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AUTOR(ES)

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EQUATORIAL PARTICLE PRECIPITATION DURING MAGNETIC STORMS AND RELATIONSHIP TO EQUATORIAL THERMOSPHERIC HEATING

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Abstract. We compare optical observations of ring current particle precipitation from a near equatorial site in Brazil with variations in the AE and Dst indices. Precipitation occurs during ring current injection when AE is large, but for AE large without ring current injection, little precipitation is seen. Comparisons are also made with 630 nm observations of thermospheric heating made simultaneously in Peru. The thermospheric temperatures have been corrected for instrumental drift and the temperature enhancements of several hundred Kelvins appear to be mainly due to transport of heat from middle and high latitudes, rather than due to the heating effects of the precipitation.

Introduction

The effects of the precipitation of energetic neutral atoms at mid, low, and equatorial latitudes were discussed by Prolss (1973) and reviewed by Tinsley (1981). These atoms of H, O and He, of mean energy in the range 1kev to 100kev, arise from charge exchange of trapped ions in the inner magnetosphere with exospheric hydrogen. Various aspects of such events have been discussed by Tinsley et al. (1982), Rohrbaugh et al. (1983), and Tinsley et al. (1986). In the present paper we examine the relationship between the time variations of optical emissions observed at Cachoeira Paulista, Brazil and the AE and Dst indices for two storms not previously reported and for a moderately active and a quiet period. The Dst index is a measure of hourly averages of the total global energy content of the ring current, which is the stormtime enhancement of the magnetospheric trapped particle population. The AE index is a measure of high latitude Joule heating.

For the events considered in this paper we are able to compare the optical data on particle precipitation with simultaneous Fabry Perot measurements of thermospheric temperature made at Arequipa, Peru. Biondi and Meriwether (1985) have previously discussed these measurements. The timing of the temperature enhancement for the storm of 1983 June 12-13 was considered to be more consistent with the concept of local energy deposition than with the transport of energy from high latitudes. However, it has now been found that instrumental drift was occurring on the night of June 12-13, and we use corrected temperatures for the comparisons in this paper. The other periods for which comparisons are made are the storm of 1983 Aug. 7-8, the less active night 1983 May 11-12 and the quiet night, 1983 Aug. 6-7.

The appearance of heating at lower latitudes due to the transport of high latitude energy by winds and waves has been modelled and compared with mid-latitude observations by Roble et al. (1978) and Hernandez and Roble (1978). We provide estimates of the amount of heating that could be produced by direct energy deposition by the precipitating particles and then examine the Arequipa temperature data for evidence of such heating and for transport of energy from higher latitudes.

Observations

The optical measurements of particle precipitation were made in N_2^+1N emission and in other emissions by an eight color tilting filter photometer located at Cachoeira Paulista, Brazil (22.7°S, 45.0°W geographic, 12°S dip lat.) as described by Tinsley et al. (1982). The Fabry Perot observations of the (OI) 630.0 nm nightglow linewidth were made from Arequipa, Peru (16.4°S, 71.5°W geographic; 4°S dip lat.) as described by Biondi and Meriwether (1985). The two sites in Brazil and Peru are separated in longitude by about 3000 km, and in local time by 2 hours. In Figs. 1 and 2 we compare the time variations of the N_2^+1N(391.4 nm) emission for two storms, 1983 June 12-13 and 1983 Aug. 7-8, with variations of the AE and Dst indices and the thermospheric temperature. In Figs. 3 and 4 we show comparisons of optical and magnetic data for two periods of lesser activity, 1983 May 11-12 and 1983 Aug 6-7.

In Fig. 1, the data for 1983 June 12-13 show that the storm was preceded by a long period of quiet conditions. The onset of the increase of both AE and the precipitation occurred about 01 UT, and the main phase occurred between then and 06 UT, as Dst was becoming rapidly more negative, i.e., there was a rapid injection and energization of particles into trapped orbits in the magnetosphere. During this period AE reached a maximum of 1460 nT near 04 UT, and the 391.4 nm emission being observed in the zenith reached its first maximum at about the same time. The 630.0 nm emission was measured from Arequipa at 60° observation zenith angle in the directions N, S, and W, and sets comprising two of three such observations have been averaged together. There is an increase in temperature by 280 K between 00 and 01 UT, followed by a decrease, and then an increase by about 100 K between 03 and 05 UT, again followed by a decrease.

