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Penetration of the solar wind electric field into the magnetosphere/ionosphere system

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[1] On April 17, 2002 an intense, long duration electric field penetration event was captured by the Jicamarca incoherent scatter radar. Other radars in the U. S. chain detected the event as well, although not with as much clarity. The Interplanetary Electric Field (IEF) is available from the ACE satellite as well. The ratio of the dawn-to-dusk component of the IEF to the dawn-to-dusk electric field in the equatorial ionosphere for periods less than about two hours is 15:1. We suggest that this corresponds to the ratio of the size of the magnetosphere to the length of the connection line between the Inter-planetary Magnetic Field (IMF) and the Earth's magnetic field. Simultaneous magnetic field measurements at Piura (off the magnetic equator) and at Jicamarca (under the magnetic equator) in Peru, reveal the same high frequency components and suggest that a chain of stations or an equatorial fleet of satellites in low earth orbit could be used to monitor the connection length continuously. *INDEX TERMS:* 2411 Ionosphere: Electric fields (2712); 2415 Ionosphere: Equatorial ionosphere; 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736). **Citation:** Kelley, M. C., J. J. Makela, J. L. Chau, and M. J. Nicolls, Penetration of the solar wind electric field into the magnetosphere/ionosphere system, *Geophys. Res. Lett.*, *30*(4), 1158, doi:10.1029/2002GL016321, 2003.

1. Introduction

[2] On April 17, 2002 a magnetic storm was captured by numerous ground and space-based instruments. In particular, a storm watch was in progress at the worldwide system of incoherent scatter radar observatories. In this letter, we report on ground-based measurements of the electric field as well as space-based measurements of the Interplanetary Electric Field (IEF). In addition, we present measurements of the magnetic field gained from ground-based magnetometers and compare them to the equatorial zonal electric field.

[3] The key instrument in this paper is the Jicamarca Radio Observatory, which has the most sensitive ionospheric electric field detector ever built. The radar can easily detect an electric field in the equatorial plane with a magnitude of 25 microvolts per meter, better than the capability of satellite instruments. This sensitivity is limited to the zonal component of the field, but this is the most important component since it causes the equatorial ionosphere to rise or fall depending on its sign.

[4] Penetration events were first deduced from the magnetic field they generated in the equatorial electrojet [*Nishida*, 1968]. Several Indian scientists repeated these observations and speculated on how the IEF could penetrate this far into the magnetosphere/ionosphere system [e.g., *Reddy et al.*, 1979]. A breakthrough came when the equatorial electric field was found by *Gonzales et al.* [1979] to have an identical structure to the zonal electric field in the auroral zone. *Kelley et al.* [1979] proposed the concept of under and over shielding of the magnetospheric electric field by the Alfven Layer at the edge of the ring current. Considerable effort has gone into understanding this phenomenon and its effects in the intervening years [e.g., *Fejer and Scherliess*, 1997, and reference therein].

[5] *Earle and Kelley* [1987] studied the zonal equatorial electric field as a function of Kp and found that for periods of one hour the solar wind source dominated other sources of geophysical noise for Kp values greater than about three. They speculated, following the theoretical work of *Vasyliunas* [1970], that the ring current acted as a high pass filter letting the Atmosphere-Ionosphere-Magnetosphere (AIM) system directly feel the IEF for periods less than a few hours. An event of comparable variability to the one considered here was detected on February 17/18, 1976 using the Jicamarca and Chatanika, Alaska radars as well as magnetometers in Trivandrum, India and on IMP-8 [*Gonzales et al.*, 1979; *Earle and Kelley*, 1987].

[6] A question never resolved to date is the efficiency with which this penetration occurs. The remarkable conclusion we come to here is that, for this frequency range, the full electric field at the reconnection line is felt throughout the equatorial plane of the magnetosphere.

2. Data Presentation

[7] The zonal component of the equatorial electric field as measured at the Jicamarca Radio Observatory from April 15–18, 2002 is plotted in Figure 1 in two formats. The color plot shows the data as a function of time and altitude over the three day period. Below, a line plot shows the component averaged over the height range 300–495km. From the beginning of the data until the end of April 16, the measurements show the classical behavior for the zonal component of the equatorial electric field. It is eastward during the day and westward at night. During the daytime of April 17, the electric field is extremely variable. Periods of such variability are rare but have been observed before [e.g., *Gonzales et al.*, 1979; *Earle and Kelley*, 1987].

