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12 Ionospheric effects of the March 13, 1989, magnetic
   storm at low equatorial latitudes
14 13943-13952
30 Journal of Geophysical Research
31 96
32 A8
40 En
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42 <E>
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68 PRE
76 AERONOMIA
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(SP)><FORTALEZA (CE)>
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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. A8, PAGES 13,943–13,952, AUGUST 1, 1991

Ionospheric Effects of the March 13, 1989, Magnetic Storm at Low and Equatorial Latitudes

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The great geomagnetic storm of March 13, 1989 (Σ Kp = 60, Ap = 246) caused severely anomalous behavior in the equatorial and low latitude ionosphere in the Brasilian longitude sector. The ionograms over Fortaleza (4°S, 38°W) indicated F region upward plasma drifts exceeding 200 m s^{-1} at 1830 LT as compared to normal values of 40 m s^{-1} for this epoch. Large negative phases were observed in $foF2$ over Fortaleza and Cachoeira Paulista (22.5°S, 45°W) and in total electron content measured over São José dos Campos (23°S, 46°W). The equatorial ionisation anomaly was totally absent either because of its anomalous expansion to higher latitudes or because of inhibition of its development on the two nights following the storm. Many anomalous variations in F region peak density and height, occurring simultaneously with sharp variations on H component of magnetic field over Fortaleza and with auroral substorms, give strong evidence of penetration of magnetospheric electric fields to equatorial and low latitudes. Auroral type sporadic E and night E layers are observed after 1830 LT over Cachoeira Paulista, the latter showing peak electron density of about 6 × 10^4 el cm^{-3}, therefore comparable to the E layer peak density in the morning hours at that station. The Fortaleza ionograms show the presence of the $F1$ layer at night, a phenomenon that has never been observed over our two stations before. The role played by electric fields penetrating from high to low latitudes, particle precipitation, and composition changes in explaining the observations is discussed.

1. INTRODUCTION

The earlier work of *Matsushita* [1959] has established that the mid-latitude F region response to magnetic storms is characterized by a positive phase in electron density (an enhancement in relation to the quiet day values), followed by a negative phase (a decrease in electron density in relation to the quiet day values). Over the low and equatorial latitudes mainly positive phases are observed. Although this ionospheric behavior characterizes the *mean response* to *magnetic* disturbances, many variations are observed, because the ionospheric effects are dependent on the storm time and intensity [*Titheridge and Buonsanto*, 1988], as well as on the latitude of the station, and its location in the summer or in the winter hemisphere [*Essex et al.*, 1981; *Schödel et al.*, 1974]. *Adeniyi* [1986] has classified the ionospheric effects at a low-latitude station according to the time of occurrence of the initial and main phase of the storms and observed that this factor is significant in ionospheric storm morphology. The classification becomes even more difficult when very intense and successive magnetic disturbances occur, as was the case on the March 13, 1989, event that will be discussed here.

The great magnetic storm of March 13, 1989, was a part of a longer period of high solar activity that lasted for 2 weeks (March 6 to 19) and had many important consequences at Earth and in near-Earth space [*Allen et al.*, 1989]. The storm began with a sudden commencement at 0127 UT on March 13, 1989, and the daily Ap was 246, the second largest on record since 1932, when the data series began. Kp indices as large as 9_0 occurred, and the daily sum of Kp reached 65. The ionospheric effects of that storm over low and equatorial latitudes, in Brazil, as seen from some ground-based instruments, were also very strong and quite unusual. A dramatic rise of the F layer height was registered simultaneously over Fortaleza (4°S, 38°W; -8.5° dip) and Cachoeira Paulista (22.5°S, 45°W; -26° dip), starting at around 1800 LT on March 13. For approximately 2 hours around 2000 LT the F layer traces were outside the usual 900 km height range of the ionograms at the two locations. At the same time the critical frequency of the F-layer ($foF2$) decreased by factors as high as 1 order of magnitude, in relation to the quiet time observations. Also the total electron content (TEC) measured at São José dos Campos (23°S, 46°W; -26° dip) showed a very big depletion. Besides the described effects there were some peculiar types of layers in the ionograms, such as an $F1$ trace at night over Fortaleza, and night E and auroral type Es over Cachoeira Paulista. Some of these events were observed almost simultaneously by ground-based equipments and by DMSP F8 and F9 satellites [*Greenspan et al.*, this issue]. In this work the ionospheric effects observed at those three locations in Brazil are analyzed in relation to existing theories and using a low-latitude numerical model to try to explain some of the phenomena.

Paper number 91JA01263.
0148-0227/91/91JA-01263$05.00

2. OBSERVATIONS

We use in this study ionograms and magnetograms registered at Fortaleza and Cachoeira Paulista, and TEC measurements from São José dos Campos. Cachoeira Paulista and São José dos Campos are located near the South Atlantic anomaly center (approximately at 27°S, 53°W), and very close to the crest of the equatorial ionization anomaly (EIA); Fortaleza is very close to the magnetic equator. Figure 1 shows, together with the variations in the auroral indices AU and AL, the variations in the horizontal component of the Earth magnetic field (ΔH), the F layer critical frequency ($foF2$), the maximum height of the F layer peak (represented by $hpF2$), and the relative TEC for the period March 12-14, 1989. It should be noted that the parameter $hpF2$ could depart from the $hmF2$ obtained by the height ionogram inversion by $\leq$50 km during daytime and by $\leq$10 km at night. This difference will not, however, influence our discussion on the variabilities in the parameters.