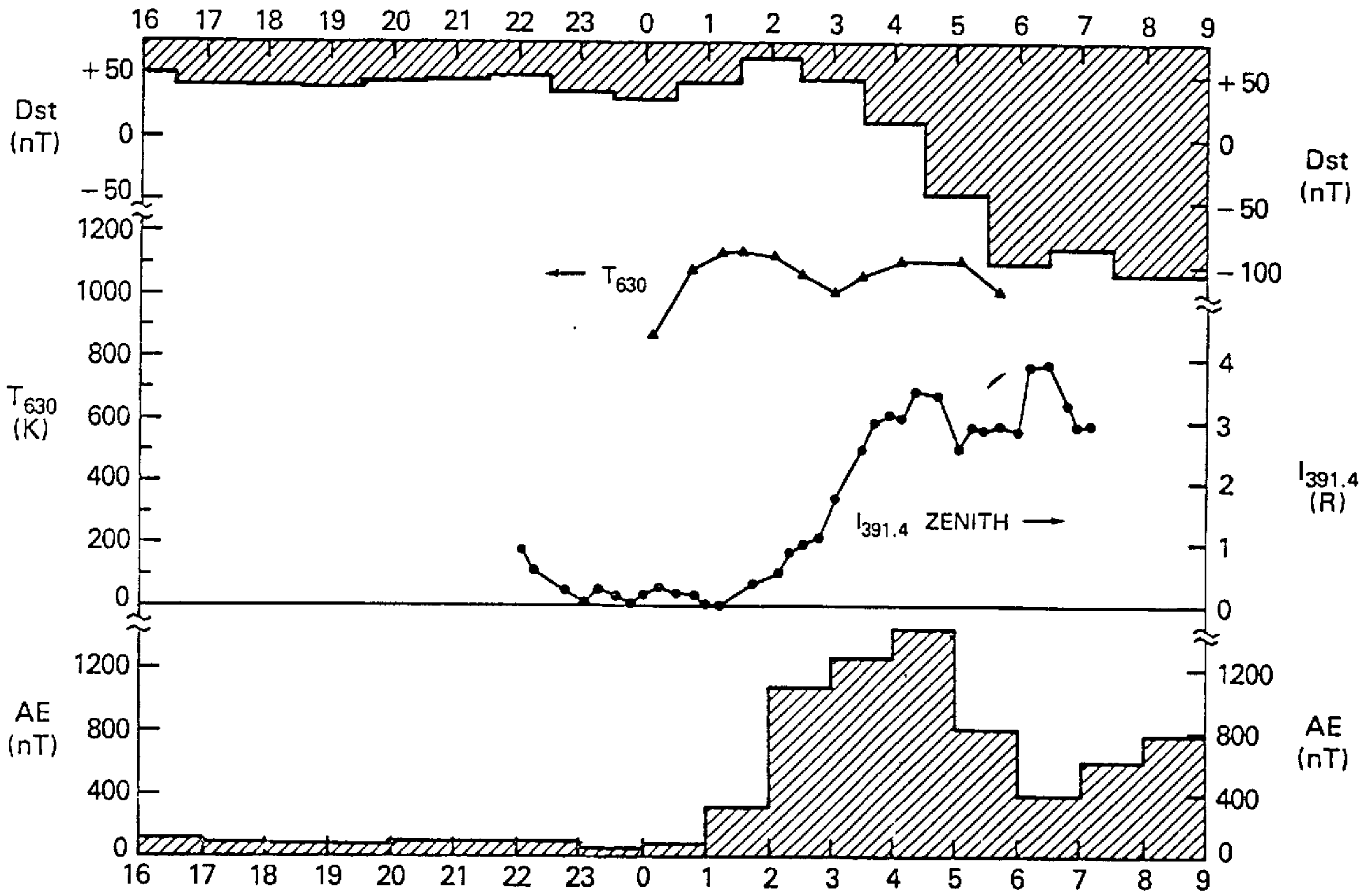

FIGURE 1. UNIVERSAL TIME (HRS) 12-13 JUNE 1983

Figure 1. Time variations of 391.4 nm emission measured from Cachoeira Paulista, Brazil; thermospheric temperature T630, measured by Fabry Perot interferometer from Arequipa, Peru, and the Dst and AE indices for the magnetic storm of 1983 June 12-13.

