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Low-Latitude Aurorae and Storm Time Current Systems

B. A. TINSLEY, R. ROHRBAUGH, AND H. RASSOUL

The University of Texas at Dallas, Richardson

Y. SAHAI AND N. R. TEIXEIRA

Instituto de Pesqusas Espaciais, São Jose des Campos, São Paulo, Brazil

D. SLATER

Battelle Pacific Northwest Laboratory, Richland, Washington

An analysis is made of the vibrational development shown in N_2^+ 1 N (first negative) emissions in low-latitude aurorae during the last half century. The data imply collisional excitation by energetic heavy particles (oxygen, helium, or hydrogen ions or neutrals) of velocity of the order of 10^7 cm s^{-1}, and there may be additional pumping in some cases due to solar photons and low-energy electrons. When low-energy electrons are present as large fluxes, they produce bright red (O I 6300 Å) emission, with weaker emission from N I 5200 Å and other features of excitation potential only a few electron volts. From about 40° dip latitude to the auroral zone the decrease of N_2^+ 1 N vibrational development with increasing latitude is consistent with satellite observations of the increase with increasing latitude of the mean energy of precipitating O^+ fluxes and the increasing fraction of H^+ in the ion precipitation. From the equator to about 40° dip latitude the intensity and the latitudinal gradients of the emissions are consistent with energetic neutral precipitation as the primary source. The intensity variations of low-latitude displays show large-amplitude changes on a time scale of 0.1 hour, which are closely related to the magnetic signatures of the storm time current system. The brightest emissions occur when $|Dst|$ is large and specifically when positive H excursions take place, with first positive then negative D excursions, as recorded on magnetograms from nearby observatories. The positive ΔH at low latitudes is accompanied by the negative ΔH of large substorms as recorded at higher latitude observatories. The 0.1-hour time scale of these fluctuations implies that the ring current is incompletely shielded, allowing ionospheric currents and the injection of the ring current to unusually low latitudes.

INTRODUCTION

Aurorae which are seen at low latitudes at the time of large magnetic storms have spectral characteristics which are quite distinct from the "ordinary" aurora excited by keV electrons which are the most frequently seen in the auroral zone. Such aurorae have been recorded visually for many centuries in southern Europe and the United States, Japan, India, Singapore, Cuba, and Hawaii, and reviews of such observations have been given in eight articles by *Loomis* [1859–1861], *Barbier* [1949], *Seaton* [1956], *Chapman* [1957*a*, *b*], and *Chamberlain* [1961]. Recent observations of the spectral characteristics of such aurorae from McDonald Observatory, southwest Texas, have been discussed by *Tinsley et al.* [1984]. The low-latitude aurorae are characterized by (1) N_2^+ 1 N emission with high vibrational development, where 1 N means first negative, (2) a high (> 10) ratio of red (6300 Å) to green (5577 Å) atomic oxygen lines, and (3) prominence of atomic/ionic lines O, O^+, N, and N^+ as compared to molecular bands.

In this paper we study the spectral characteristics of low-latitude aurorae recorded during the last 60 years, and especially the vibrational populations for the N_2^+ $B^2\Sigma_u^+$ state which give rise to the N_2^+ 1 N bands, with a view to evaluating contributions from several excitation mechanisms. We also examine latitude variations of vibrational development and emission rate and compare the time variation of some low-latitude displays with the magnetic signatures from nearby observatories with a view to identifying characteristics of the associated storm time current systems.

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EXCITATION MECHANISMS FOR LOW-LATITUDE AURORAE

There are three mechanisms which can produce the high vibrational excitation of N_2^+ 1 N. The first is precipitation of heavy particles (ions or neutral atoms of H, He, O) at velocities of $< 10^8$ cm s^{-1}. This mechanism was the first to be proposed, resulting from a comparison of an auroral spectrum observed near London with the spectrum excited by cathode rays in air [*Rayleigh*, 1922]. It was supported by measurements of the spectra of the impact of heavy particles in air [*Fan*, 1956] and in nitrogen [*Carleton*, 1957].

The second mechanism is resonant scattering of sunlight on N_2^+ X ions. *Bates* [1949] suggested this as additional to heavy particle impact in low-latitude aurorae. Support for this interpretation was the realization that a number of spectra of low-latitude aurorae were obtained with exposures that included periods when the upper atmosphere being observed was sunlit. The aurora reported by *Rayleigh* [1922] can be shown to have been sunlit.

The third mechanism is collision of large numbers of low-energy electrons with N_2^+ X ions [*Degen*, 1981]. Support for this interpretation is the strong 6300-Å emission seen in many low-latitude aurorae, implying large fluxes of electrons of energy of ~1 eV.

In great low-latitude aurorae the most prominent feature usually observed is this 6300-Å line of oxygen, which is from metastable $O(^1D)$ with an excitation potential of 1.96 eV. Usually, the second most prominent feature is the N_2^+ 1 N emission. From a study of low-latitude aurorae at McDonald Ob-

TABLE 1. Spectroscopy/Photometry of Low-Latitude Aurorae

Event	Location	Reference
May 13–14, 1921	Terling, England	*Rayleigh* [1922]
June 7, 1928	Flagstaff, Ariz.	*Slipher and Sommer* [1929]
May 29, 1932	Flagstaff, Ariz.	*Slipher* [1933]
Jan. 25–26, 1938	Lyon, France	*Dufay and Gauzit* [1938]
	Arosa, Switzerland	*Goltz* [1938]
March 29, 1940	Arosa, Switzerland	*Gotz and Brunner-Hogger* [1940]
March 1, 1941	Lyon, France	*Dufy et. al.* [1941]
Sept. 18–19, 1941	Arosa, Switzerland	*Gotz* [1941]
	Haute Provence, France	*Dufay and Tcheng* [1942]
	Arosa, Switzerland	*Gotz and Schmid* [1942]
April 17–18, 1947	Arosa, Switzerland	*Gotz* [1947]
	Haute Provence, France	*Barbier* [1947]
Jan. 21, 1957	Haute Provence, France	*Dufay and Moreau* [1957]
Sept. 29–30, 1957	Haute Provence, France	*Dufay* [1957]
Feb. 11, 1958	Sacramento Park, N. M.	*Manrung and Pettit* [1959]
	Niigata, Japan	*Hikosaka* [1958]
	Memambetsu Observatory, Japan	*Huruhata* [1958]
	Abastumani, Armenia, U.S.S.R.	*Fishkova and Markova* [1958]
July 8, 1958	Sydney, Australia	*Duncan* [1959]
1959–1961	Niigata, Japan	*Hirao et al.* [1965]
1960–1962	Christchurch, New Zealand	*Tinsley* [1963]
Jan. 7, 1967	Socorro, N. M.	*Tinsley* [1968]
1972	orbit, equatorial	*Levasseur and Blamont* [1973]
1972–1973	orbit, equatorial	*Meier and Weller* [1975]
1972	orbit, low latitude	*Shepherd et al.* [1976]
1975–1976	Adelaide, Australia	*Chamberlain and Jacka* [1979]
July, 1975	orbit, equatorial	*Paresce* [1979]
May 2–3, 1976	Arecibo, Puerto Rico	*Burnside et al.* [1980]
1976–1977	Huancayo, Peru	*Tinsley* [1979]
April–May, 1978	Arecibo, Puerto Rico	*Meriwether and Walker* [1980]
Sept. 29, 1978	Arecibo, Puerto Rico	*Tinsley and Burnside* [1981]
1981–1982	Hawaii, Brazil	*Tinsley et al.* [1982]
1981–1982	Texas, Hawaii, Brazil	*Rohrbaugh et al.* [1983]
Sept. 21–22, 1982	Logan, Utah	*Torr and Torr* [1984]
June 13, 1983	Texas	*Tinsley et al.* [1984]

servatory, Texas, we have found that the ratio of the intensity of the 6300-Å emission, $I(6300)$, to the intensity of the N_2^+ 1 N band system, $I(N_2^+$ 1 N sys.) is quite variable, sometimes being much greater than unity and sometimes being much less [*Tinsley et al.*, 1984]. We have suggested that two populations of exciting particles are present, the first being energetic neutrals or ions, with energies of a few keV for oxygen, hydrogen, and/or helium, and the second being low-energy or hot electrons, of energy $kT \sim 1$ eV, such that the Maxwellian high-energy tail will excite much 6300-Å emission with excitation potential of 1.96 eV, but little 5577 emission with excitation potential of 4.17 eV. The hot electrons would also excite 5200-Å emission from $N(^2D)$ at 2.37 eV and a small amount of 10,400-Å emission from $N(^2P)$ at 3.56 eV.

