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Observations of ion and sodium layer coupled processes during AIDA

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Abstract—Extended measurements of the neutral sodium layer using lidar and of the lower ionosphere using Incoherent Scatter Radar were conducted at Arecibo during the spring 1989 AIDA campaign. We present results from four nights of these rather extensive, almost common volume, simultaneous observations of the 80–110 km altitude region. Although in each set of results there are unique features that appear to be associated with the diverse dynamics of the atmosphere, the general nocturnal motion of both the sodium and ion layers is controlled by the tidal wind. Additionally, there is often a very strong correlation between the presence of narrow ionization and narrow sodium layers below 100 km altitude. These sporadic *E* and sporadic sodium layers usually occur at the same heights and with a sometimes striking correspondence in the details of vertical and temporal structure. These details are seen most clearly in a series of time–height plots of sodium concentration over which are overlaid the corresponding time–height trajectories of the ionization layers. Included in this series of plots are the two most spectacular of the layering events observed during AIDA. The most intense of the events occurred on the night of 30–31 March and was characterized by ion and sodium layers, with about 6 km vertical extent, that formed near 95 km altitude. During this event the sodium column content was observed to increase by a factor of about 10, from $1.5–2.0 \times 10^9$ to 20×10^9 cm^{-2}, in 90 min. The second of the major events occurred on the night of 5–6 April and was characterized by a strong vertical oscillation of the sodium layer with a peak-to-peak amplitude of 2–3 km and a period of 10.4 min. For contrast with the two major events and because of the completeness of the data sets, results from the nights of 4–5 April and 7–8 April are also given.

1. INTRODUCTION

The first simultaneous, almost common volume, Incoherent Scatter Radar (ISR) and sodium lidar measurements were made at Arecibo in January 1989 and reported by BEATTY *et al.* (1989). These measurements were the first to unambiguously link the so-called Sporadic or Sudden Sodium Layer (SSL) with sporadic *E* or low-lying Tidal Ion Layers (TILs) (MATHEWS *et al.*, 1993; companion paper). With the more extensive AIDA (Arecibo Initiative in Dynamics of the Atmosphere) campaign observations, reported here and in companion papers, we continue to explore the sporadic *E*/sporadic sodium layer linkage. The sporadic sodium layer was first reported by CLEMESHA *et al.* (1978, 1980); however, only with the observations of VON ZAHN *et al.* (1987) was the unusual nature of the SSL truly recognized. Since then observations of SSLs have been reported from Illinois, Hawaii, Norway, and Puerto Rico (KWON *et al.*, 1988; SENFT *et al.*, 1989; HANSEN and VON ZAHN, 1990; BEATTY *et al.*, 1989).

The Sporadic Sodium Layer or SSL is in some respects similar to sporadic *E* as 'seen' by the ionosonde. That is, the SSL appears over a relatively short period of time as a distinct, narrow-in-height, layer superimposed on the usual background layer of neutral sodium that extends from just above 80 km altitude to just over 100 km altitude (HANSEN and VON ZAHN, 1990). Furthermore, the time–height trajectories of SSLs (KWON *et al.*, 1988) appear similar to those of TILs (MATHEWS and BEKENY, 1979; MATHEWS *et al.*, 1993), at least at low latitudes. This result further strengthens the suggestion, made by VON ZAHN and HANSEN (1988) and others, that the neutral sodium and plasma processes are linked.

In this report we present results from four nights of a set of joint lidar and ISR measurements obtained at Arecibo during the spring 1989 AIDA campaign. In these measurements, the lidar was pointed vertically while the ISR was operated in a 'beam-swinging' mode at an 11° zenith angle. This configuration resulted in a separation of about 20 km between the radar and lidar beams at 100 km altitude. The results of these observations yield some additional hints concerning the actual chemical and dynamical processes that link the neutral sodium layer, the SSL, and the TILs and sporadic *E*. This hypothesized link is the subject of considerable attention (e.g., VON ZAHN and MURAD, 1990; HANSEN and VON ZAHN, 1990; CLEMESHA *et al.*, 1988; ZHOU *et al.*, 1993), but so far no clear picture of the process or processes involved has emerged. However, perhaps the most compelling of the hypotheses (BEATTY *et al.*, 1989) involves storage of sodium in meteoric dust or smoke particles (HUNTEN *et al.*, 1980) or in relatively simple molecular form and releasing neutral sodium via electron reactions (e.g., $NaHCO_3 + e^- \rightarrow Na + HCO_3^-$; VON ZAHN and MURAD, 1990) or via heating effects due to large electron currents flowing in the ion layers (MATHEWS *et al.*; 1993). KANE *et al.* (1993) discuss the chemistry of the 30–31 March 1989, SSL, also discussed extensively here, assuming neutral sodium production proportional to the product of the electron and source species concentrations and loss proportional to the product of sodium and neutral 'sink' species concentrations. ZHOU *et al.* (1993; companion paper) suggests the importance of a temperature-dependent mechanism and the dynamics of the mesopause region in producing both the SSLs and associated sporadic *E*.