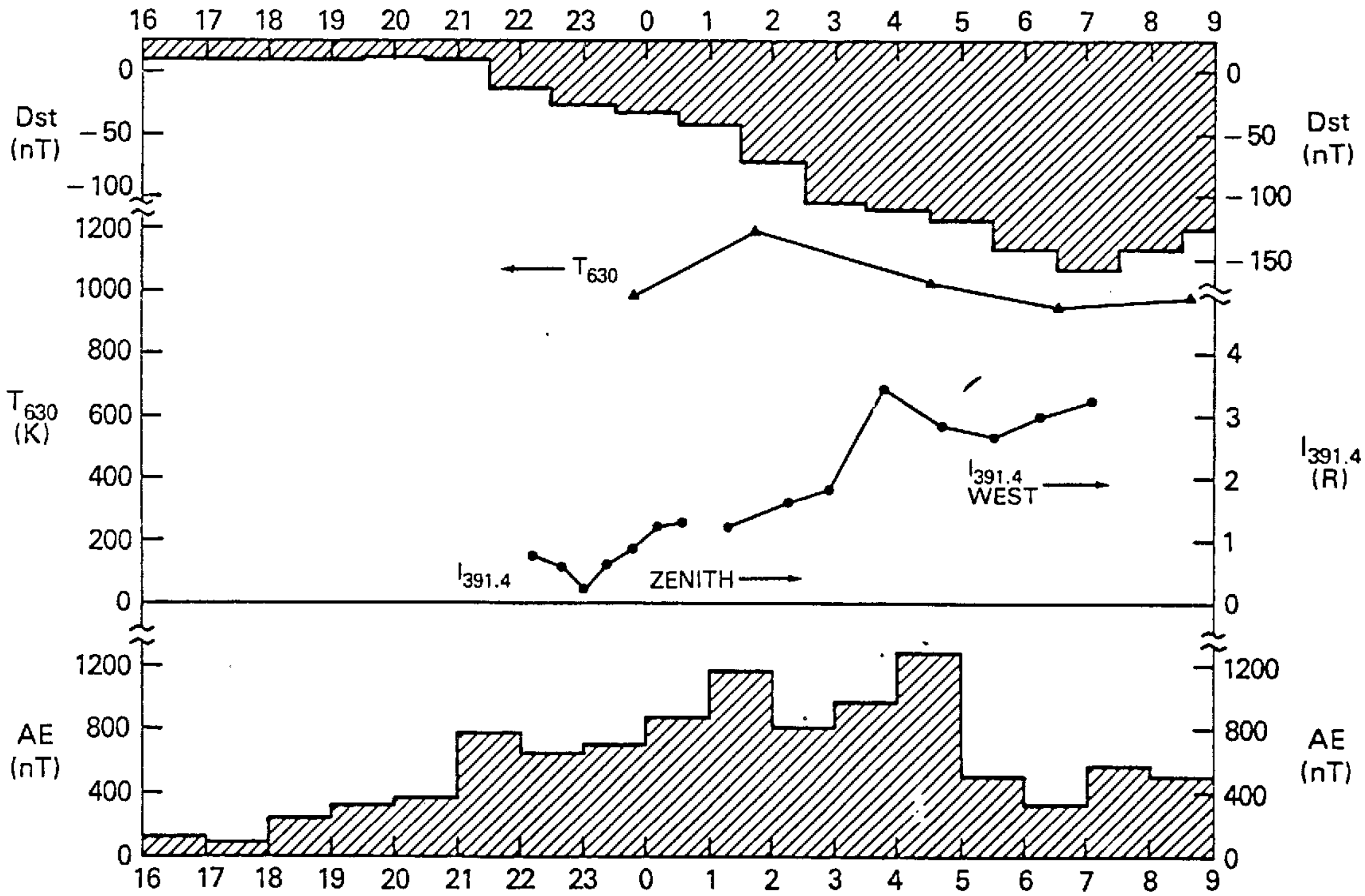

FIGURE 2. UNIVERSAL TIME (HRS) 7-8 AUGUST 1983

Figure 2. As for Fig. 1, but for the magnetic storm of 1983 August 7-8.