[8] A recent study by *Anderson et al.* [2002] shows that daytime measurements of ΔH (the difference between the horizontal component of the magnetic field at an equatorial and a slightly off-equatorial station) can be used to infer the equatorial vertical $\mathbf{E} \times \mathbf{B}$ drift (eastward electric field). Such

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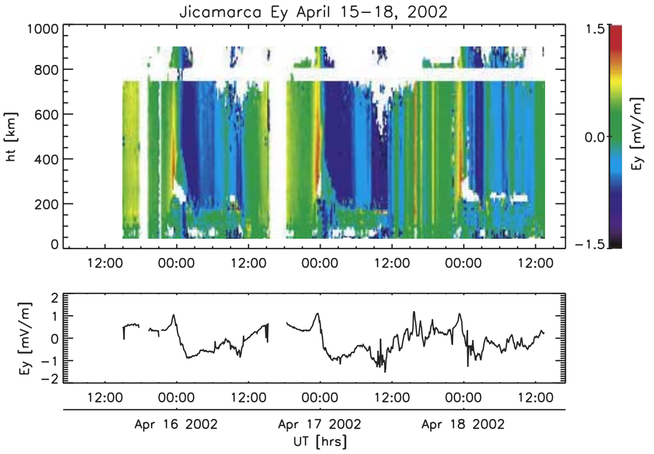

Figure 1. Zonal electric field at the Jicamarca Radio Observatory for April 15–18, 2002. The top panel shows the zonal component as a function of height and time. The bottom panel shows the zonal electric field averaged over the height range 300–495 km.

a difference accounts for the ring current contribution to the two magnetometer measurements. Figure 2 shows this for April 17, 2002 where ΔH using the Jicamarca, Peru and Piura, Peru magnetometers has been superposed on the Jicamarca eastward electric field. Once the daytime conductivity is established, the two parameters track each other amazingly well, and we have confidence that we can substitute measurements of ΔH for the eastward electric field when measurements of the latter are not available from the radar.

[9] Data from the Sondrestrom incoherent scatter radar are presented in Figure 3. We have superimposed the Jicamarca field adjusted by the factor $L^{3/2}$ which corresponds to the hypothesis that the eastward electric field component is constant in the equatorial plane [*Mozer*, 1970] and is equal to the value measured at Jicamarca. Although not as clear as the comparison with the equatorial magnetometer, the eastward electric field measured at Sondrestrom tracks the equatorial electric field rather well from 12:00 UT until the Sondrestrom radar turns off at 15:54 UT. For example there are three oscillations in both fields with comparable magnitudes and periods. Note in viewing these data that the Jicamarca data includes a transition in sign at about 12:00 UT corresponding to the contribution of the neutral wind dynamo, seen also in the previous two days shown in Figure 1.

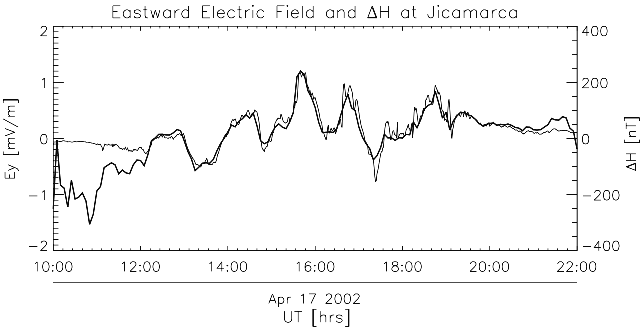

Figure 2. Comparison of the measured eastward electric field at Jicamarca (bold line, lefthand scale) and the difference between the horizontal component of the Jicamarca and Piura magnetograms (thin line, righthand scale).

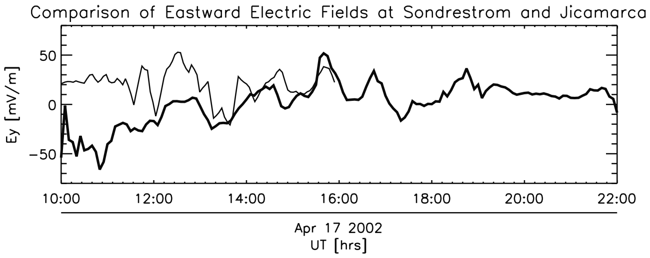

Figure 3. Eastward electric field as measured at Sondrestrom (thin line) and Jicamarca (bold line). The Jicamarca data has been scaled by $L^{3/2}$ for this comparison.

[10] To study the source of these penetrating electric fields measured by ground stations from the equator to high-latitudes, we turn our attention to the solar wind. Using solar wind velocity and interplanetary magnetic field measurements made at L1($\sim$1.42 × 10^6 km from Earth) by the ACE satellite, we have calculated the dawn-to-dusk component of the interplanetary electric field (IEF). This is plotted in the top panel of Figure 4. We wish to study how well the fluctuations seen in the IEF from 11:00 UT to 18:00 UT correlate to the fluctuations seen in the equatorial eastward electric field from 12:00 UT to 19:00 UT. To accomplish this, we first low-pass filter the IEF with a high-frequency cutoff corresponding to the five minute data sampling rate used at Jicamarca. We then time-shift the filtered IEF using the solar wind speed as reported by the ACE spacecraft to estimate the travel time from L1 to