The *D* and *E* region uses of the Arecibo ISR have been described by MATHEWS (1984, 1986), while the University of Illinois sodium lidar has been described by KANE *et al.* (1993). The lidar equation used to convert from photon counts to Na concentration as a function of altitude is exactly analogous to the Incoherent Scatter Radar equation given in the references cited above. That is, volume-filled scattering occurs and thus return signal strength falls off as range-squared. Conversion from the initial signal-plus-noise 'photon count' first involves the removal of the noise baseline and the correcting for the range-squared variation. Next the mesospheric sodium signal profile is normalized to the Rayleigh photon count over an altitude range (approximately 32–38 km) that is free of aerosols. Finally, the 'lidar constant', which accounts for lidar power, atmospheric transmission, and sodium back-scattering efficiency, is utilized to convert the normalized sodium photon count into sodium concentration. Although we follow the general guidelines for the CEDAR lidar provided by the University of Illinois, the data processing procedure is independent. In particular, the effective backscatter cross-section we use for sodium is 5.0×10^{-15} m^{-2}. In this paper we compare, in various formats, electron/ion and neutral sodium concentrations.

In Section 2 we present results from four nights of joint lidar and ISR observations of the mesosphere and lower thermosphere. We also present average sodium and ion concentrations for the entire AIDA campaign. These results provide additional insight into the relationship between mesopause region ion and sodium chemistry. Details of both the lidar and ISR operational modes during AIDA are given in KANE *et al.* (1993). Section 3 contains the summary and conclusions.

2. AIDA LIDAR/ISR RESULTS

Our analysis of AIDA joint lidar/ISR observations has, to date, concentrated on four nights—30–31 March, 4–5, 5–6, 7–8 April 1989—for which rather extensive data were obtained and which seemed interesting in terms of further exploring the SSL/ion layer linkage. In this section, we compare and contrast the sodium and ion layer properties for these nights and note that, of these four, the nights of 30–31 March and 5–6 April, have received particular attention because the events occurring during these nights seem unique. Lidar data availability during the entire AIDA campaign is summarized in figs 1–4 of the companion paper (MATHEWS *et al.*, 1993). In Section 2.4 we give some results obtained by averaging over the entire AIDA data base.

2.1. *The* 30–31 *March* 1989 *results*

Two major and, for different reasons, interesting SSL events occurred during the AIDA campaign. In Fig. 1 we give the sodium concentration and ion layer trajectory information for the night of 30–31 March 1989. The sodium concentration is indicated by color level and is plotted vs time and height with the color scale given by the vertical bar at the right, where red represents the highest concentration, 6×10^4 per cc in this case. The individual red dots give the location of peaks of the various ion layers and should be recognized as a 'detail' from the ion layer trajectory plot in fig. 2 of MATHEWS *et al.* (1993). Also shown in Fig. 1 is the average sodium concentration profile for the plot and the sodium column abundance as a function of time indicated by the left and bottom color bars, respectively. The time and height resolution of the sodium data are 60 s and 150 m, respectively, obtained by averaging from the original 30 s and 37.5 m resolution data. The height resolution for the ISR data is 600 m while the time resolution varies from 1 to 6 min depending on the phase of the observation cycle. As is obvious in the plot, the lidar results are interpolated across those intervals when the observations were interrupted, usually by clouds. Interpolated regions are identified in Fig. 2.