Figures 1*b* and 1*e* show the variation in the horizontal component of the Earth's magnetic field (ΔH, in gammas) registered at Fortaleza and Cachoeira Paulista, respectively. Because of the discontinuity in the data after 0000 UT on March 14 over Cachoeira Paulista, there is an uncertainty in the level on this day. The H component showed a regular quiet time behavior on March 12, until the storm onset at 0127 UT on March 13 with a sudden commencement. After the sharp increase the H component started decreasing rapidly until around 0300 UT. During March 13, large fluctuations are observed in the H component, superimposed on the main phase of the magnetic storm. Some of these fluctuations are coincident with the extreme magnetospheric compression observed by the satellite GOES 7 showing that during some periods on March 13, the magnetopause, typically located at 10 R_E (Earth radii), moved inside geostationary orbit at 6.6 R_E [*Allen et al.*, 1989]. From Figure 1*b* we can see that the main phase H minimum

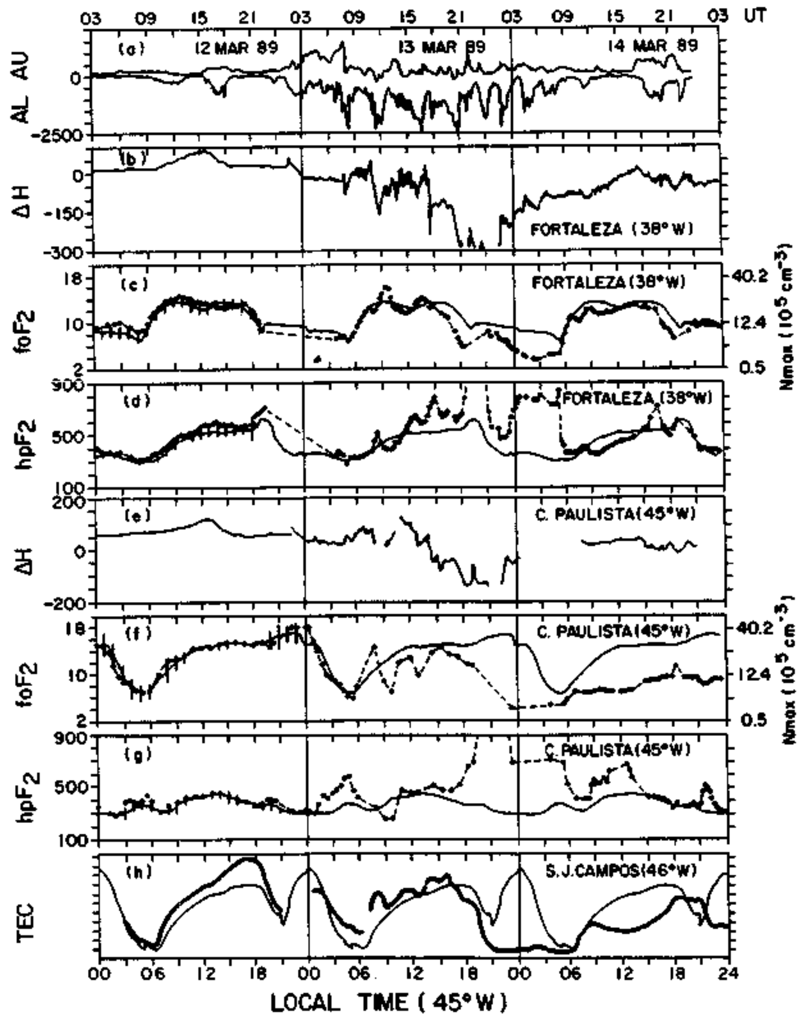

Fig. 1. *(a)* Auroral electrojet indices. *(b)* Horizontal component of the magnetic field in Fortaleza, in gammas. *(c)* and *(d)* $foF2$ (in megahertz) and $hpF2$ (in kilometers) over Fortaleza for the period March 12-14, 1989 (open circles), and quiet time reference curve (thin line). *(e)* Horizontal component of the magnetic field at Cachoeira Paulista, in gammas. *(f)* and *(g)* $foF2$ (in megahertz) and $hpF2$ (in kilometers) over Cachoeira Paulista. *(h)* Relative changes in total electron content over São José dos Campos for the period March 12-14, 1989 (thick line), and quiet time mean (thin line). Each division on the vertical axis of TEC is equal to a variation of 1.1×10^{17} el m^{-2} in TEC (or 180° in Faraday rotation angle).

occurred between approximately 1830 and 2230 LT (the magnetometer became saturated during this period). The recovery phase probably started around 2230 LT and was also characterized by many fluctuations in the geomagnetic field H component.

It is interesting to note that the negative excursions of the H component observed on March 13 over Fortaleza (around 0500, 0900, 1300, and 1500 LT) are almost in phase with the extreme negative variations on the auroral index AL, shown in the upper panel of Figure 1, together with the AU index. It may be noted that the fluctuations in ΔH, especially during the day hours of the March 13, appear to show larger amplitude over Fortaleza than over Cachoeira Paulista which might suggest enhancement of the electrojet current (eastward or westward) arising from the electric field penetration to low latitude associated with the substorm activity. Although the Fortaleza data are off scale for some periods between 1800 and 2200 LT, it appears that the drops in AL around 1800 and 2100 LT are also in phase with the negative incursions on ΔH over Fortaleza, but the drop in AL around 2300 LT coincides with a peak on ΔH instead. The relevance of the correlations of the auroral indices and magnetic field variations to the ionospheric phenomena will be discussed in section 3.1.

2.1. *Ionosonde Data*

Figures 1*c*, 1*d*, 1*f*, and 1*g* show the critical frequency of the F layer, *foF*2, and the maximum height of the F layer peak, *hpF*2, as measured by ionosondes operating in Fortaleza and Cachoeira Paulista. The solid line represents the mean of the 5 quietest days of March 1989, and the error bars represent twice the standard deviation of the data for the 5 days used in the mean. Error bars are plotted only hourly to avoid overcrowding, even when data are available at shorter time intervals. Between 1800 and 2400 LT it was not possible to obtain the quiet days' mean over Fortaleza as a result of the presence of range spread F over that station. For this reason we have used a mean behavior based on other quiet time period data.

On March 12 *foF*2 and *hpF*2 followed very closely the quiet time mean curve over both the locations. Around 0800 LT on March 13, more than 9 hours after the storm sudden commencement, fluctuations started in both parameters, the F region peak electron density (N_{max}) and its height. It is clear from Figures 1*c* and 1*f* that there are fluctuations in *foF*2 that are out of phase at the two stations, in the sense that when a peak is observed over Fortaleza a depletion is observed over Cachoeira Paulista, and vice versa (note that data over Fortaleza were available each 15 min and over Cachoeira Paulista each hour). After 1500 LT on March 13, *foF*2 started decreasing to values lower than the quiet days' mean over both the stations. This negative phase persisted until around 0600 LT on March 14 over Fortaleza, when *foF*2 seems to have recovered to the undisturbed mean value. The negative phase in *foF*2, over Cachoeira Paulista, was much more pronounced and of longer duration than over Fortaleza. In fact, *foF*2 showed only negative deviations after 0900 LT on March 13, over Cachoeira Paulista, and only after sunrise on March 15 (not shown here) did it recover to the undisturbed mean values.