Thus if $I(N_2^+$ 1 N sys.) $\gg I$([O I] 6300 Å), we infer predominantly energetic neutral atom/ion excitation and describe the event as a neutral atom/ion aurora, or heavy particle aurora, and if I([O I] 6300 Å) $\gg I(N_2^+$ 1 N sys.), we infer predominantly low-energy electron excitation and describe the event as a low-energy electron aurora.

In some cases, H Balmer β is present and covaries with the N_2^+ 1 N emission, and at other times it appears to be absent.

In both types of aurorae the N_2^+ 1 N emission which is present has high vibrational development. The obvious source of precipitating energetic neutral atoms or ions to excite the N_2^+ 1 N emission is the trapped ions of the ring current, which carry a quantity of energy comparable to that dumped in the auroral zones during a magnetic storm. We now know that these species are O^+, H^+, and He^+, which are sometimes precipitated directly at middle and high latitudes but usually precipitated at low and equatorial latitudes as O, H, and He due to the charge exchange of the trapped ions with exospheric neutral hydrogen. The ionic content of the ring current has been reviewed by *Williams* [1981], and measurements of precipitating O^+, H^+, and He^+ have been made by *Sharp et al.* [1976*a*, *b*]. Neutral atom precipitation has been reviewed by *Tinsley* [1981].

The source of the low-energy electrons for low-latitude aurorae would appear to be different from the source of such electrons for stable auroral red (SAR) arcs [*Rees and Roble*, 1975; *Kozyra et al.*, 1982], where the hot electrons at thermospheric altitudes are thought to result from advection or heat conduction down from a region above 1000-km altitude, possibly from a source involving interaction between the ring current and thermal plasma. The SAR arcs are narrow in latitude, of long east-west extent (perhaps girdling the earth), of many hours duration, and found in relatively quiet (recovery phase) conditions.

The low-latitude auroral 6300-Å emission, by contrast, is of relatively short duration (tens of minutes), during active (main phase) magnetic conditions, and as we will show, the intensity is closely related to local magnetic perturbations. A possible source of thermospheric hot electrons would be storm time currents passing through the thermosphere. Some contribution to 6300-Å emission may be due to collisional excitation by precipitating ions/neutrals and their secondaries [*Torr et al.*, 1974].

Table 1 lists published spectroscopic and photometric

TABLE 2. Spectral Features Observed in Low-Latitude Aurorae

Feature	λ, Å	Excitation Potential, eV	First Reported
Atomic lines			
[N I]$^2D^0$–$^4S^0$	5198–5201	2.37	*Slipher and Sommer* [1929]
[N I]$^2P^0$–$^2D^0$	10,395–10,404	3.56	*Dufay* [1957]
[O I]^1D–^3P	6300	1.96	*Rayleigh* [1922]
[O I]^1S–^1D	5577	4.17	*Rayleigh* [1922]
[N II]^1S–^1D	5755	18.57	*Dufay* [1957]
[O II]^2P–^2D	7319–7330	18.61	*Dufay* [1957]
N I 3^4P^0–3^4P	8216	11.79	*Dufay* [1957]
N I 3^4D^0–3^4P	8680	11.71	*Dufay* [1957]
O I 5^3D^0–3^3P	5958	12.97	*Dufay* [1957]
O I 4^5D^0–3^5P	6157	12.70	*Dufay* [1957]
O I 3^5P–3^5S^0	7774	10.69	*Dufay* [1957]
O I 3^3P–3^3S^0	8446	10.94	*Dufay* [1957]
O I 3^5D–3^5P	9266	12.05	*Dufay* [1957]
O II 3^2D^0–3^2P	4416	26.14	*Tinsley* [1979]
H Baα 3^2D–2^2P^0	6563	12.04	*Levasseur and Blamont* [1973]
H Baβ 4^2D–2^2P^0	4861	12.69	*Tinsley* [1979]
He I 2^3P^0–2^3S	10,830	18.83 (twilight)	*Tinsley* [1968]
He II Lyα 2^2D–1^2P^0	304	40.76	*Meier and Weller* [1975]
He II Paα 4^2D–3^2P	4686		*Tinsley* [1979]
Molecular Bands			
N_2^+ 1 N		15.5 (twilight)	*Rayleigh* [1922]
		18.7 (night)	*Barbier* [1947]
N_2^+ Meinel		16.7	*Dufay and Moreau* [1957]
N_2 1 P ? (weak)		7.3	*Dufay* [1957]

measurements on individual low-latitude aurorae, starting with Rayleigh's aurora of 1921. Table 2 lists spectral features established in low-latitude aurorae.

The incoming keV neutrals and ions will lose most of their energy in the height range 230–300 km [*Torr and Torr*, 1979], and the relative importance of atomic lines of O, N, O^+, and N^+ in comparison with the spectra of keV electron aurorae can be understood in terms of the collisions with atmospheric constituents in this height range, where the ratio of atomic oxygen to molecular oxygen and nitrogen is much greater than at 100–120 km, which is typical of keV electron aurorae.

The keV neutrals and ions will collisionally excite high-excitation potential lines of O, N, O^+, and N^+, which will radiatively cascade. The O^+ doublet states will cascade to $O^+(^2P)$ and $O^+(^2D)$, which may then charge exchange with N_2 to give N_2^+ in the *A* state and emission of the Meinel bands. Transfer of momentum from the primaries to neutral and ion secondaries occurs as a mixed beam of ions and neutrals is formed, as in the model for hydrogen precipitation [*Van Zyl et al.*, 1984]. Thus some $O^+(^2P)$ and $O^+(^2D)$ will be produced with a few electron volts of energy. By incorporating 0.1 eV or 1.8 eV of kinetic energy as excitation energy, the O^+ metastables can charge exchange with N_2^+ to yield N_2^+ $B\Sigma_u^+$ and hence N_2^+ 1 N emission. This charge exchange mechanism was suggested in the context of twilight emission by *Dalgarno and McElroy* [1966] and discussed by *Broadfoot* [1967] and was considered likely to lead to enhanced vibrational excitation. This mechanism would be an additional source of N_2^+ 1 N emission above that produced by direct collisional ionization of N_2 by the primaries.

The H Balmer α and H Balmer β would be the result of collisional excitation of hydrogen primaries when present. The He^+ emissions were observed near the magnetic equator and may arise from a more energetic population of trapped ions than the main storm time ring current [*Meier and Weller*, 1975].

The observation of He 10,830-Å emission noted in Table 2 was made by *Tinsley* [1968] in twilight from a site in New Mexico. An emission rate of 3.8 kR was observed in the north at 60° zenith angle when the solar zenith angle was 108°. The *Kp* value at the time was 6 +. At the same time in Haute Provence, France, which is about the same dip latitude, G. Weill (personal communication, 1967) observed an auroral type event with a maximum slant emission rate toward the north of 1.3 kR of O I 6300 Å.

The characteristics of the low-latitude aurora discussed above are quite similar to those of red type A aurora observed at high latitudes and in particular the aurora of February 10–11, 1958, as recorded at Saskatoon, Canada [*Vallance Jones*, 1960], and at College, Alaska [*Clark and Belon*, 1959; *Belon and Clark*, 1959]. Vallance Jones recorded the enhancement of the O I 7774 Å and 8446 Å lines by about 5 times relative to the N_2^+ Meinel bands in ordinary aurorae, and the $O^+(^2P$-$^2D)$ doublet at 7319–7330 Å appeared with an even greater enhancement. In Alaska the nighttime spectra showed the N_2^+1 N bands with high vibrational development and prominent atomic and ionic emissions.