The sodium concentration results in Fig. 1 are dominated by the intense SSL events that span the interval from 2200 to 0000 AST near 95 km altitude. For convenience of discussion, we separate the first SSL from the second at 2300 AST, when the layer

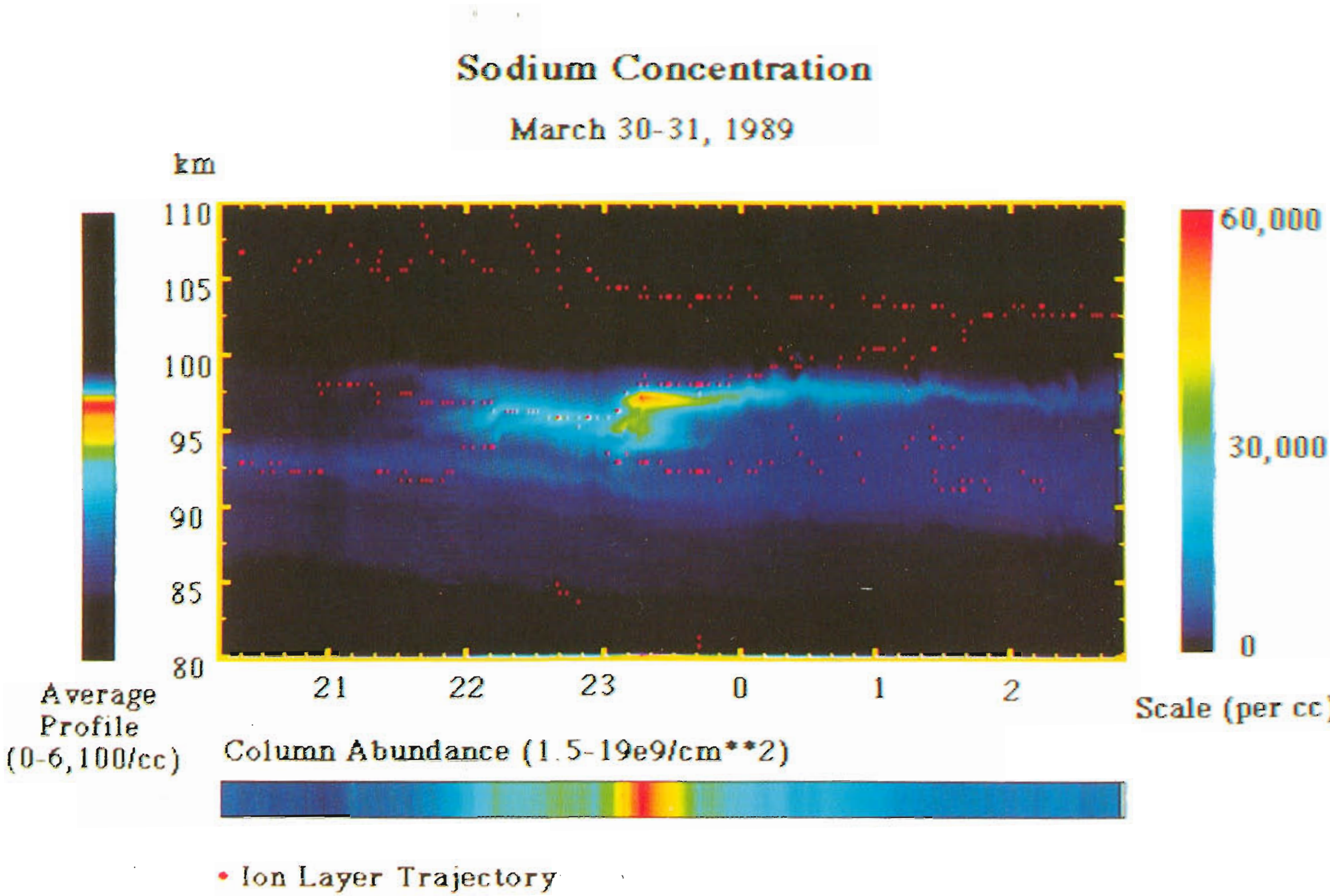

Fig. 1. Combined sodium concentration and ion layer trajectory information. The sodium concentration is indicated on the color scale with red indicating the highest concentrations. The peak of the ion layers is indicated by quantized red dots. The height resolutions for the radar and lidar are 600 and 150 m, respectively. Note that the sodium and ion layers track each other in altitude. A medium-sized Sporadic Sodium Layer (SSL) occurred at 2140 AST followed by a large SSL event at 2300 AST. Both SSL events coincide with the jumps in layer height. Missing lidar data are interpolated at times indicated in Fig. 2.