Beginning at 1800 LT on March 13, a spectacular rise of the layer was observed and between 1900 and 2000 LT over Fortaleza and between 1930 and 2130 LT over Cachoeira Paulista, the ionosphere completely "disappeared" from the ionosonde register. During this period the F layer trace was totally absent in the usual 900 km height range of the ionogram. N_{max} was decreasing when this abrupt rise started but after the gap in the data (due to the height limitation of the register), N_{max} over Fortaleza was more than a factor of 2 higher than the last registered value (it increased from 3.7×10^5 el cm^{-3} to more than 8×10^5 el cm^{-3}). Despite this increase, N_{max} stayed below its normal quiet time value during the whole night, recovering to the undisturbed values only after sunrise on March 14 (Figure 1*c*). Over Cachoeira Paulista a very drastic reduction of electron density was observed during the period following the rise of the layer (Figure 1*f*). N_{max} decreased by a factor of 7 when compared to the value observed before the rising of the layer and almost 1 order of magnitude when compared to the quiet days' mean. The high N_{max} values usually observed around local midnight during quiet time over Cachoeira Paulista (solid curve, Figure 1*f*) are the manifestation of the equatorial ionization anomaly (EIA). We can notice that the EIA was not visible over Cachoeira Paulista on March 13 and 14.

Over Fortaleza (Figure 1*d*), after the dramatic rise around 1800 LT on March 13, *hpF*2 decreased until 2245 LT after which it started increasing again. The layer remained very high (700-800 km) until around 0545 LT on March 14. During daytime hours, between 0800 and 1500 LT, *hpF*2 stayed below its quiet time value, but again it started rising and around 1630 LT on March 14 it was much higher than the quiet day curve, recovering to undisturbed values after that. Over Cachoeira Paulista (Figure 1*g*), after 0100 LT on March 13 (about 2 hours after the SSC), *hpF*2 increased to values much larger than the quiet days' mean. During March 13-14, *hpF*2 remained above the quiet day level almost all the time, except for a short-duration period around 0900 LT on March 13 and for the afternoon recovery on March 14. Only after sunrise on March 15 (not shown here) did *hpF*2 recover to the undisturbed values.

Another very unusual phenomena observed over Fortaleza was the formation of an *F*1 layer at night on March 13, just after the rise of the main F layer to values outside the ionogram height range. Until 1845 LT, standard F traces with no *F*1 stratification have been observed on the ionograms. From 1900 to 2000 LT, no F trace was observed and at 2015 LT it reappeared on the ionogram at 680 km virtual height ($h'F$), descending to 300 km in less than 1 hour. Only from 2045 LT onward, after the lowering of the F trace to ~350 km, was it possible to identify the *F*1 stratification on the ionogram F trace, with $h'F2$ ~840 km (please note that the *F*1 parameters are not plotted on Figure 1). The critical frequency of the *F*1 trace was around 2 MHz (5×10^4 el cm^{-3}), and it persisted for six consecutive ionograms (from 2015 to 2130 LT, every 15 min), after which a night E layer appeared around 150 km ($h'E$), with peak density around 3×10^4 el cm^{-3}. A sporadic E layer was also present during this night.

Sporadic E layers were also observed over Cachoeira Paulista between 1800 and 1900 LT on March 13. The signatures of these Es layers were very similar to the auroral type a and r observed at high latitudes associated with energetic particle precipitation. From 1900 LT onward, a night E layer was observed over Cachoeira Paulista, starting with a peak density around 8×10^4 el cm^{-3} and decreasing to $\sim 5 \times 10^4$ el cm^{-3}. This layer persisted during the whole night.

2.2. *Total Electron Content (TEC) Data*

A VHF electronic polarimeter is used to monitor the Faraday rotation angle of the geostationary satellite (GOES 3) beacon signals at São José dos Campos (−26° dip). The subionospheric point at 350 km for reception from São José dos Campos is 21.4°S and 50.3°W. Note that Cachoeira Paulista and São José dos Campos have the same dip latitude and are only 110 km apart. Figure 1*h* shows the relative changes in TEC (in el m^{-2}) as a function of local time for the period March 12-14, 1989. The thin line represents the mean of the 5 quietest days in March 1989, and the thick line represents the relative changes in TEC for the 3 days analyzed in this paper. Each division in the y axis represents a TEC change of 1.1×10^{17} el m^{-2}, or 180° of polarization change of the Faraday rotation angle. The very prominent maximum in TEC, observed around local midnight in the quiet days' mean, is a manifestation of the equatorial ionization anomaly. We can see that the behavior of TEC on March 13-14 is quite anomalous. Strong fluctuations are observed on March 13 during local daytime hours. Around local midnight on March 13 and 14 the observed TEC is much below the quiet time curve (Figure 1*h*), indicating that the EIA has been inhibited and/or expanded to poleward of the quiet time crest latitude on both nights following the magnetic storm sudden commencement. Also, from 1800 LT on March 13 to 0600 LT on March 15, TEC measurements from São José dos Campos showed values most of the time well below the quiet days' mean. TEC variations measured by the VHF polarimeter in São José dos Campos are very consistent with the variation in *foF*2 over Cachoeira Paulista. Both measurements show the fluctuations during daytime hours on March 13 (despite the difference in time resolution of the measurements we can see that the fluctuations in *foF*2 and in TEC are in phase) and the strong negative phase from 2100 LT on March 13 until around sunrise on March 15.

3. DISCUSSION

Many of the recent studies of ionospheric effects of magnetic storms at low and equatorial latitudes have emphasized the N_{max} and TEC variations during the storms [*Titheridge and Buonsanto*, 1988; *Tian-Xi*, 1985; *Essex et al.*, 1981; *Schödel et al.*, 1974]. Besides those studies, other investigations exist on the electric field behavior during the disturbed periods, classifying them as caused by direct penetration of magnetospheric electric fields and by disturbance dynamo fields [*Fejer et al.*, 1979, 1983, 1990; *Gonzales et al.*, 1979, 1983]. Such electric fields could drastically alter the EIA latitude structure. Such alterations can be verified, in our case, by significant changes in the F layer key parameters, *foF*2 and *hmF*2 (*hpF*2), and TEC at locations inside the EIA. Other causes that modify these parameters are the disturbance neutral winds [*Rishbeth*, 1975] and the thermospheric neutral gas composition change characterized by increased N_2/O ratio [*Prölss and von Zahn*, 1977; *Prölls*, 1980, 1987], both generated by the deposition of storm energy at high latitude. In this work we analyze the behavior of the ionospheric density (through N_{max} and TEC) and peak height (*hpF*2) at two stations in the same longitude sector during a very severe geomagnetic storm. In particular, the fact that one of these stations is located near the geomagnetic equator and the other near the EIA crest provides a good opportunity to check the influence of a penetration electric field at equatorial latitudes and its direct and indirect effects that intensify or inhibit the EIA formation.