VIBRATIONAL DEVELOPMENT IN LOW-LATITUDE AURORAE

Tinsley et al. [1984] published a spectrum obtained from McDonald Observatory on June 13, 1983, at around 0600 UT (2300 LT). On this occasion the N_2^+ 1 N emission predominated. The shadow line was above 800 km, and resonant scattering effects would be small. We have analyzed the relative

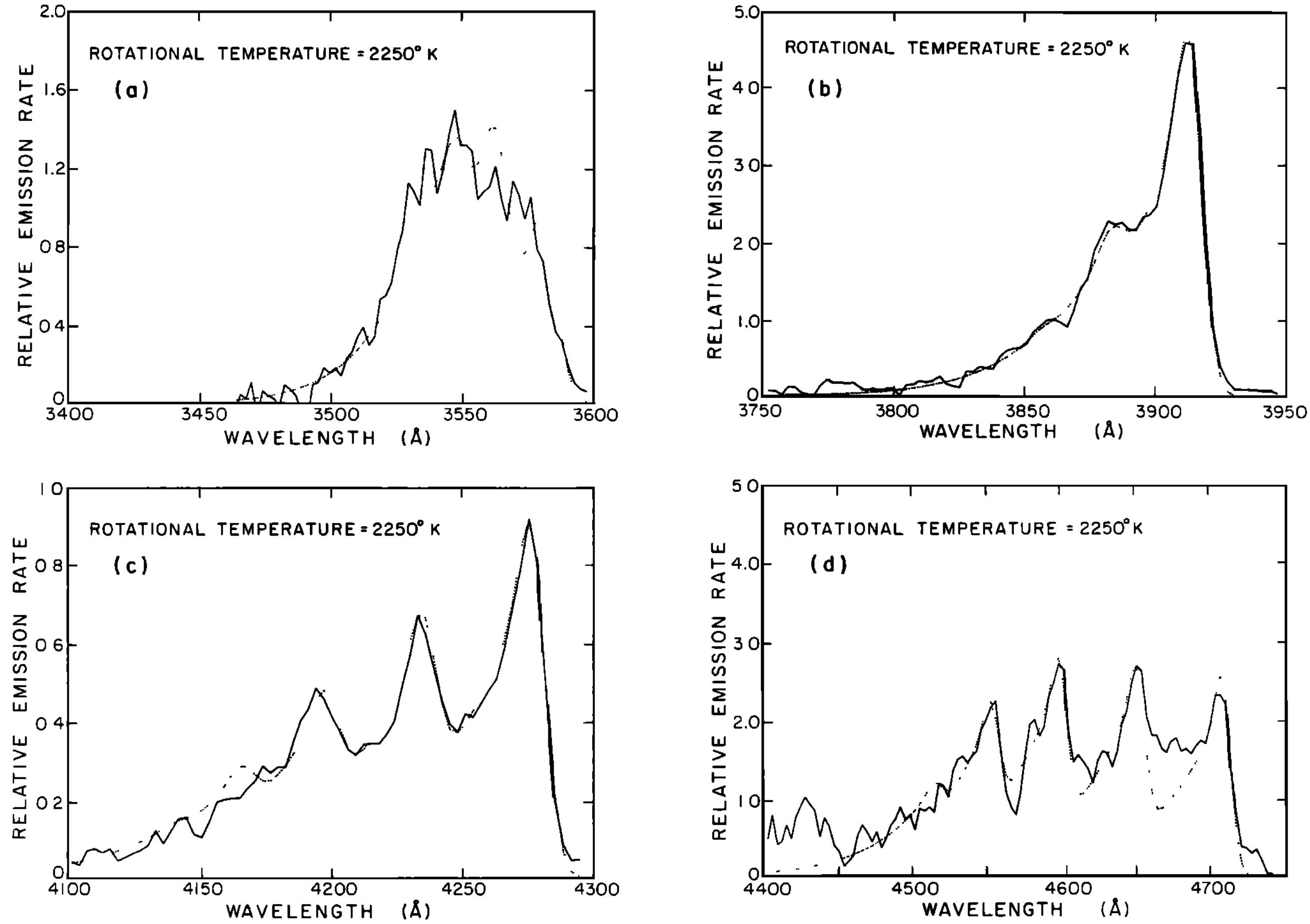

Fig. 1. Comparison of observed (solid line) and synthetic (dotted line) spectra for N_2^+ 1 N bands observed June 13, 1983, from McDonald Observatory. The $\Delta V = 1, 0, -1$, and -2 sequences are shown in Figures 1*a*, 1*b*, 1*c*, and 1*d*, respectively. A spectrum containing the airglow background has been subtracted from the observed data in Figures 1*a*, 1*b*, and 1*c* but not Figure 1*d*. The relative vibrational populations for the synthetic spectra for the $v' = 0, 1, 2, 3, 4$ levels are 50:21:16:10:3.

populations of the N_2^+ $B^2\Sigma_u^+$ vibrational levels for the June 13, 1983, spectrum by fitting synthetic spectra to the observed spectra. The results are given in Figure 1, which shows the first negative band sequences $\Delta v = +1$, $\Delta v = 0$, $\Delta v = -1$, $\Delta v = -2$. All four synthetic spectra have the same relative populations $N(v' = 0)$: $N(v' = 1)$: $N(v' = 2)$: $N(v' = 3)$: $N(v' = 4)$ for the $v' = 0, 1, 2, 3$, and 4 levels of 50:21:16:10:3. The best fit for rotational temperature was 2250°K. The overall fit is reasonably good but might be improved by using a nonthermal equilibrium rotational population distribution.

Table 3 lists relative vibrational populations for N_2^+ $B^2\Sigma_u$, which have been obtained from laboratory work, theoretical studies, and observations of other auroras and of the June 1983 Texas aurora. The population ratios for the $v' = 0, 1$, and 2 levels for keV electron excitation in the dark are given by the ratios of the Franck-Condon factors and are about 87:11:1 [*Bates*, 1949, Table 2]. The increase of population of the upper vibrational levels for collisions of low-energy electrons or the scattering of sunlight on N_2^+ X depends on the ion lifetime, which is of the order of 10 s at 300 km [*Broadfoot and Hunten*, 1966]. The recent calculation by *Degen* [1981] yields ratios of $N(v' = 0)$:$N(v' = 1)$:$N(v' = 2)$ of 72:20:7 for an electron flux of 10^{12} cm^{-2} s^{-1}, if the ion lifetime $\tau = 100$ s corresponding to heights above 400 km. His recalculation of populations produced by scattering of sunlight gives ratios of 71:17:8 for $\tau = 2$ s and 52:24:15 for $\tau = 100$ s. Precipitation of ions or neutrals of velocity of $< 10^8$ cm s^{-1} into an atmosphere of pure N_2 lead to relative vibrational populations, with populations of the higher vibrational levels increasing as the particle speed is reduced, neutrals having a lower cross section but producing higher vibrational excitation than ions at a given speed. Relevant laboratory studies are those of *Fan* [1956], *Carleton* [1957], *Moore and Doering* [1969*a*], *Birely* [1974], and *Van Zyl et al.* [1983]. The laboratory results for pure N_2 are not directly applicable to measured spectra, since a precipitating beam of O and O^+ entering the thermosphere with O as the major constitutent above 200 km would produce a cascade of secondary O and O^+ of lower energy in momentum transfer collisions with ambient O [*Torr and Torr*, 1979] which, together with slowed down primaries, would contribute to the excitation and produce higher vibrational excitation than initially produced by the primaries. Neither the necessary laboratory measurements nor modeling to establish the primary energy from the observed vibrational distribution has been carried out, but a lower limit for the mean primary energy can be set on the assumption that all the N_2^+ 1 N emission is produced by primary O^+ ions at their initial energy.

The rotational temperature of 2250°K which best fitted the observed profiles is much higher than the temperature of about 1000°K likely for the ambient thermosphere. The collisions of ions or neutrals with N_2 have been found to increase

TABLE 3. Relative Vibrational Population for N_2^+ $B(v')$

	$N(v'=0)$	$N(v'=1)$	$N(v'=2)$
keV electrons on N_2 (ordinary aurorae) ($T_v(N_2)$ = 1000 K [*Bates*, 1949, Table 11])	87	11	1
eV electrons on N_2^+ X, τ = 100 s ($T_v(N_2)$ = 1500 K, flux 10^{12} cm^{-2} s^{-1})	72	20	7
Sunlight on N_2^+ X, τ = 2 s [*Degen*, 1981]	71	17	8
Sunlight on N_2^+ X, τ = 100 s [*Degen*, 1981]	52	24	15
Neutrals, 4.4×10^7 cm s^{-1}; ions, 1.7×10^7 cm s^{-1} [*Moore and Doering*, 1969*a*; *Birely*, 1974; *Van Zyl et al.*, 1983]	51	24	16
Neutrals, 2.8×10^7 cm s^{-1}; ions, 1×10^7 cm s^{-1} [*Moore and Doering*, 1969*a*; *Birely*, 1974; *Van Zyl et al.*, 1983]	40	26	20
Haute Provence, observed April 17–18, 1947 (judged not sunlit [*Barbier*, 1947])	40	26	18
Texas, observed June 13, 1983 (not sunlit, not red [*Tinsley et al.*, 1984])	50	21	16
Alaska, observed February 10, 1958 (sunlit, red type A [*Clark and Belon*, 1959])	52	24	15
Logan, observed September 21–22, 1982 (not sunlit [*Torr and Torr*, 1984])	68	17	10
Alaska, observed February 10, 1958 (not sunlit, red type A [*Clark and Belon*, 1959])	71	19	7
Alaska, observed March 8, 1978 (not sunlit, proton aurora [*Sivjee*, 1980])	77	19	...

the excitation of the higher rotational levels [*Moore and Doering*, 1969*b*].

