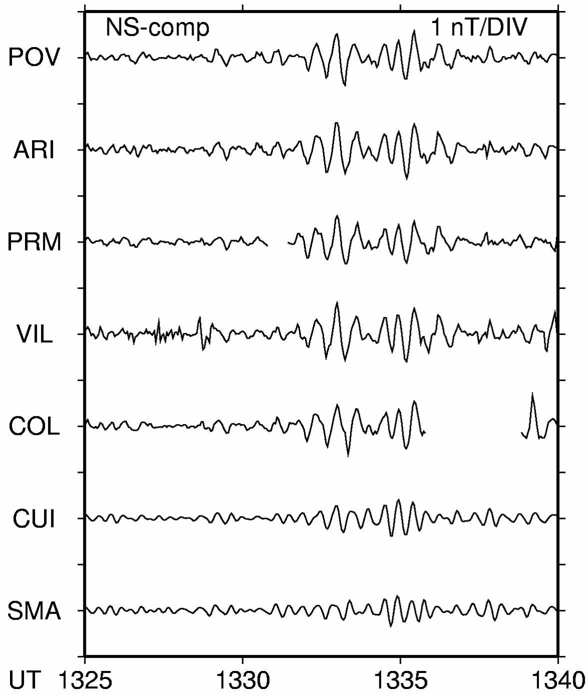

Figure 4 - Stacked plots of band-pass-filtered H-component variations along the meridian 10^o for the time interval 1325-1340 UT on 29 October 1994.