3.1. *Evidence for Electric Field Penetration*

It is now well accepted that, during periods of strong geomagnetic disturbances, the electric fields and current patterns at mid-latitudes and low latitudes can be very different from the quiet day observations. The equatorial electric field perturbations are most commonly observed in opposite direction to the normal *Sq* electric field [*Fejer et al.*, 1979]. The EIA is controlled by the east-west electric field at the magnetic equator that generates a vertical $\mathbf{E} \times \mathbf{B}$ drift, upward during the day and downward at night. The upward drift drives the ionization to higher altitudes, and it diffuses to low latitudes through the magnetic field lines generating the two peaks of ionization at $\sim$ 15° north and south of the geomagnetic equator. Thus the electric field at the equator has a great influence on the equatorial F layer peak height as well as on the latitudinal distribution of N_{max} at low latitudes.

Figure 2 shows a comparison between *foF*2 and *hpF*2 at Fortaleza and Cachoeira Paulista for part of March 13, 1989. The upper panel shows the auroral electrojet indices during the same time interval. One point that deserves attention in Figure 2 is the variation in *foF*2 in opposite sense at the two locations after around 0845 LT. Until around 0800 LT *foF*2's measured at the two different latitudes were very similar, indicating that the EIA was not developed. Under quiet conditions the F layer peak over Fortaleza rises during daytime hours (see solid line in Figure 1*d*) but on March 13, around 0745 LT the layer showed a sharp rise and then a descent starting at ~0830 LT. Accompanying the rise a decrease was observed in *foF*2 over Fortaleza. As one can see from the *AL* indices in Figure 2, the sharp rise in the F layer height (starting at 0800 LT) and the associated variations in the *foF*2 could be produced by an equatorial eastward electric field that probably accompanied the development of a substorm (see, for example, *Fejer et al.* [1986]). The descent of the layer starting slowly around 0830 LT and more rapidly at 0845 LT (within the 15-min sounding resolution at Fortaleza) also was accompanied by changes in *foF*2 that were in opposite phases at the two stations, over Fortaleza the change in *foF*2 being almost out of phase with that of the F layer peak height. The precise phases of the *foF*2

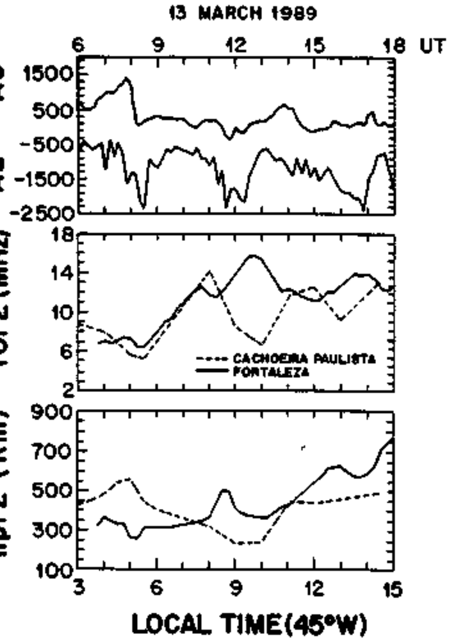

Fig. 2. Auroral electrojet indices, *foF2* and *hpF2*, over Fortaleza and Cachoeira Paulista.

and *hpF2* variabilities at Cachoeira Paulista are rather uncertain as a result of the 1-hour data resolution. Considering also the possible role of the fountain diffusion time, the appearance earlier or later of the effects on these parameters over Cachoeira Paulista as compared to those over Fortaleza should not be taken seriously. There is reason to associate the rapid descent of the *F* layer height starting at 0845 LT to the onset of a recovery of the substorm indicated by the *AL* variation at this time. The delayed decay of the shielding charges in the inner magnetosphere associated with a decrease in substorm activity (see, for example, *Kelley et al.* [1979], *Fejer* [1986]) could have caused penetration to equatorial ionosphere of a dusk to dawn (westward on the day side) electric field that seems to have been responsible for the observed decrease of the *F* layer height at both Fortaleza and Cachoeira Paulista (where the 1-hour sounding resolution does not permit us to identify the precise onset time of the effect). This westward electric field will generate a downward $\mathbf{E} \times \mathbf{B}$ drift at the equator that will lower the *F* region and, at the same time, will prevent ionization from being removed from the equator to low latitudes through diffusion. This is what is observed over Fortaleza after around 0845 LT on March 13 (see Figure 2): an increase in N_{max} and a decrease in *hpF2*. The initial effect at low latitudes is a compression of the EIA with the peak moving closer to the equator followed by a decrease in electron density due to inhibition of the fountain effect (see also *Abdu et al.* [1991]). Successive dayside passes of the DMSP F9 satellite confirm that the crests of the EIA are moving equatorward during this local time interval on March 13. The sharp rise of the layer at Fortaleza starting around 0745-0800 LT that lasted for ~30 min (accompanied by *foF2* decrease) could in fact represent an EIA expansion in response to a transient eastward electric field possibly associated with the substorm development. This transient EIA expansion could not be identified from the DMSP passes that were separated in time longer than the duration of this event. We may further note that when the above sequence of events occurred the *H* component variation over Fortaleza was going though a rapid negative change (Figure 1*b*) that was accompanied by similar, but in varying magnitude, decreases in mid-latitude and low latitude magnetograms as well, thus implying the role of injection of energetic ions from the plasma sheet into the ring current. However, the possible effects on the *F* layer associated with the ring current enhancement seems to be overruled by that of the substorm development and recovery phases.