A further complication for interpretation of observations is that the production of $O^+(^2P)$ and $O^+(^2D)$ in the cascade with more than a few electron volts of kinetic energy makes possible the production of vibrationally and rotationally excited N_2^+ by the charge exchange mechanism, and again there is a lack of laboratory measurements and models. The very strong $O^+(^2P\text{-}^2D)$ emission at 7319–7330 Å observed by *Vallance Jones* [1960] is an indication of the need of further study of this mechanism.

For the Texas aurora of June 13, 1983, the absence of sunlight and of sufficient low-energy electrons to excite appreciable 6300-Å emissions rules out resonant scattering and low-energy electrons as N_2^+ excitation mechanisms. The vibrational population ratios of 50:21:16 can be compared to the laboratory data for heavy ions on N_2 [*Moore and Doering*, 1969*a*] and lead to a lower limit for the mean primary velocity of 2×10^7 cm s^{-1} (mean primary energy 3 keV) for O/O^+ primaries.

The Haute Provence 1947 aurora with population ratios 40:26:18 [*Bates*, 1949] was judged by *Barbier* [1947] not to be sunlit, although *Seaton* [1956] questioned this. However, the vibrational excitation is too high to be produced by sunlight on the basis of *Degen*'s [1981] calculations and also too great to be explained by a low-energy electron flux, unless it was significantly greater than 10^{12} cm^{-2} s^{-1}, or the N_2^+ lifetime significantly longer than 100 s. Again, an explanation in terms of a precipitating O/O^+ flux is indicated, in this case with a lower limit on mean primary energy of about 1 keV.

The aurora of February 10, 1958, was observed at many low-latitude sites, with characteristic low-latitude spectral features, and also in Alaska, where a series of spectra were taken which also showed the features characteristic of low-latitude aurorae, rather than the keV electron aurorae ordinarily seen at those latitudes. The spectra taken in sunlight showed a vibrational population ratio of 52:24:15, which can be explained by the action of sunlight according to *Degen* [1981] if the height were above 400 km and the N_2^+ X lifetime of the order of 100 s. However, a contribution from low-energy electrons and ion/neutral precipitation is also plausible, especially since the sunlit aurora in the 400- to 500-km-height region observed by *Vallance Jones and Hunten* [1960] had vibrational population ratios of only 71:17:8.

The aurora of September 21–22, 1982, observed at Logan, Utah, was found to have a ratio of the (0-1) to (1-2) bands of N_2^+ 1 N of typically 3–3.5 [*Torr and Torr*, 1984] (see also *Ishimoto et al.* [1986]). This and the ratio of the (0-1) to (2-3) bands of about 7 in Figure 4 of *Torr and Torr* [1984] correspond to a population ratio of about 68:17:10 and by referring to *Moore and Doering* [1969*a*] translates into a lower limit for the mean primary velocity of about 4×10^7 cm s^{-1} and a mean O^+ primary energy of about 13 keV. *Torr and Torr* [1984] argued that the effects of any flux of low-energy electrons on the vibrational distribution of N_2^+ emission was likely to have been small in view of the absence of significant vibrational excitation of the N_2 second positive bands.

The aurora of February 10–11, 1958, was also observed in the dark atmosphere by *Clark and Belon* [1959] and showed a population ratio of 71:19:7, with less development than for the earlier sunlit aurora. *Degen* [1981] interpreted this as due to low-energy electrons, and ion/neutral precipitation is an additional mechanism that cannot be ruled out. If ion/neutral precipitation was dominant, then a lower limit for the mean primary energy of O^+ would be about 15 keV. For comparison, proton aurora observed by *Sivjee* [1980] had a relative vibrational population ratio for $N(v'=0):N(v'=1)$ of 77:19, and the analysis in conjunction with laboratory results implied the precipitation of protons of energy of $\sim$1.2 keV. The vibrational development is still about twice as much as for a typical keV electron aurora with population ratios of about 87:11:1.

LATITUDE VARIATIONS IN N_2^+ 1 N EMISSION

The population ratios derived from various observations of nonsunlit aurora in Table 3 shows an interesting trend with dip latitude of the observation site. The auroras of the lowest latitude sites, Texas and Haute Provence (both near dip lati-

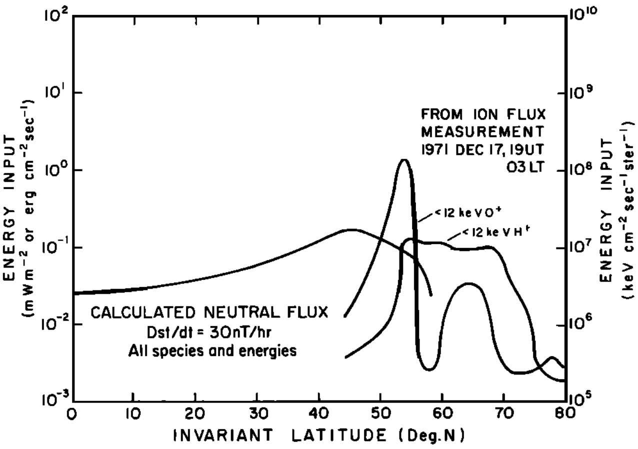

Fig. 2. Representative latitude variation of energy input of ion and neutral precipitation. The ion flux measurements were made by *Sharp et al.* [1976*b*] in the energy range 0.7–12 keV, and the neutral flux is from *Tinsley* [1979] for a ring current at $L = 4$.

tude ~ 40°, $L \sim 1.8$), had the greatest vibrational development; that of Logan (dip latitude ~ 50°, $L \sim 2.4$) had an intermediate amount, and *Clark and Belon*'s [1959] spectrum from College, Alaska (dip latitude ~ 65°, $L = 5.4$), had the least vibrational development.

The trend in decreasing vibrational development with increasing latitude is consistent with two trends seen in the satellite data of *Sharp et al.* [1976*b*]. These are (1) an increase in the mean energy of the precipitating O^+ ions with latitude and (2) an increase in the fraction of H^+ in the total flux at a given energy. Their Figure 2 shows an energy spectrum peaked near 10 keV at the highest latitude sampled ($L = 9.4$), changing into a much softer spectrum with a peak near 1 keV for the lowest latitude sampled ($L = 2.8$). Also, their Figure 4 shows the H^+ energy flux increasing with respect to the O^+ energy flux toward higher latitudes. Neither of the above trends is very smooth, and the optical and particle comparisons involve a number of different events, but taken together, they add support to the concept of ion/neutral precipitation being the source of the observed high vibrational excitation of N_2^+ 1 N.

The latitude gradients in intensity of N_2^+ 1 N emission are also worth examining. The observations from Haleakala on April 13, 1981, showed little intensity difference between looking north and south at 70° zenith angle [*Rohrbaugh et al.*, 1983], although those of July 14, 1982, show about 2 times greater emission in the north. There was no appreciable latitude gradient in the July 13–14, 1982, results from Brazil. These results are consistent with the relatively small gradients predicted from a theoretical model for neutral atom precipitation [*Tinsley*, 1979].

The longitude separations among the sites at McDonald Observatory (Texas), Haleakala (Hawaii), and Cachoeira Paulista (Brazil) are too great to allow latitude gradients in emission rates to be determined among these sites from simultaneous data. Comparisons of time variations of emission rates and the magnetic variations with which they are correlated show that the longitudinal scale of the variations is smaller than the separation among the three sites. In general terms one can say that in Texas, for stronger magnetic storms the emission rates of the N_2^+ 1 N bands reach hundreds to thousands of rayleighs, whereas in Hawaii and Brazil a few rayleighs to a few tens of rayleighs are all that appear.

The models of *Tinsley* [1979] predict latitude gradients in the precipitation of energetic neutral atoms such that the expected fluxes in the region observed from McDonald Observatory (near 40° dip latitude) would be expected to be no more than 4 times greater than the fluxes observed from the two equatorial stations, at 5°–25° dip latitude. The theoretical ratio depended on the L shell and the length of time the pitch angle distribution had been evolving from a distribution initially isotropic to the loss cone, defined by a mirror height of 375 km. The general observational result that emission rates at McDonald Observatory (and other sites of similar dip latitude such as Haute Provence) are hundreds of times those at the equatorial sites implies that direct ion precipitation is required there in addition to the neutral atom precipitation extending from the equator to mid-latitudes. The direct ion precipitation would begin at dip latitudes near 40° and extend up to high latitudes as measured by *Sharp et al.* [1976*b*].

Figure 2 illustrates the above concept of the latitude variation of the ion and neutral precipitation. The measurements of ion flux were taken from *Sharp et al.* [1976*b*, Figures 7 and 9], and the calculated neutral flux energy input is from *Tinsley* [1979] for energy loss by charge exchange equivalent to a 30-nT/h decay rate for the ring current. The ring current is assumed to have a pitch angle distribution isotropic to a loss cone at 375 km and to be located on a drift shell of $L = 4$, representative of a more realistic ring current distributed over drift shells from $L = 3$ to $L = 5$.