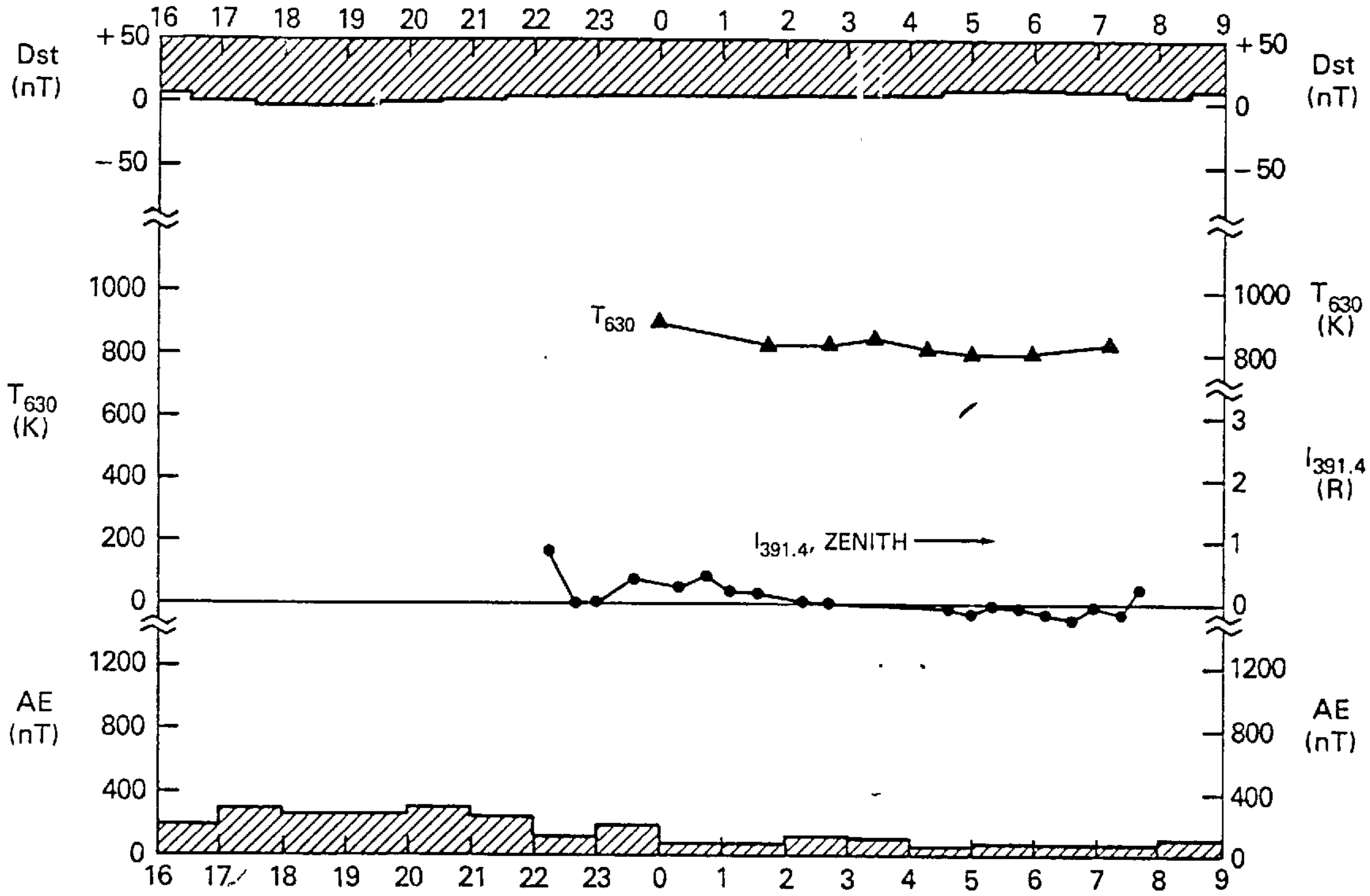

FIGURE 3. UNIVERSAL TIME (HRS) 6-7 AUGUST 1983

Figure 3. As for Fig.1 but for the magnetically quiet period of 1983 August 6-7.