Around 1230 LT on March 13 it seems that another event similar to the one just described, had occurred (see Figure 2). Around this time the *foF2* began to rise with the *hpF2* showing a slow down and than a decrease at 1300 LT over Fortaleza, while the *foF2* decreased over Cachoeira Paulista. This was associated with an auroral substorm and indicated the penetration of a westward electric field. The phase of the substorm, whether development or recovery, responsible for this response feature, is ambiguous in this case. This is also true for the remaining response sequences that continued for the rest of this day. It can also be noted that for both the decreases in *foF2* over Cachoeira Paulista (around 0900 and 1300 LT) a simultaneous TEC decrease was observed over São José dos Campos indicating that the decrease in N_{max} was not the result of a vertical redistribution of ionization in the layer. As will be shown on section 4, such effects can be simulated using a low-latitude numerical model.

A very clear effect of electric field penetration to low and equatorial latitudes is the pronounced uplift of the *F* layer simultaneously over Fortaleza and Cachoeira Paulista starting at 1800 LT on March 13, coinciding with a sharp and large amplitude (>300 nT) decrease in the *H* component of the magnetic field at Fortaleza, and with the onset of a substorm recovery phase. The equatorial *F* region quiet day behavior is such that the layer height increases after sunset due to an intensification of the eastward electric field (*F* region dynamo) before its reversal. But on March 13 the increase was so pronounced that, for approximately 2 hours, no *F* trace was observed on the ionograms, i.e., the minimum virtual height was above the 900 km height range of the ionograms. Figure 3 shows the *F* region vertical drift velocity inferred from *h'F* derived from ionograms [*Abdu et al.*, 1981*a*; *Batista et al.*, 1986] during that event. Values greater than 200 and 140 m s^{-1} were observed over Fortaleza and Cachoeira Paulista, respectively (the peak quiet time value over Fortaleza is of the order of 40 m s^{-1}). As the *F* layer is very high, *h'F* can give a good estimate of the vertical drift [*Bittencourt and Abdu*, 1981], although this method generally underestimates the *F* region vertical plasma drift [*Batista et al.*, 1990; *Fejer et al.*, 1989]. On the other hand, the very high negative vertical drift velocity observed over Fortaleza after 2000 LT may not represent the real drift velocity because of the possible existence of a nighttime ionization source, as will be discussed on section 3.3. The DMSP F9 satellite passed near this region at 0050 and 0232 UT on March 14 and observed strong depletions in electron density between approximately ±20° magnetic latitude, and upward plasma drifts as high as 275 m s^{-1} [*Greenspan et al.*, this is-

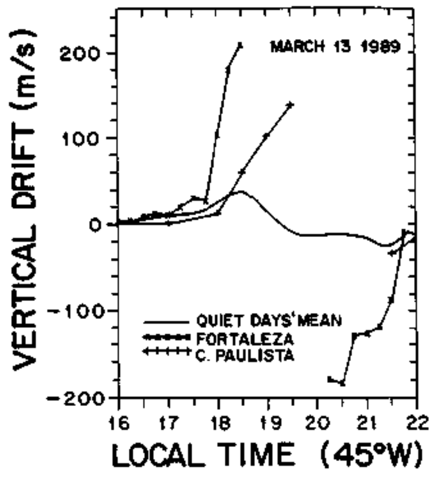

Fig. 3. Vertical plasma drift inferred from ionograms over Fortaleza (crosses) and Cachoeira Paulista (plusses) around local sunset on March 13, 1989. The full line represents the quiet time vertical drift over Fortaleza.

sue]. DMSP F8 measurements at dusk also observed a vertical ion drift velocity consistent with the rise of the F layer at Fortaleza and Cachoeira Paulista after 1800 LT on March 13. This event occurs at the same local time sector as that of the one observed by *Fejer et al.* [1990] over Jicamarca on January 18-19, 1984 (see Figure 1 of that paper), where the pronounced eastward electric field perturbation was attributed to direct penetration of magnetospheric electric fields, but the event observed here was much stronger. On March 13, when the vertical drift reached values greater than 200 m s^{-1} over Fortaleza, the corresponding eastward electric field should be of the order of 4 mV/m, a very high value even when compared with the measurement over Jicamarca on January 18, 1984, when the peak value for the eastward electric field was ~1.5 mV/m [*Fejer et al.*, 1990]. This very strong eastward electric field, acting at the equatorial and low latitudes, lifted the layer to unusually high altitudes where diffusion is so efficient that a great amount of ionization was removed from the regions where the upward $\mathbf{E} \times \mathbf{B}$ drift was more effective (i.e., equatorial and low latitude regions) to higher latitudes, implying an expansion of the equatorial ionization anomaly. The latitudinal expansion of the anomaly as well as the spectacular depletions that occur as a result of the continuing action of such strong electric field are clearly demonstrated in the DMSP F9 latitude profiles at 840 km given in Figure 3 of *Greenspan et al.* [this issue].

The ion density at 840 km measured by the DMSP F9 satellite at low latitudes during the two passes that detected the large depletions was of the order of 2×10^4 cm^{-3} (see Figure 3*c* and 3*d* of *Greenspan et al.* [this issue]). The satellite first entered the depletion at 312° geographic longitude at ~0046 UT and left it at 304°, ~0056 UT. A comparison between satellite and ground observation over Fortaleza and Cachoeira Paulista is shown in Table 1. At almost the same time when the satellite was registering an ion density of 2×10^4 cm^{-3} at 840 km, the F region peak height over Fortaleza was 550 km, with a peak density of 6.8×10^5 el cm^{-3} (spread F prevented an accurate reduction of $foF2$ and $hpF2$ over Fortaleza at 0045 UT, but one rough calculation showed that the values are not very different from the ones observed at 0030 UT and listed on Table 1). The ratio between the density measured by the satellite at 840 km and the peak electron density is only 0.03 over Fortaleza, for a $\Delta h = 290$ km, and 0.1 over Cachoeira Paulista for a $\Delta h = 170$ km. At 0030 UT, N_{max} over Cachoeira Paulista was ~ 6×10^5 el cm^{-3} and the peak height was not very different from that observed at 0200 UT (~670 km). These values were not used on Table 1 because there was an uncertainty in their reduction due to the presence of range spread F on the ionograms until 0130 UT. If the 0030 UT value were used, then the ratio over Cachoeira Paulista would be even lower than the calculated here. This means that, if the same depletion at 840 km is occurring over Fortaleza and Cachoeira Paulista, the upper part of the F region has a very sharp gradient. Using the international reference ionosphere (IRI) model [*Bilitza*, 1987] a ratio of 0.2 for n_e/N_{max} is obtained for $\Delta h = 290$ km, over Fortaleza, and 0.3 for $\Delta h = 170$ km, over Cachoeira Paulista. So the topside F region over Fortaleza is decreasing ~7 times faster than the IRI predictions and ~3 times faster over Cachoeira Paulista, indicating that the upper part of the F layer was strongly compressed (eaten up) during that time period. The hypothesis of a sharp longitudinal gradient should not be rejected either because the density measured by DMSP F9, over the Atlantic, one orbit before the observations of the depletions was ~ 4×10^5 cm^{-3} (Figure 3*b* of *Greenspan et al.* [this issue]), which was comparable to the peak densities over Fortaleza and Cachoeira Paulista.