During direct precipitation of ions some process must be continually repopulating the part of the ion velocity distri-

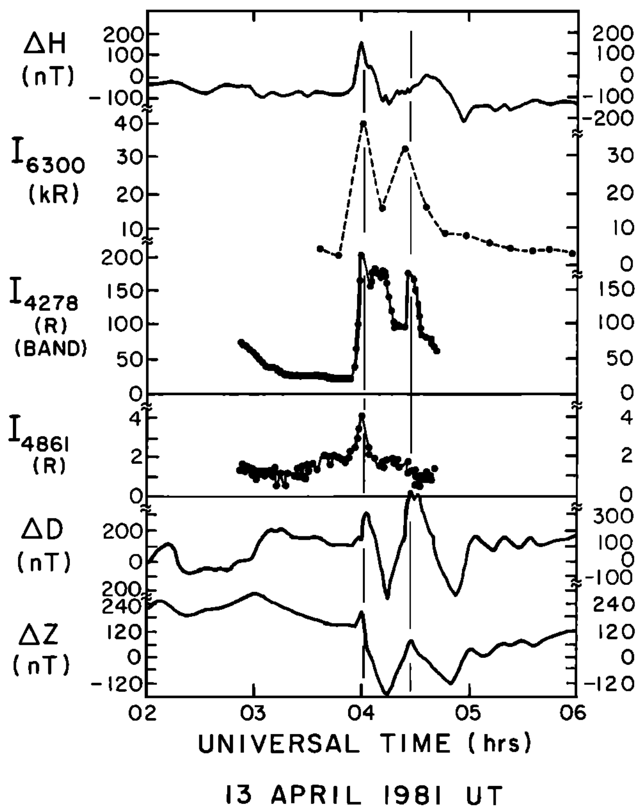

Fig. 3. Magnetograms from Boulder, Colorado, compared with time variations of emissions observed April 13, 1981. The 4287-Å and 4861-Å emissions were observed from McDonald Observatory, Texas, and the 6300-Å emission from McColly Observatory, Montana, both looking into a volume of space almost directly above Boulder.

bution within the loss cone. Processes which populate the loss cone during conditions when low-latitude aurorae are detected (i.e., during substorms or the main phases of magnetic storms) include the lowering of mirror heights by adiabatic inward convection and strong and weak pitch angle diffusion [*Tinsley and Akasofu*, 1982]. The faster the rate of lowering mirror heights of ions, the greater the fraction that will be precipitated directly rather than as energetic neutrals following charge exchange. For weaker magnetic activity one might expect that the time constant for lowering of mirror heights would be longer than for stronger activity, and then energetic neutral precipitation would predominate over direct ion precipitation at dip latitudes of 40° and greater, and the ratio of intensity above 40° would not be so large in comparison to the equatorial intensity. We do not have sufficient data to test this prediction as yet.

TIME VARIATIONS AND CURRENT SYSTEMS

Central U.S. Data

An analysis of the time variations of emission features with respect to each other and with respect to magnetic and ionospheric data is relevant to identifying the excitation process and to how the precipitation processes fit into the overall picture of substorm development and ring current losses. Figure 3 shows time variations of emissions observed April 13, 1981, at McDonald Observatory. The N_2^+ 1 N (0, 1) band at 4278 Å and the H Balmer β line at 4861 Å were observed 30° above the northern horizon. The [O I] 6300-Å emission was observed from McColly Observatory, Montana (latitude 48.6°N, longtiude 107.1°W), looking south at 80° zenith angle and intercepting the line of sight from McDonald observatory at 400-km altitude. The optical time variations are compared with magnetic variations measured from Boulder, a site almost directly under the volume of the thermosphere being observed. A good correlation of the intensity variations with

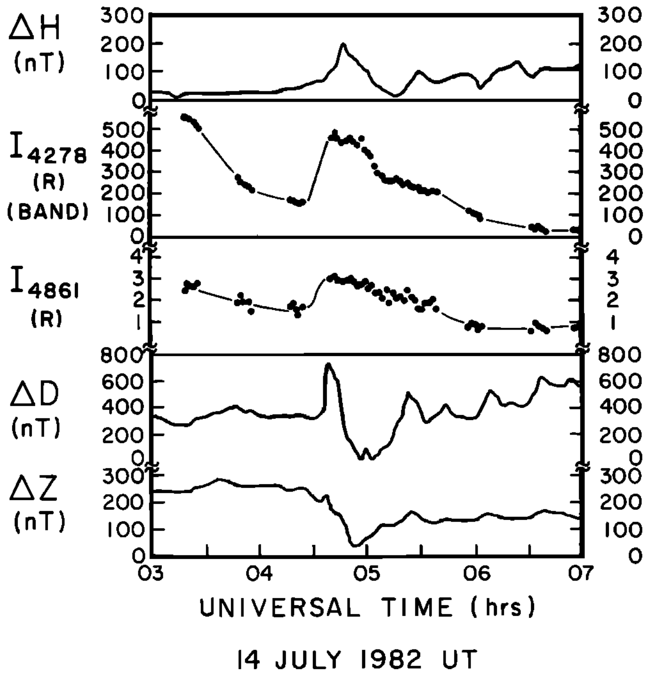

Fig. 4. Magnetograms from Boulder, Colorado, compared with time variations of emission observed July 14, 1982, from McDonald Observatory.

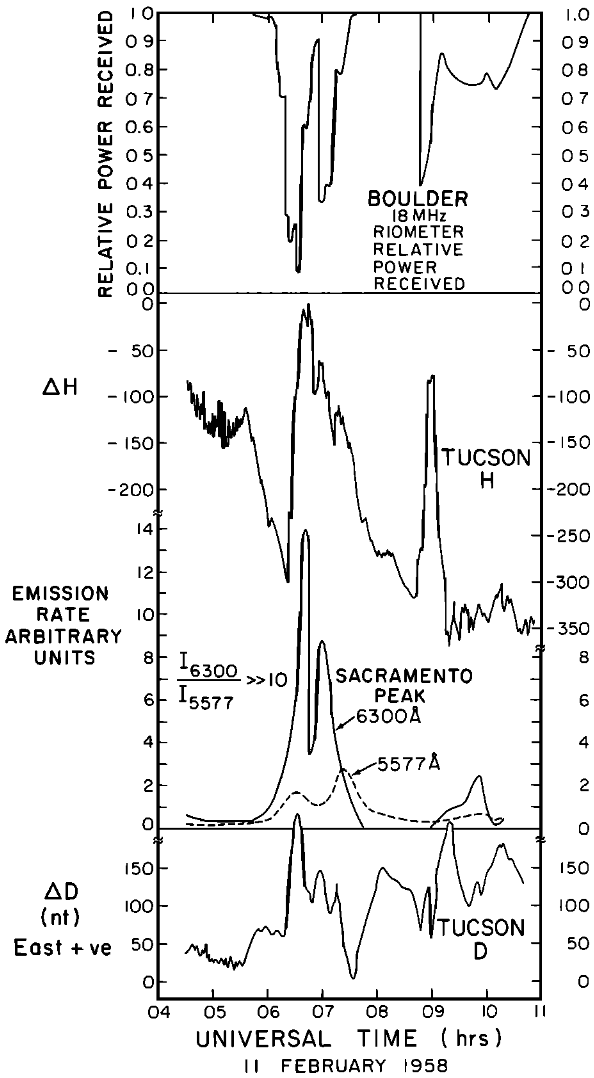

Fig. 5. Magnetograms from Tucson, Arizona, compared with time variations of emission observed from Sacramento Peak, New Mexico, UT February 11, 1958, and with ionospheric absorption recorded on a riometer at Boulder, Colorado.

the disturbance magnetic field can be seen. The absence of H Balmer β during the latter part of the event can be understood as a more rapid loss of hydrogen ions from the inner ring current than oxygen or helium ions, owing to the larger charge exchange cross section for H than O. An alternative interpretation is that the accumulation of O^+ ions in the trapped population from an ionospheric source eventually outnumber the initial H^+ from a solar wind source. Similar good correlations between optical and magnetic time variations apply to July 14, 1982, data (Figure 4). In both cases the precipitation is associated with positive excursions in the *H* trace and first positive then negative excursions in the *D* trace of the magnetograms from nearby observatories.