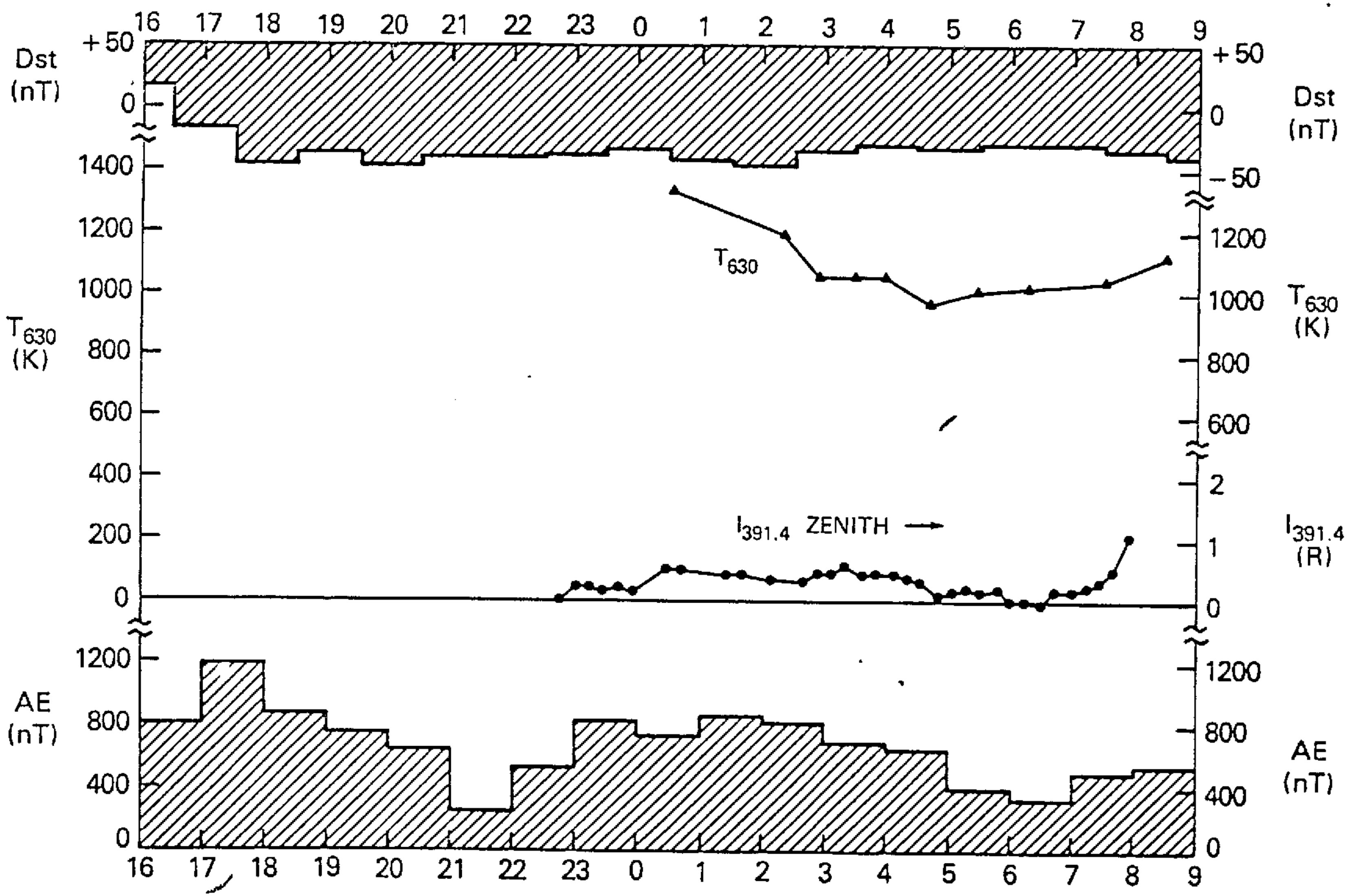

FIGURE 4. UNIVERSAL TIME (HRS) 11-12 MAY 1983

Figure 4. As for Fig. 1, but for the moderately active period of 1983 May 11-12.

In Fig. 2 the data for 1983 Aug 7-8 are shown. The 391.4 nm emission was observed in the zenith until 00 UT, and then separate observations were made in the E and W after 0040 UT. The E emission was coming from the region of the South Atlantic Anomaly and reached double the emission rate of the W emission at 07 UT. Since this is in the opposite direction to Arequipa, these emission rates are not included in Fig. 2, and the peak W emission rate is about 3R. The emission rate for 630 nm was weaker than usual, and evaluation of temperature required longer than usual integration times. The plotted points are averages of N, S, E, and W observations, and contain larger statistical uncertainties than for the other figures. In averaging the data, a number of noisy observations with error bars for temperature greater than 800 K were omitted. Fig. 2 shows that the precipitation onset and first maximum again occurred during the main phase, and maxima of both AE and the emission rate occurred near 04 UT, when AE was reaching values near 1300 nT. There is an increase in temperature by about 200 K between 2300 and 0200 UT, but a decrease from then until 09 UT.