TABLE 1. Comparison Between the Ionospheric Parameters Measured by the Satellite and From Ground-Based Observations

		Ground Observations	
	DMSP F9 Satellite	Fortaleza	Cachoeira Paulista
Geographic longitude	304° → 312°	322 °	315°
Magnetic latitude	+20° → -10°	-4°	-13°
Universal time	00:49	00:30	02:00
Altitude, km	840	550 (peak)	670 (peak)
Density, cm^{-3}	2×10^4	6.8×10^5 (peak)	1.9×10^5 (peak)
Δh (km) = h(sat.) - h(peak)	—	290	170
Density(840)/ peak density	—	0.03	0.1

3.2. *Evidence for Composition Changes at Low Latitudes*

According to *Prölss* [1980, 1987] the negative ionospheric storms are well correlated with the neutral gas composition changes that increase the N_2/O ratio at high and mid-latitudes during a magnetic storm. The composition change is generated at the high-latitude composition disturbance zones due to the large amount of energy deposited during magnetospheric storms [*Prölss and von Zahn*, 1977] and transported to mid-latitudes through a circulation cell created by heating of the high-latitude atmosphere [*Richmond*, 1979]. The larger storms can carry such composition changes observed at mid-latitudes to lower latitudes [*Titheridge and Buonsanto*, 1988] and negative phases in N_{max} at equatorial latitudes during the main phase of some strong storms have been attributed to the extension of these high- and mid-latitude effects to the low and equatorial latitudes [*Adeniyi*, 1986].

N_{max} over Cachoeira Paulista was reduced by a factor of ~10 on the night of March 13-14 and by a factor of 3.6 on the following night (Figure 1*f*) when compared to the quiet time mean. TEC observations over São José dos Campos on the night of March 13-14 showed a depletion of $\sim 10^{14}$ el cm^{-2} from the quiet time level. On the following night the depletion was $\sim 6 \times 10^{13}$ el cm^{-2} (Figure 1*h*). During both the nights the EIA was not present on the data, but it seems that the mechanisms that caused the "inhibitions" were different in the two cases. On the first night it seems that the "inhibition" was caused by the penetration of very intense eastward electric field as discussed in the previous section (EIA expansion to higher latitudes). On March 14-15, on the other hand, the F layer peak height and electron density over Fortaleza did not show any evidence of a disturbed electric field after sunset (a sharp increase in $hpF2$ was observed over Fortaleza after ~1500 LT followed by a decrease in $foF2$). On March 14, around and after sunset over Fortaleza, $hpF2$ showed a behavior quite similar to the undisturbed mean. The increase in $hpF2$ after 1800 LT over Fortaleza (probably due to the development of the normal F region dynamo fields) is accompanied by a decrease in $foF2$ over Fortaleza and by an increase over Cachoeira Paulista. Despite the fact that the conditions at the magnetic equator seemed to be propitious to its growth the EIA did not develop and the F region peak density over Cachoeira Paulista (and TEC) remained low during the whole night, indicating that a strong loss mechanism could be acting at low latitudes. It appears that one possible explanation for this behavior could be the increase in the effective loss coefficient at the peak of the F layer due to an increase in the ratio N_2/O or, in other words, the high-latitude composition changes have been transported to magnetic latitudes as low as 13°S. However, it is quite possible that these effects are modulated by disturbance neutral winds as suggested by the significant $hpF2$ variation over Cachoeira Paulista.

3.3. *Evidence for an Ionization Source at Night*

During the night March 13-14, 1989, besides the very pronounced rise of the F layer in the early evening hours, many other interesting and very unusual phenomena were observed. From 1800 to 1900 LT on the 13th an auroral type sporadic E layer was observed on Cachoeira Paulista ionograms at 100 km. From 1900 LT onward a night E layer was detected around 150 km, with peak electron density as high as 8×10^4 el cm^{-3} at 1930 LT and decreasing to 5×10^4 el cm^{-3} at 0400 LT. At auroral latitudes the appearance of these layers are associated with particle precipitation. As the South Atlantic anomaly region has intensified and broadened during the magnetically disturbed period March 11-20, 1989 [*Allen et al.*, 1989], the night E and auroral type Es observed over Cachoeira Paulista could be caused by particle precipitation in the South Atlantic anomaly (see also *Batista and Abdu* [1977]).

At the same time that an auroral type Es was observed over Cachoeira Paulista, Fortaleza ionograms showed a spread sporadic E layer at 100 km, as well as indication of ionization below the F region, with peak density less than 3×10^4 el cm^{-3}. From 2015 to 2130 LT an $F1$ layer was observed on Fortaleza ionograms, with peak electron density of the order of 6×10^4 el cm^{-3} and decreasing to half of this value in only one hour. Clear evidence of ionization below the F layer was seen on Fortaleza ionograms until around sunrise, even after the disappearance of the $F1$ trace. Between 2215 and 2330 LT on March 13 and in the time intervals 0315-0400 LT and 0515-0700 LT on March 14, sporadic E layers were observed on Fortaleza ionograms. All these observed events occurred in the same night when Cachoeira Paulista ionograms registered a night E layer probably due to particle precipitation.