An additional example is the February 10–11, 1958, aurora observed from Sacramento Peak, New Mexico, by *Manrung and Pettit* [1959]. Their optical data have been compared with Tucson magnetograms in Figure 5, and the same relationship to ΔH and ΔD can be seen as for the 1981–1982 storms. The 6300-Å and 5577-Å emission rates are whole-sky averages. The 6300-Å intensities reached at least a factor of 1000 greater than the normal airglow intensities for that time, and the

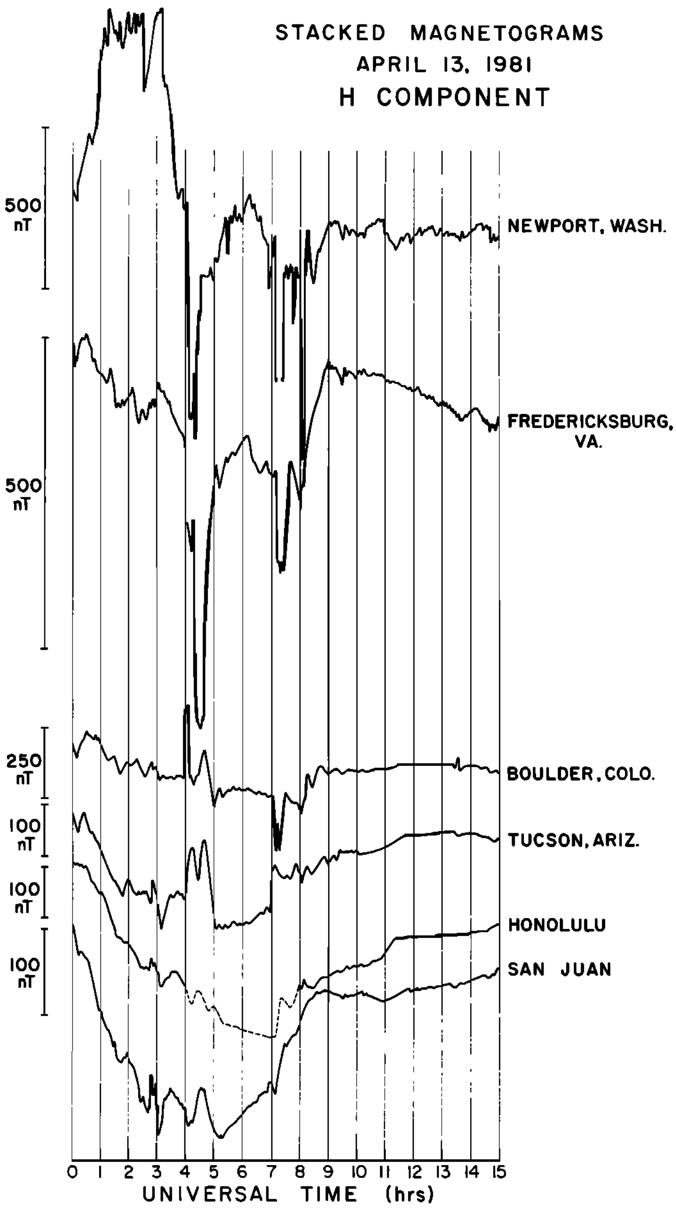

Fig. 6. Stacked magnetograms from observatories across the United States showing the H component for the April 13, 1981, events. The observations of Figure 3 correspond to the substorm of 0400–0500 UT, and those of Figure 14 to the substorm of 0700–0800 UT. The H trace saturated in Honolulu, and the dashed part of the curve is inferred from the Tahiti trace.

5577-Å emission rates a factor of 10 above normal. The I(6300 Å) to I(5577 Å) intensity ratio was greater than 10, indicating the presence of a large flux of low-energy electrons. In addition, Figure 5 shows the large increase in ionospheric absorption of 18 MHz on the Boulder riometer located 8° poleward of Sacramento Peak [*Warwick*, 1958]. Absorption of cosmic noise at these frequencies is usually produced by enhanced ionization at E region heights or below [*Little and Leinbach*, 1958]. It indicates the presence of more energetic particles penetrating more deeply into the atmosphere than low-energy electrons and perhaps heavy particles presumed responsible for the lower latitude display.

Sets of stacked magnetograms from observatories across the United States for periods covering the April 1981 and July 1982 storms are given in Figures 6, 7, 8, 9, 10, and 11. Only the perturbations in the components are shown, and a large baseline value has been subtracted here and in other figures in the paper, where the perturbations in the components are labeled ΔH, ΔD, and ΔZ. Figure 12 shows the location of most of the observatories on a chart of magnetic dip angle. The observatories from which records are shown are, in order of decreasing dip latitude, Newport, Washington; Fredericksburg, Virginia; Boulder, Colorado; Tucson, Arizona; Honolulu, Hawaii; and San Juan, Puerto Rico. The substorms of interest for the observations of Figures 3 and 4 are those of 0400–0500 UT on April 13 and 0500–0600 UT on July 14. Examination of Figures 6 and 7 shows that the positive excursions in H at the lower latitude observatories at the time of the optical emissions are associated with negative H excursions at higher latitude observatories in the same longitude sector, i.e., at the time of occurrence of large substorms.

Figures 8 and 9 show D component magnetograms in order of increasing east longitude. The signature in D is such that the change from eastward perturbation to westward perturbation occurs close to the time of peak amplitude of the perturbation in H. The eastward magnetic field perturbation is associated with the growth of the substorm current system,

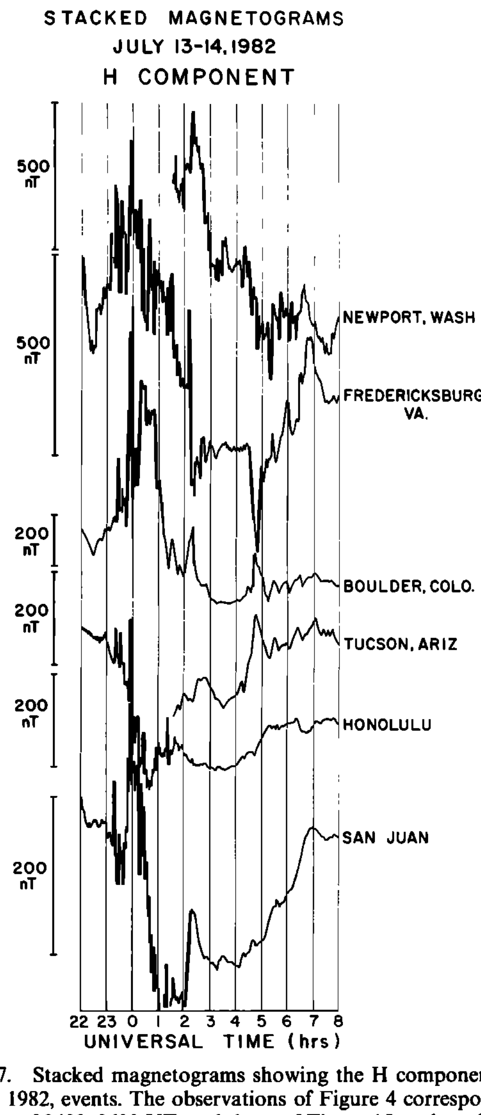

Fig. 7. Stacked magnetograms showing the H component for the July 14, 1982, events. The observations of Figure 4 correspond to the substorm of 0400–0600 UT, and those of Figure 15 to the substorm at about 0000 UT.

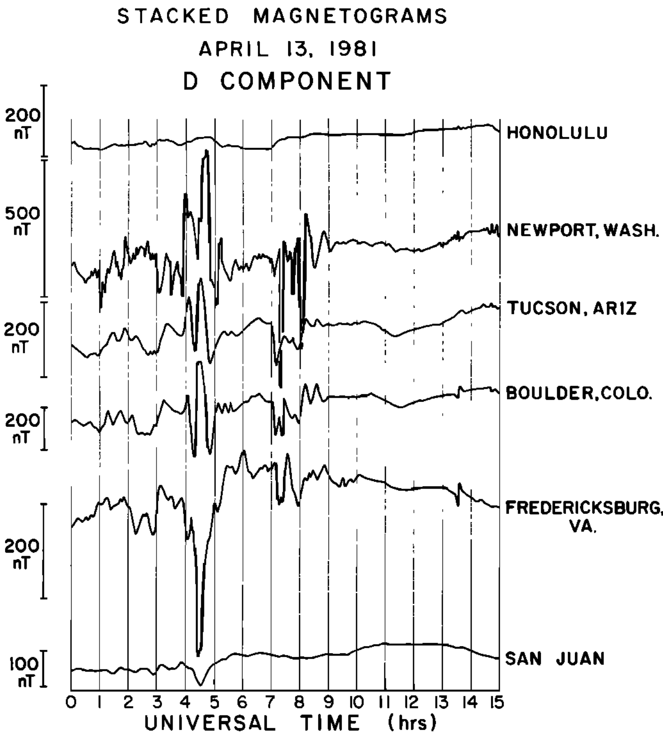

Fig. 8. Stacked magnetograms showing the D component for the April 13, 1981, events.

and the westward magnetic field perturbation to its decay. The signatures of the substorms in the Z component are shown in Figures 10 and 11. Generally, there is a decrease in the Z component at all latitudes during the events.