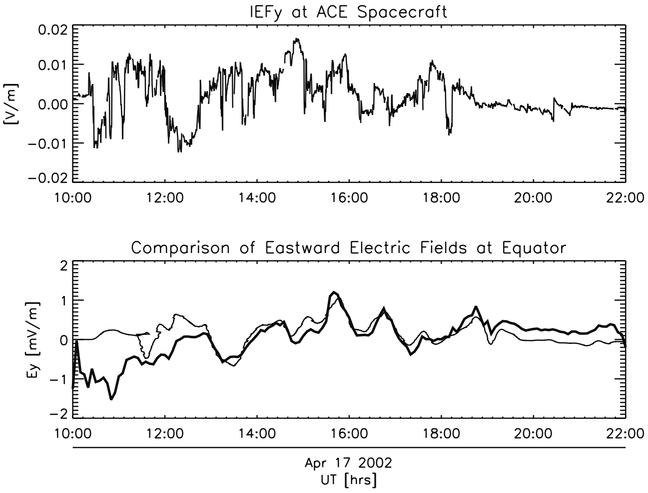

Figure 4. The top panel shows the calculated dawn-to-dusk component of the Interplanetary Electric Field (IEF) calculated at the ACE spacecraft. The bottom panel shows the eastward electric field at the equatorial plane measured at the Jicamarca Radio Observatory (bold line) and the dawn-dusk component of the filtered IEF measured by the ACE spacecraft scaled-down by a factor of 15 (thin line). This component has been time-shifted by the travel time from L1 to the magnetopause estimated from the solar winds speed in addition to the lag found to give the largest correlation coefficient.

the magnetopause. The instantaneous values are used in this time-shift for each measurement of the IEF, as during the time of rapid fluctuations the solar wind speed varies from about 480 km/s to over 600 km/s. We then perform a cross-correlation between the filtered and time-shifted IEF and the equatorial eastward electric field. The maximum correlation coefficient is 0.773 and corresponds to an additional lag time of 10 minutes. This additional lag may correspond to the retardation of the solar wind by the bow shock and subsequent acceleration of the solar wind in the magnetosheath. We have plotted the measured equatorial electric field (bold line) and the filtered and time-shifted IEF (thin line) in the bottom panel of Figure 4. The agreement is quite good (recall again that the Jicamarca field is undergoing a sign transition near 12:00 UT due to the neutral wind dynamo). The slight double-valued feature seen in the IEF before 12:00 UT is due to the tremendous increase in the solar wind velocity from 350 km/s to 450 km/s at 10:20 UT.

3. Discussion

[11] The comparison of the IEF and the eastward electric field in the equatorial ionosphere shown in Figure 4 is striking. The comparison of the equatorial electric field and the Sondrestrom data shown in Figure 3 is not as striking, but the similar variations seem quite real and it is well known that the geophysical noise level is much greater at higher latitude sites, and thus we do not expect the two to track each other exactly.

[12] A similar event on February 17/18, 1976 was studied by *Gonzales et al.* [1979]. In their event, there were no less than five rapid electric field pulses seen in both the equatorial plane (at Jicamarca) and the auroral zone (at Chatanika, Alaska). The auroral zone fluctuations are even better correlated to those seen at the equator than in the 2002 data presented here in Figure 3. However, unfortunate data gaps in the IMF measurements during the February 17/18, 1976 event prevented a cross-correlation between the IEF and the equatorial eastward electric field to be performed as has been done here. In addition, there were just too many rapid fluctuations in the electric field to tell the relative sign of the penetration.

[13] The ratio of the dawn-to-dusk IEF and the Jicamarca zonal electric field for the April 2002 event is about 15. We suggest that this reduction factor corresponds to the ratio of the magnetopause size to the length of the connection (usually called the re-connection) line at the magnetopause. It is well known that the full potential across the magnetosphere is never impressed across the polar cap and the 7% efficiency suggested here is quite reasonable. It thus seems possible to measure the length of the connection line using the high frequency components of the IEF and the zonal equatorial electric field determined by either direct measurements or the surrogate magnetic field data.

[14] Since the fluctuating electric field in the magnetosphere is comparable to the background level, the two contribute roughly equally to the Joule heating of the thermosphere. If the ratio is determined more accurately in the future, it may be possible to use equatorial magnetograms to estimate the Joule heat input at high latitudes. The potential for this application is shown in Figure 2. Near local noon the ratio of these two quantities is 1 mV/m:200 nT. A recent study by *Anderson et al.* [2002] gives an equation that can be used to infer the $\mathbf{E} \times \mathbf{B}$ drift based on measurements of ΔH. Using their equation, for a ΔH of 200 nT, we would expect an $\mathbf{E} \times \mathbf{B}$ drift of 80 m/s, which corresponds to a eastward electric field of 1.86 mV/m, significantly higher than what we have presented in Figure 2. However, as pointed out in *Anderson et al.* [2002], the relationship they describe was calculated using data from 1998, and a solar cycle and seasonal dependance is probable. A more extensive, long-term study comparing magnetograms and measured $\mathbf{E} \times \mathbf{B}$ drifts is being performed to better determine the relationship as a function of solar activity.

[15] If this solar-cycle dependence of the relationship between ΔH and the $\mathbf{E} \times \mathbf{B}$ drift were resolved, a chain of equatorial magnetometers could be used to constantly monitor the zonal component of the equatorial ionospheric drift. As we have suggested above, the ratio of this component to the dawn-dusk component of the IEF could indicate the length of the reconnection line. Thus, it seems possible that a chain of equatorial magnetometer stations or a fleet of equatorial satellites, in tandem with a satellite at L1, could be used to continuously measure the length of the connection line.

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