As we can see from Figure 1*c*, the peak electron density over Fortaleza at 2115 LT on March 13 increased over the 1830 LT value, the last one to be observed before the time interval during which no F trace was registered on the ionograms due to the drastic rise of the layer. The peak electron density increased from 3.7×10^5 to 8.5×10^5 el cm^{-3} between 1830 and 2115 LT. At the same time the Fortaleza ionograms showed an $F1$ layer and until 2300 LT both $F1$ and $F2$ layers were descending on the ionograms. However, the DMSP F9 satellite was showing upward vertical ion drift of more than 100 m s^{-1} at 840 km above the magnetic equator, approximately 13° to the west of Fortaleza, at 0049 UT (see Figure 5*c* of *Greenspan et al.* [this issue]). If the same effects observed by DMSP F9 satellite are occurring over Fortaleza's longitude then, at 840 km the ionosphere is moving up while the height of the peak (and below) is going down. An electric field configuration that could explain these observations should suffer drastic inversion either with height or longitude (see also *Greenspan et al.* [this issue]). Another explanation that seems reasonable is that the downward movement of the F layer is in fact apparent; what we are really seeing is an increase in ionization at low altitudes due to an extra source, causing the abnormal gradients in the ionosphere, discussed before. The argument of an extra ionization source is strengthened by the possibility that particle precipitation must be occurring over Cachoeira Paulista, near the center of the South Atlantic anomaly. Evidence for ionospheric effects from magnetic disturbance associated with enhanced particle precipitation in the anomaly region has been shown earlier from ionosonde and VLF propagation experiments [*Abdu et al.*, 1981*b*; *Batista and Abdu*, 1977].

4. NUMERICAL MODEL

In this section we use a numerical model in order to test quantitatively the role of penetrating electric fields in causing part of the anomalous behavior observed over Brazilian low and equatorial latitudes during the March 13, 1989, magnetic storm. The model calculates the electron and ion densities as a function of altitude, latitude, and local time by numerically solving the time-dependent continuity equation

$$\frac{\partial N}{\partial t} + \nabla.(N\mathbf{V}) = P - L, \qquad (1)$$

where N is the ion number density. $\mathbf{V}$ is the velocity, P and L are the ion production and loss rate per unit volume, respectively, and t is the time. Following the procedure described by *Moffet and Hanson* [1965], (1) can be rewritten as

$$\frac{dN}{dt} = P - L - \nabla.(N\mathbf{V}_{\parallel}) - N\nabla.\mathbf{V}_{\perp}, \qquad (2)$$

where $\mathbf{V}_{\parallel}$ and $\mathbf{V}_{\perp}$ are the ion velocity components parallel and perpendicular to the Earth magnetic field line, respectively. The perpendicular drift is given by $\mathbf{V}_{\perp} = \mathbf{E} \times \mathbf{B}/B^2$, where $\mathbf{E}$ is the electric field and $\mathbf{B}$ is the magnetic field.

Equation (2) was solved assuming an ionosphere with only one ionic species (O^+). The ion production by solar ultraviolet radiation is included as an input to the model, as well as the loss through charge exchange with N_2 and O_2 and transport by diffusion, neutral wind and $\mathbf{E} \times \mathbf{B}$ drift [*de Paula*, 1987]. The critical input parameter in our case is the perpendicular drift that is controlled by the electric field, which becomes highly disturbed during magnetic disturbances. We have used F region vertical plasma drift measurements from Jicamarca [*Fejer et al.*, 1989] during equinoxes, solar maxima period, to represent the quiet time reference drift. The disturbed drifts were obtained adding perturbations to the quiet time reference plasma drift measurements, as shown in Figure 4. The solid line in that figure is the vertical plasma drift measured at Jicamarca [*Fejer et al.*, 1989], and the dashed curves are the perturbations superimposed to the quiet time drift. The negative peak centered at 1000 LT represents the simulation of a westward electric field acting between 0900 and 1100 LT, while the positive peak centered at 1830 LT is the simulation of an eastward electric field acting between 1730 and 1930 LT.

The results of the simulation using the negative perturbation on the vertical plasma drift centered at 1000 LT are shown in Figure 5, for the peak electron density and its height over Fortaleza and Cachoeira Paulista. The full lines in the figure represent the result of the

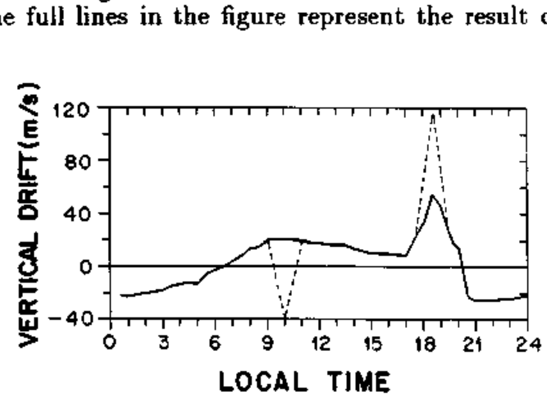

Fig. 4. Equatorial F region vertical plasma drift for equinox, solar maxima conditions (solid line), and disturbances due to penetrating electric fields (dashed lines).

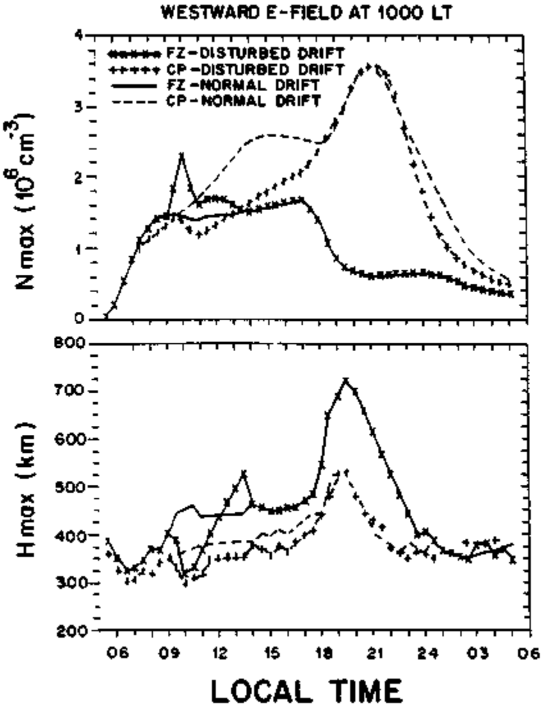

Fig. 5. Effect of a westward electric field at 1000 LT, on the F region peak density and height over Fortaleza (FZ) and Cachoeira Paulista (CP).

simulation over Fortaleza for quiet time period (solid line) and for disturbance in vertical drift centered at 1000 LT (solid-crossed line) as shown in Figure 4. The dashed curves represent the results over Cachoeira Paulista for quiet time period (dashed line) and for the same perturbation in drift at 1000 LT (dashed plussed line). We can see that the effect of a westward electric field centered at 1000 LT (i.e., a negative peak in the vertical plasma drift at the magnetic equator) is a rapid and sharp increase in the peak electron density over the magnetic equator (Fortaleza) and a decrease over Cachoeira Paulista (14°S magnetic latitude). This is very much the same as we have observed for $N_{max}(foF2)$ over Fortaleza and Cachoeira Paulista after 0845 LT on March 13, 1989 (see middle panel of Figure 2).