Figure 3 compares data for the quiet day of Aug. 6-7. Sets of 630.0 nm observations for the four azimuths N, S, E, and W have been averaged together, while the 391.4 nm observations were made in the zenith. During the period when the optical observations were made, the excursion in Dst was only about 10 nT, AE did not exceed 134 nT, and no significant heating or 391.4 nm emission was seen. Several hours earlier AE had been higher, but not above 313 nT.

Figure 4 compares data for the moderate magnetic storm of 11-12 May 1983. During the observation period Dst remained within 10 nT of -40 nT, and the maximum value of AE was 876 nT. Sets of 630.0 nm observations were made in N,S, W and Z (zenith) directions, and the average of each set is plotted, while the 391.4 nm observations were made in the zenith. No significant 391.4 nm emission or heating is seen, but the thermospheric temperature seems to be declining from an earlier enhancement probably associated with the large AE value of 1186 nT for 17^h UT.

We now examine mechanisms for production of equatorial heating and then discuss the observations in the context of the mechanisms.

Estimates of Heating by Ring Current Precipitation

During magnetic storms some of the very large amount of energy contained in the ring current in the form of trapped particles is deposited in the thermosphere. The resulting optical emissions are detectable at middle and low latitudes and, if sufficiently intense, can be observed visually as middle and low latitude aurorae. The deposition occurs in two different ways. At middle latitudes some of the trapped ring current ions are dumped directly into the thermosphere, if their mirror heights are lowered to the thermosphere sufficiently fast. There is also a more continuous flux of energetic neutrals spraying from higher altitudes in all directions, as the ions charge exchange with the exospheric constituents over a much greater range of mirror heights. The scale height for exospheric hydrogen is 1000-2000 km near the earth. The latitude variation of the resulting flux of energetic neutrals into the thermosphere was calculated by Tinsley (1979), and for an isotropic pitch angle distribution it maximizes at mid-latitude, but with a significant amount of energy input into the thermosphere at latitudes down to the magnetic equator.

The results discussed by Tinsley et al. (1986) indicated that, in the region poleward of 40° dip latitude, the flux of directly precipitated ions predominates over the flux of energetic neutrals, but that equatorwards of 40° the neutral flux usually predominates. From the geometry of the charge exchange process, the source of the equatorially precipitating energetic neutrals is likely to be particles near their mirror altitudes of a few thousand km near the feet of magnetic shells of L-value 2-3 at mid-latitudes, so that the particles arrive at equatorial regions travelling almost horizontally. Even if they became collisionally ionized, their pitch angles would be small in the nearly horizontal magnetic field. Atoms of H, O and He are possible, with O likely to predominate (Tinsley, et al. 1982). Observations of OI 777.4 nm emission are probably another signature of such precipitation (Burnside et al. 1980, Rohrbaugh et al. 1983). These O atoms would deposit their energy significantly higher that at the 250 km altitude calculated by Kozyra et al. (1982) for heating during precipitation of O^+ with isotropic pitch angles. (For the same pitch angle distribution, the precipitation of O^+ is equivalent to that of O after the first few collision path lengths, since both fluxes produce the same equilibrium beam mixture of ions and neutrals, with a predominance of neutrals).

An estimate of the heating effect produced by precipitation in the thermosphere at equatorial latitudes can be obtained as follows: the atmospheric energy input at the equator for a 20 nT/hr ring current loss rate by charge exchange of H^+ ions was calculated by Tinsley (1979) to be 0.05 mW m^{-2}, with the corresponding charge exchange lifetime for loss of H^+ ions of energy 1-30 keV at L=3 of 1 hour at the time when the pitch angle distribution was isotropic to the loss cone. If the ions are O^+, the lifetime would be about a factor of five longer, and the loss rate 5 times less. A 20 nT/hr loss rate is comparable with the observed net rate of increase of energy content of the ring current in Fig. 1 and 2. This loss rate implies that the amount of energy lost by charge exchange is equal to that retained as trapped particles in the main phase of the storms. Additional loss from the ring current and (mid latitude) atmospheric heating would result from direct precipitation of the ring current ions. The bulk of the ring current is assumed to be located at L=3.