The magnetograms from low-latitude stations show the positive ΔH of an eastward electrojet, and the higher latitude magnetograms in the same longitude sector show the large negative ΔH of an intense westward electrojet in accordance with the normal substorm pattern [*Ahn et al.*, 1984]. However, the large D oscillation from eastward to westward does not appear in the normal pattern and appears to be characteristic of the rapid growth and rapid decay of these unusually large substorms. This rapidity is perhaps the most important factor responsible for the injection of the positive ions to unusually low latitudes, for the shielding currents which flow will not have sufficient time to halt the penetration of the electric fields driving the ions. (A discussion of the penetration of high-latitude electric fields into low latitudes is given by *Kamide and Matsushita* [1981]). The geometry of these currents, some of which may be carriers of the large fluxes of low-energy electrons which are implied by the optical observations, remains to be worked out.

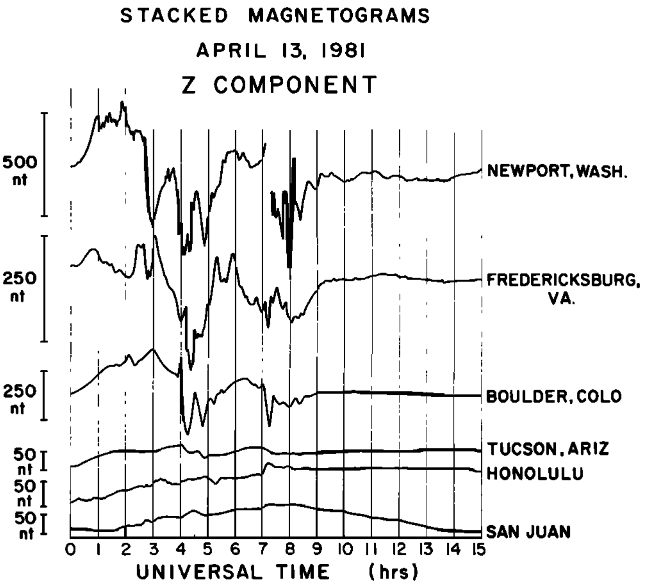

Fig. 10. Stacked magnetograms showing the Z component for the April 13, 1981, event.

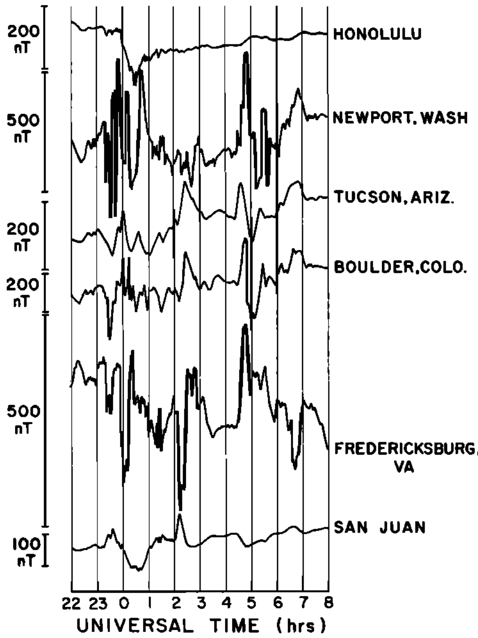

Fig. 9. Stacked magnetograms showing the D component for the July 14, 1982, events.

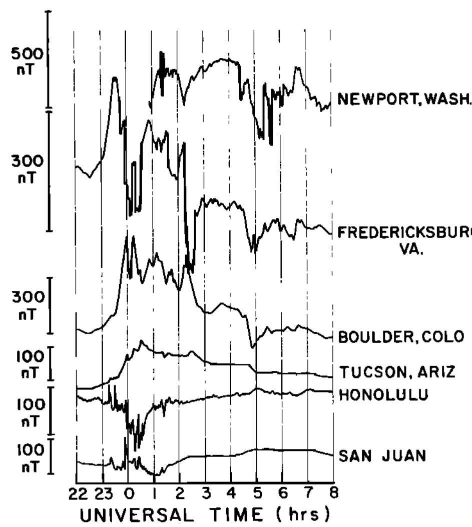

Fig. 11. Stacked magnetograms showing the Z component for the July 14, 1982, event.

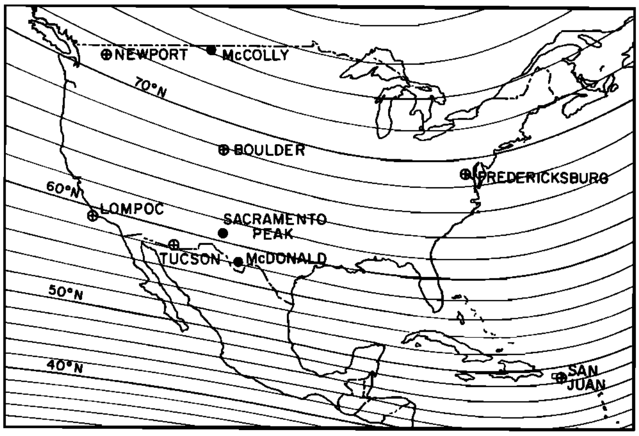

Fig. 12. Map showing location of magnetic and optical observatories in the continental United States and Puerto Rico. The contours of dip angle are taken from the map compiled by the *U.S. Geological Survey* [1975]. Dip angles of 60° and 70° correspond to 41° and 54° dip latitude, respectively.

Data From Mount Haleakala, Hawaii, and Cachoeira Paulista, Brazil

Figure 13 shows a comparison of emission rate variations observed at Mount Haleakala, Hawaii, for the July 14, 1982, magnetic storm with magnetograms from Honolulu and Newport. A substorm at the later universal time of 0900–1100 UT is involved on account of the longitude difference. The relationship of the emission rate variations to the local (Honolulu) ΔH and ΔD charges is similar to that observed in Texas and New Mexico, and the Newport variations fit the pattern of the higher latitude substorm signatures. For the storm of April 13, 1981, shown in Figure 14, the Honolulu H trace went off scale, and a comparison of emission rate variations is made with the two stations of Newport and Lompoc on the west coast of the continental United States (see Figure 12). The ΔX and ΔY signatures are in accordance with the pattern established for ΔH and ΔD, except that the Lompoc ΔY does not first show a positive excursion in Y before the negative emission occurs. Figure 15 compares emissions observed for the July 13–14, 1982, magnetic storm in Cachoeira Paulista, Brazil (latitude 22.7°S, longitude 45.0°W, dip latitude 12°S) with magnetograms from the nearby station of Vassouras (latitude 23°S, longitude 46°W). Corresponding mid-latitude magnetograms are given in Figures 7, 9, and 11.

As in the case of the central U.S. data the precipitation occurs at the time of a strong westward electrojet at mid-latitudes produced by a substorm. The low to equatorial latitude region would be more effectively shielded from substorm-associated electric fields than the mid-latitude region, and local ionospheric currents would be expected to be small. Thus the D signature apparently represents the integrated effect of the distant magnetospheric-ionospheric current systems associated with the substorm.

Figures 13–15 also show the *Dst* parameter, which is a measure of the total energy content of the trapped particles which constitute the ring current, obtained from the longitudinal average of ΔH values measured at low-latitude observatories. (For a definition of *Dst* and other magnetic parameters and their relationship to storm time current systems, see, for example, *Akasofu and Chapman* [1972].) As can be seen from the

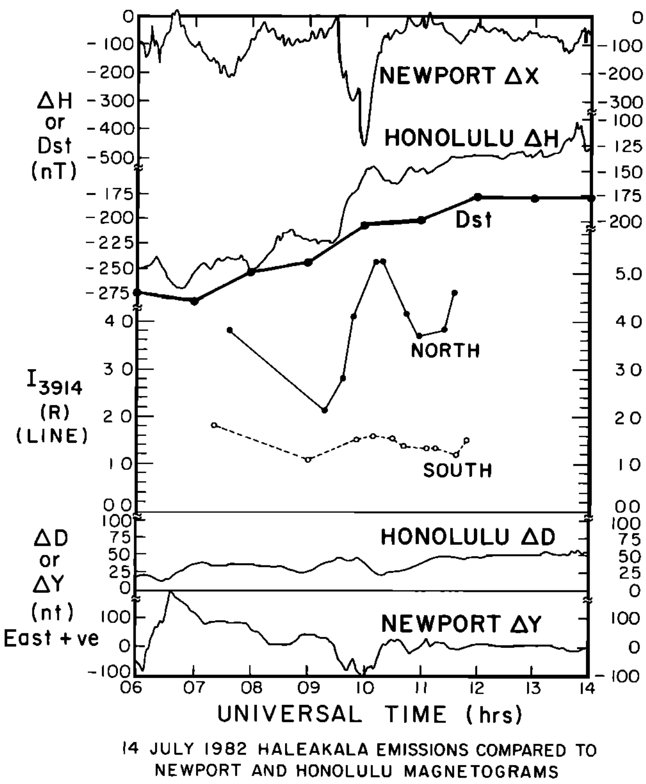

Fig. 13. Magnetograms from Honolulu and Newport compared with time variations of emissions observed on July 14, 1982, from Haleakala, Hawaii.