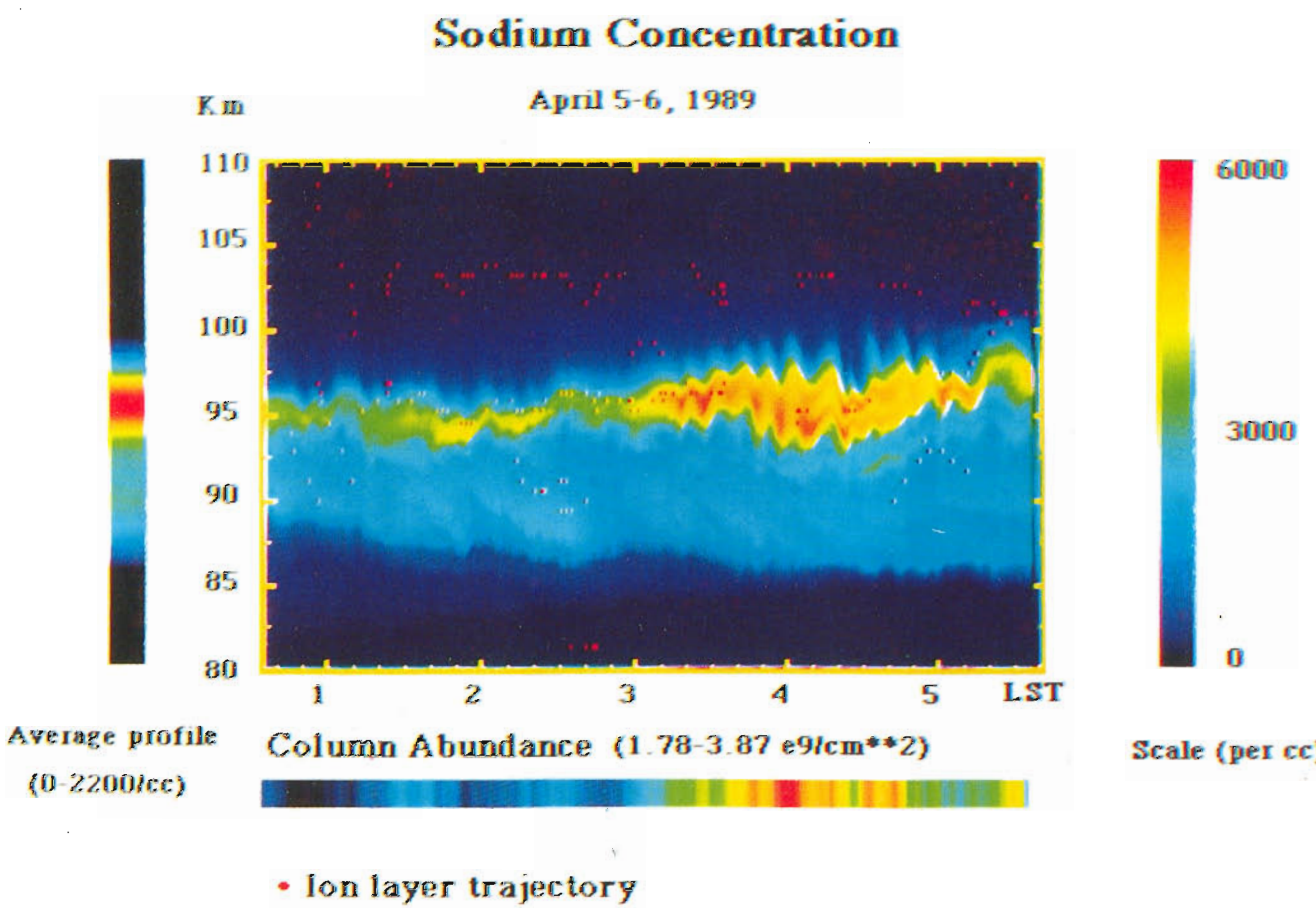

Fig. 3. Similar to Fig. 1 except for the night of 5–6 April 1989. A small SSL event occurs at about 0300 (2700) AST. Note the striking effects of an acoustic-gravity wave on the layer envelope. The period of the wave is approximately 9 min.