The lower part of Figure 5 shows the results of the simulation for the F region peak height. As we can see, the effect of a westward electric field centered at 1000 LT is a lowering of the F layer peak height of about 150 km over Fortaleza and a less pronounced lowering over Cachoeira Paulista. Again these results are in agreement with our observations over these two locations (see bottom panel of Figure 2). The consistency between the results of the simulation and the observations strengthen the hypothesis of a westward electric field penetrating to equatorial latitudes in the Brazilian longitude sector and compressing the EIA.

Another result of the simulation is shown in Figure 6, this time for the positive perturbation on the vertical plasma drift centered at 1830 LT and reaching a value about 120 m s^{-1} (see Figure 4). We can see from Figure 6 that the F region peak height has undergone a drastic rise after 1800 LT over Fortaleza due to the intensified eastward electric field used in the simulation. Over Fortaleza the F layer peak has reached ~940 km

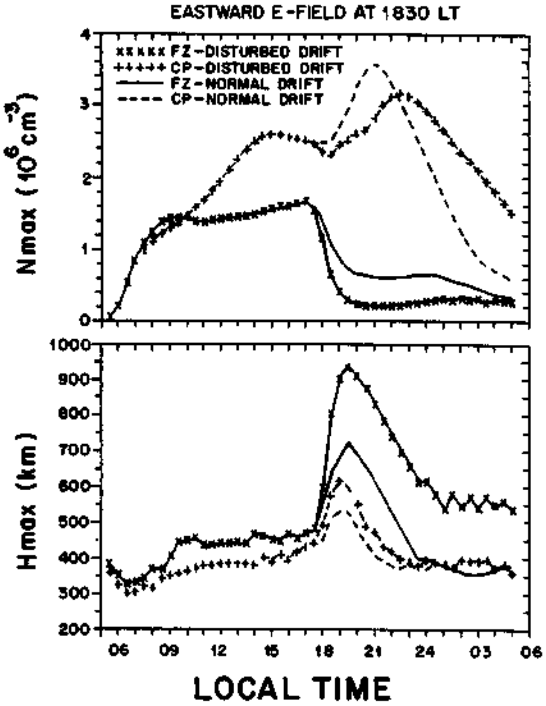

Fig. 6. Effect of a eastward electric field at 1830 LT on the F region peak density and height over Fortaleza (FZ) and Cachoeira Paulista (CP).

and ~600 km over Cachoeira Paulista. Our observations have shown a drastic rise on the F layer peak height over both stations Fortaleza and Cachoeira Paulista, with inferred vertical drift of 200 m s^{-1}, much higher than the value of 120 m s^{-1} used in this simulation.

The upper part of Figure 6 shows the effect of the enhanced eastward electric field around 1830 LT on N_{max} over Fortaleza and Cachoeira Paulista. The peak electron density becomes lower over both stations, and the EIA is expanded to higher latitudes.

We have used isolated perturbations in the numerical model to simulate the effects observed on the data. But during the March 13, 1989, magnetic storm, many strong substorms have occurred, so the rapid recovery seen in the simulation probably is not observed in the data because of the onset of another perturbation and/or because of the delayed effects from disturbance dynamo electric field.

5. CONCLUSIONS

The ionospheric effects of the great geomagnetic storm of March 13, 1989, over Brazilian low and equatorial latitudes were analyzed using ground-based equipment. We have observed that most of the sharp negative variations of the H component of the magnetic field at Fortaleza occurred simultaneously with auroral substorms characterized by extreme negative variations of the auroral electrojet index AL. For two of these negative excursions of the magnetic field that occurred during daytime (~0900 and 1300 LT) there is strong evidence for the penetration of a westward electric field to low and equatorial latitudes. The effect of this electric field is to enhance N_{max} over the magnetic equator (Fortaleza) and to decrease it over low latitudes around the EIA crest (Cachoeira Paulista). At the same time the F region peak height goes down but this lowering is more pronounced over the equator. The data and the numerical model results are consistent with the hypothesis that a westward electric field during daytime hours at low and equatorial latitudes will compress the equatorial ionization anomaly or, in other words, the EIA crest will be moved to lower latitudes.

The drastic rise of the F layer after sunset observed over Fortaleza and Cachoeira Paulista on March 13, coinciding with a sharp increase in the H component of the magnetic field at Fortaleza and with the onset of a substorm recovery phase was probably caused by a very intense eastward electric field (of the order of 4 mV/m) penetrating to low and equatorial latitudes. Also, in this case the data and the numerical model results are consistent with the hypothesis that this very intense eastward electric field at sunset expanded the EIA.

Comparison between ground-based and satellite measurements suggest that the topside ionosphere was extremely compressed during the night of March 13-14, 1989.

The presence of auroral type sporadic E and night E layers over Cachoeira Paulista, coinciding with the increase in N_{max} (after sunset) and with the detection of a $F1$ layer over Fortaleza give strong evidence for an extra ionization source at this longitude sector at night, probably due to particle precipitation in the South Atlantic magnetic anomaly that was intensified and broadened during the magnetically disturbed period.

Even though the conditions at the magnetic equator seemed to be propitious to its generation, the EIA was inhibited over Cachoeira Paulista and São José dos Campos on the night March 14-15, 1989, giving evidence for a very efficient loss mechanism at those latitudes. It is probable that the high-latitude composition changes were transported to magnetic latitudes as low as 13°S, and the increased N_2/O ratio increased the loss rates at those latitudes.

Acknowledgments. We acknowledge the useful discussions with W. D. Gonzalez. This work was partially supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP - Proc. 88/2091-0). M. A. Abdu acknowledges partial support by CNPq (Processo 30059/89.9). M. E. Greenspan acknowledges partial support by U.S. Air Force contract F19628-K-90-0015 with Boston University.

The Editor thanks M. J. Buonsanto and R. A. Heelis for their assistance in evaluating this paper.

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(Received December 31, 1990;
revised March 27, 1991;
accepted May 2, 1991.)