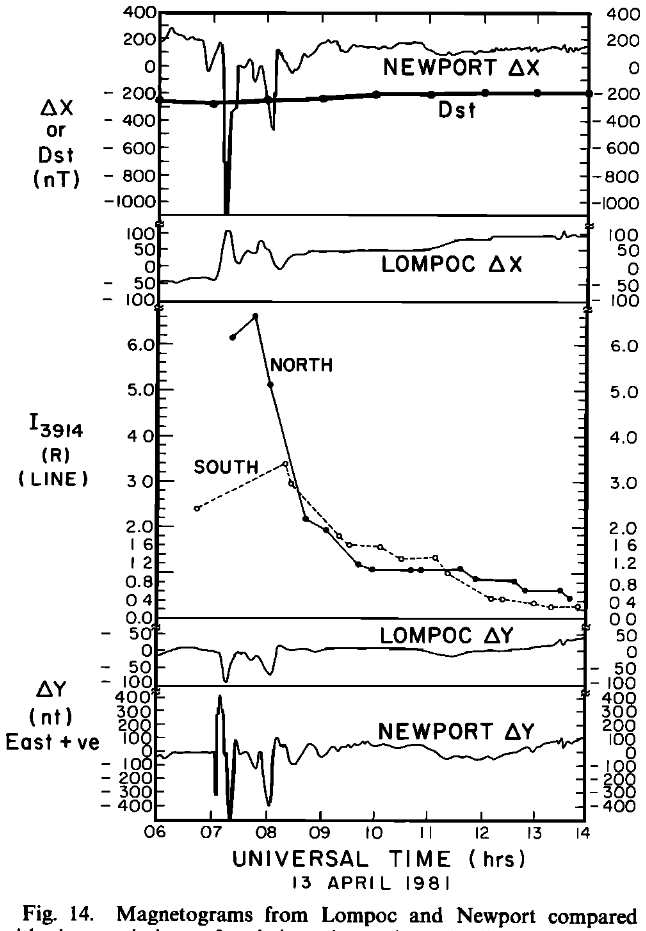

Fig. 14. Magnetograms from Lompoc and Newport compared with time variations of emission observed on April 13, 1981, from Haleakala, Hawaii.

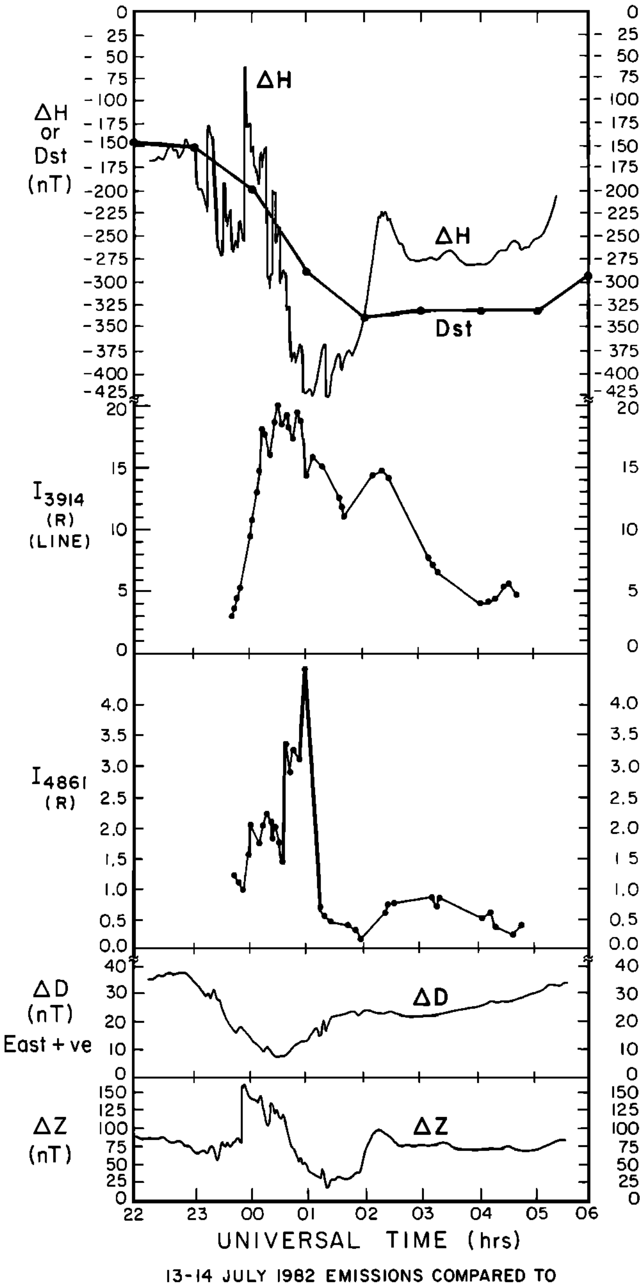

Fig. 15. Magnetograms from Vassouras, Brazil, compared to time variations of emission observed on July 13–14, 1982, from Cachoeira Paulista, Brazil.

present figures and those of *Rohrbaugh et al.* [1983], the precipitation occurs when *Dst* is large but varies with a much more rapid time scale. The close correlation with relatively localized magnetic perturbations shows that the perturbations of the trapped particles (of energy represented globally by $|Dst|$) is not global but takes place in a relatively restricted longitude range.

There is little reason to expect direct precipitation of ring current ions at sites such as Mount Haleakala and Cachoeira Paulista within 25° of the dip equator (L values of ≤ 1.2), since storm time ring current is very rarely observed inside about $L = 2$, corresponding to the limit for direct ion precipitation noted earlier at about 40° dip latitude. Hence the observed emissions can be taken as being due to energetic neutral atoms originating at several thousand kilometers altitude at mid-latitudes from the main ring current population on shells of L value of about 3, as in the model of *Tinsley* [1979]. For the July 13–14 observations at Cachoeira Paulista there was a relatively strong H Balmer β emission of 4861 Å as compared to the N_2^+ 1 N (0, 0) band at 3914 Å. This is an indication that between 0000 and 0100 UT the flux of precipitating particles consisted largely of hydrogen atoms but that the proportion decreased between 0100 and 0400 UT. The likely candidate for the dominant constituent at that time would be oxygen atoms.

CONCLUSIONS

The brighter low-latitude aurorae are found down to about 40° dip latitude, and the vibrational development of the N_2^+ 1 N bands indicates the excitation at least some of the time is due to precipitating O^+ ions with a lower limit for the mean energy of about 1 keV at 40° dip latitude, increasing to about 15 keV at 65° dip latitude. This energy increase is consistent with satellite measurement of precipitating O^+. Excitation by low-energy electrons and the resonant scattering of sunlight contribute at times to the vibrational development.

Emissions from the equator through 40° dip latitude are attributed to energetic neutral atom precipitation, which originate from charge exchange of ring current ions with exospheric hydrogen.

There are rapid variations of low-latitude auroral emissions on a time scale of ~0.1 hour, which are closely related to changes in substorm currents and involve strong perturbations of the trapped ion population and large fluxes of low-energy electrons in the thermosphere. Emission occurs at the time of positive H excursions, and first positive then negative D excursions, as recorded on magnetograms from nearby observatories. The positive ΔH at low latitudes is accompanied by the negative ΔH of large substorms as recorded at higher latitude observatories. The appearance of precipitating particles at these unusually low latitudes may be a consequence of the rapidity of the growth and decay of the unusually large substorms involved and the lack of time for shielding currents to halt the inward penetration of the electric fields driving the ions.

Further analysis of the magnetometer and other data for these events is needed to elucidate the three-dimensional current system involved that energizes and injects into the thermosphere the particle populations that give rise to these low-latitude displays.

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H. Rassoul, R. Rohrbaugh, and B. A. Tinsley, Center for Space Sciences, The University of Texas at Dallas, Box 830688, Richardson, TX 75083.

Y. Sahai and N. R. Teixeira, Instituto de Pesquisas Espaciais, Sao Jose des Campos, Sao Paulo, Brazil.

D. Slater, Battelle Pacific Northwest Laboratory, Richland, WA 99352.

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