If the 0.05 mW m^{-2} is deposited in the column above a base at 275 km (which is 25 km above the 250 km altitude calculated by Kozyra), then the neutral concentration is about $10^{15} m^{-3}$ and the scale height 50 km (U.S. Standard Atmosphere 1976), leading to an equatorial heating rate of 175 K/hr. This is sufficiently large to call for examination of the data to see if there is evidence for such direct heating.

Transfer of Heat From High Latitudes

The generation of gravity waves and meridional winds which carry heat generated by auroral zone joule heating and particle precipitation from high to low latitudes has been simulated in a numerical model by Roble et al. (1978).

As described by Hernandez and Roble (1978), the simulation produced a wave of temperature enhancement that travelled at 740 ms^{-1} (almost the speed of sound) and at 250 km altitude, producing an equatorial temperature enhancement in about 2.5 hours - this being the time interval between the high latitude heating reaching half its peak amplitude and the equatorial enhancement reaching half peak amplitude. A study by Richmond (1979) using an analytic model of the combined effect of gravity waves and meridional winds also showed a delay of about 2.5 hours between the onset of an equatorial temperature rise at 400 km altitude.

These simulations are remarkable for showing a very rapid transfer of energy to low latitude in view of all the previously reported observations of equatorial density and composition changes which show considerably longer delay times. DeVries (1972) found that, for altitudes near 170 km at the equator, there was a delay of 4.5 to 6 hours between equatorial density and AE index enhancements, and Forbes et al. (1978) found delays of from 4 to 8 hours at altitudes of 160-200 km. Berger and Barlier (1981) obtained delays between 4.5 and 6 hours for altitudes near 270 km. Prolss (1982) derived a period for the delay of about 4 hours for altitudes 240-290 km. A delay for temperature enhancements which was shorter than those for density and composition, but still longer than the models, was obtained by Nisbet et al. (1977), who found a 3-4 hour delay between AE enhancement and an equatorial temperature enhancement measured by the OGO 6 interferometer.

Observations of mid latitude heating and winds at first seemed to be in agreement with the models (Hernandez and Roble, 1978), but later work showed a number of problems, such as poleward winds rather than equatorward winds at mid latitudes in the early phases of storms (Hernandez et al. 1982, Hernandez and Roble 1984). A complicating factor is the evidence for significant amounts of energy input in the direct precipitation of ions at mid latitudes, e.g., Shelley et al.(1972), Torr and Torr (1984) and the observations made by Tinsley et al. (1984) at McDonald Observatory, Southwest Texas, dip latitude 40° N. The latter observations were actually of the same event as in Fig. 1. The auroral emission was first seen as astronomical twilight faded and thus may have been present earlier than 0330 UT. From spectrograms obtained at about 0600 UT the excitation was identified as being due to precipitation of ring current particles. Observations of the 1981 March 5 storm from Beveridge, Australia (37°S geog. lat., 48° dip lat.) by Yagi and Dyson (1985) showed mid-latitude temperature enhancements typically of 800 K, with a peak enhancement of 1400 K. Such energy deposition would be a mid latitude source of winds (Torr et al. 1982), and the equatorward component of the winds would carry additional heat to the equator. The heating due to mid-latitude precipitation of ring current particles can be very large, as Torr et al. (1982) calculated thermosphere temperature enhancements of about 400 K near 50° latitude to about 600 K near 60° latitude for a precipitating ring current energy flux which was only one sixth of that measured at the maximum of the storm of 1971 December 16-17.

Discussion

The data for thermospheric temperatures in Fig. 1 have been corrected, as noted in the Introduction, and the relationship to Dst is now different from that given by Biondi and Meriwether (1985). There is a temperature enhancement near the beginning of the active storm period, but the timing of the enhancement does not appear consistent with either transport of heat from high latitudes or heating due to direct particle precipitation. The maximum temperature occurs near 0130 UT and comes before the ring current has started to build up, just as the AE index shows the beginning of Joule heating at high or mid latitudes. Given that two and a half hours seems to be the minimum time to transport heat to the equator, the high latitude Joule heat source can be ruled out for this thermospheric temperature enhancement. However, the later maximum of temperature near 04-05 UT is compatible with the timing of both transport of heat from high latitudes starting at 02 UT, and with direct particle precipitation. The amplitude of this enhancement (about 100 K) puts an upper limit on the heating associated with either source.

For the storm of 7-8 July shown in Fig. 2, the temperature maximum near 01 UT is followed by a decline before a significant ring current has developed and before the intensity of the 391.4

nm emission reaches its maximum. It is thus unlikely that direct particle precipitation at equatorial latitudes is responsible for this temperature enhancement either. The AE index has been moderately high for four hours preceding this storm, so it is plausible that the enhancement is due to transport of heat from a high latitude Joule heating source or a mid-latitude ion precipitation source. The reduced temperature from 06-09 UT is consistent with the models that show a temperature minimum after the initial wave propagating from higher latitudes has passed. Any direct heating effect during the observation period would have to have an upper limit of 100 K.

The data for 6-7 August in Fig. 3 provide a control period when there was no significant AE activity or 391.4 nm emission and no significant heating.

The data for 11-12 May in Fig. 4 were taken in a period following activity extending over the previous 16 hours. The high temperature of 1300 K at 0030 UT was measured two to three hours after the rise in AE to 800 nT between 2200 and 2300 UT, following the temporary lull in storm activity from 21 UT. The temperature decays until 05 UT, while the AE index remains high. The absence of significant 391.4 nm emission points to transport of heat from higher latitudes as the source of the equatorial heating.

It should be noted that some uncertainty is introduced by the separation of about 3000 km in longitude between the sites in Brazil and Peru, since the precipitation may not have been spatially uniform over that range. As noted, the 7-8 August event showed a factor of two weaker 391.4 nm emission in the West (toward Arequipa) than in the East in the morning period.

An interesting aspect of the lack of equatorial particle precipitation for 11-12 May (Fig. 4) is that Dst was -40 nT during this period, and thus there was significant ring current present, and on June 12-13 (Fig. 1), when Dst was near -40 nT, there was a considerable amount of precipitation. What has been noted from previous studies (Tinsley et al. 1982, Rohrbaugh et al. 1983) is that a requirement for precipitation is rapid fluctuation in the electric and magnetic fields which control the motions of particles in the ring current, i.e. main phase conditions, so that there is continual repopulation of the lower mirror heights depopulated by the more rapid charge exchange there.

The upper limit of about 100 K for direct ring current heating implies that the ring current loss rate by charge exchange is less than the equivalent of 20 nT/hr calculated for H^+ charge exchange and more consistent with the five times lower rate calculated for O^+ ions. Observations of H Balmer beta emission from Cachoeira Paulista for the very large storm of 1982

July 13-14 (Tinsley et al. 1986) showed that energetic H was only part of the precipitating flux and that O precipitation dominated at least during the latter half of the event. It should be possible to specify the direct energy deposition more precisely in the future, when cross sections for neutral and ion excitation of 391.4 nm emission and models of the precipitation for the low latitude thermosphere become available. Also, there is now a 630 nm Fabry Perot interferometer operating at the 391.4 nm photometer site, and this should reduce the uncertainties due to longitude separation.

Conclusions

Observations of 391.4 nm emission at a near-equatorial site show particle precipitation during magnetic storms, as ring current injection is occurring, with Dst decreasing in the main phase, and when the high-latitude auroral electrojet index AE is large. For large AE without ring current injection, little precipitation is seen. The equatorial thermospheric temperature enhancements of several hundred Kelvins appear to be mainly due to transport of heat from middle and high latitudes, rather than to heating effects of the precipitation. An upper limit of precipitation heating appears to be about 100 K for the 1983 June 12-13 and 1983 August 7-8 storms.

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CAPTIONS FOR FIGURES

Figure 1. Time variations of 391.4 nm emission measured from Cachoeira Paulista, Brazil; thermospheric temperature T630, measured by Fabry Perot interferometer from Arequipa, Peru, and the Dst and AE indices for the magnetic storm of 1983 June 12-13.

Figure 2. As for Fig. 1, but for the magnetic storm of 1983 August 7-8.

Figure 3. As for Fig.1 but for the magnetically quiet period of 1983 August 6-7.

Figure 4. As for Fig. 1, but for the moderately active period of 1983 May 11-12.