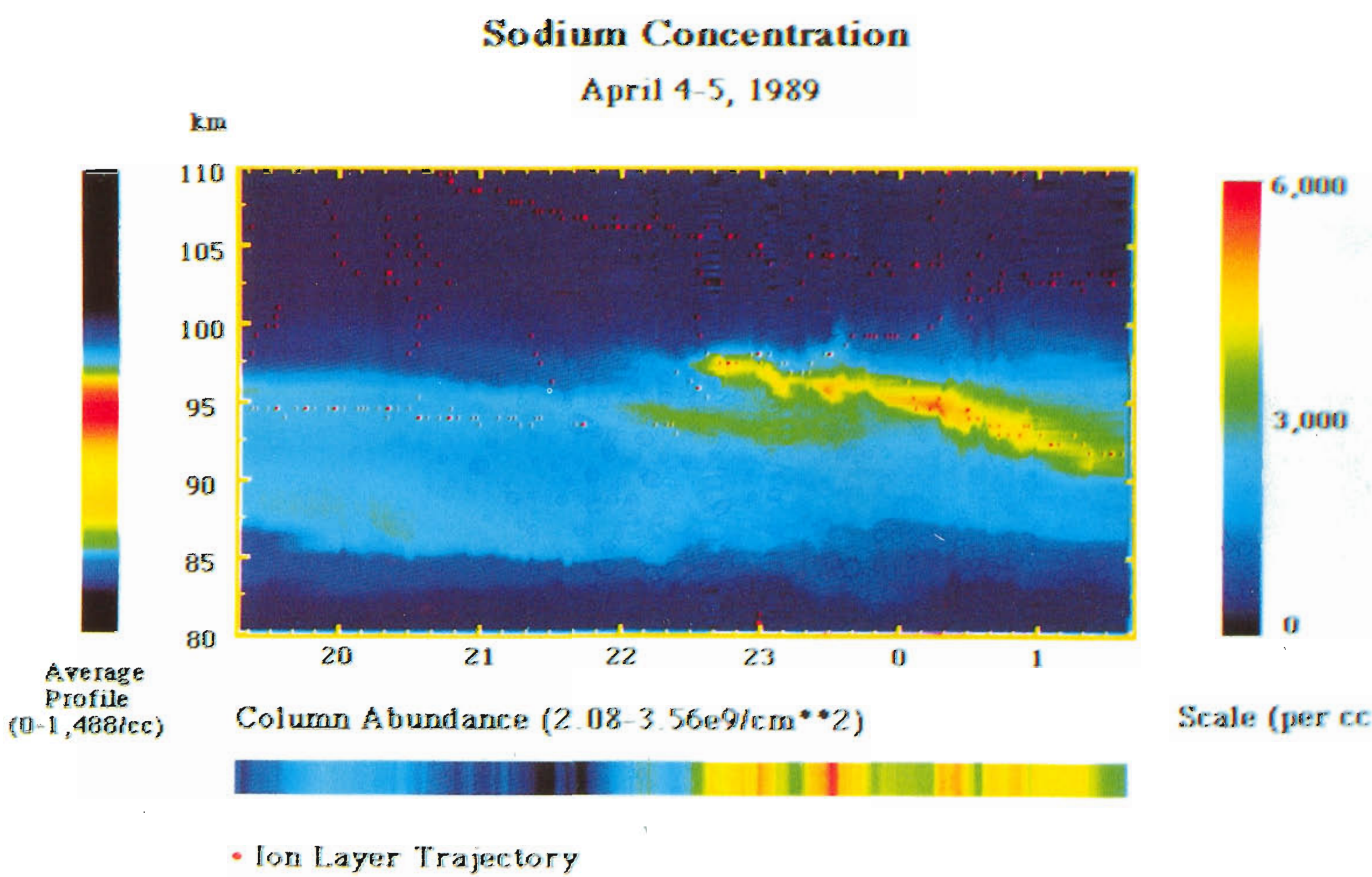

Fig. 5. Similar to Fig. 1 except for the night of 4–5 April. A moderate enhancement of sodium occurred at 2230 AST. Note that the sudden shift in ion layer trajectory accompanying the sodium increase is very similar to the events that occurred on 30–31 March 1989. Missing lidar data are interpolated at times indicated in Fig. 6.

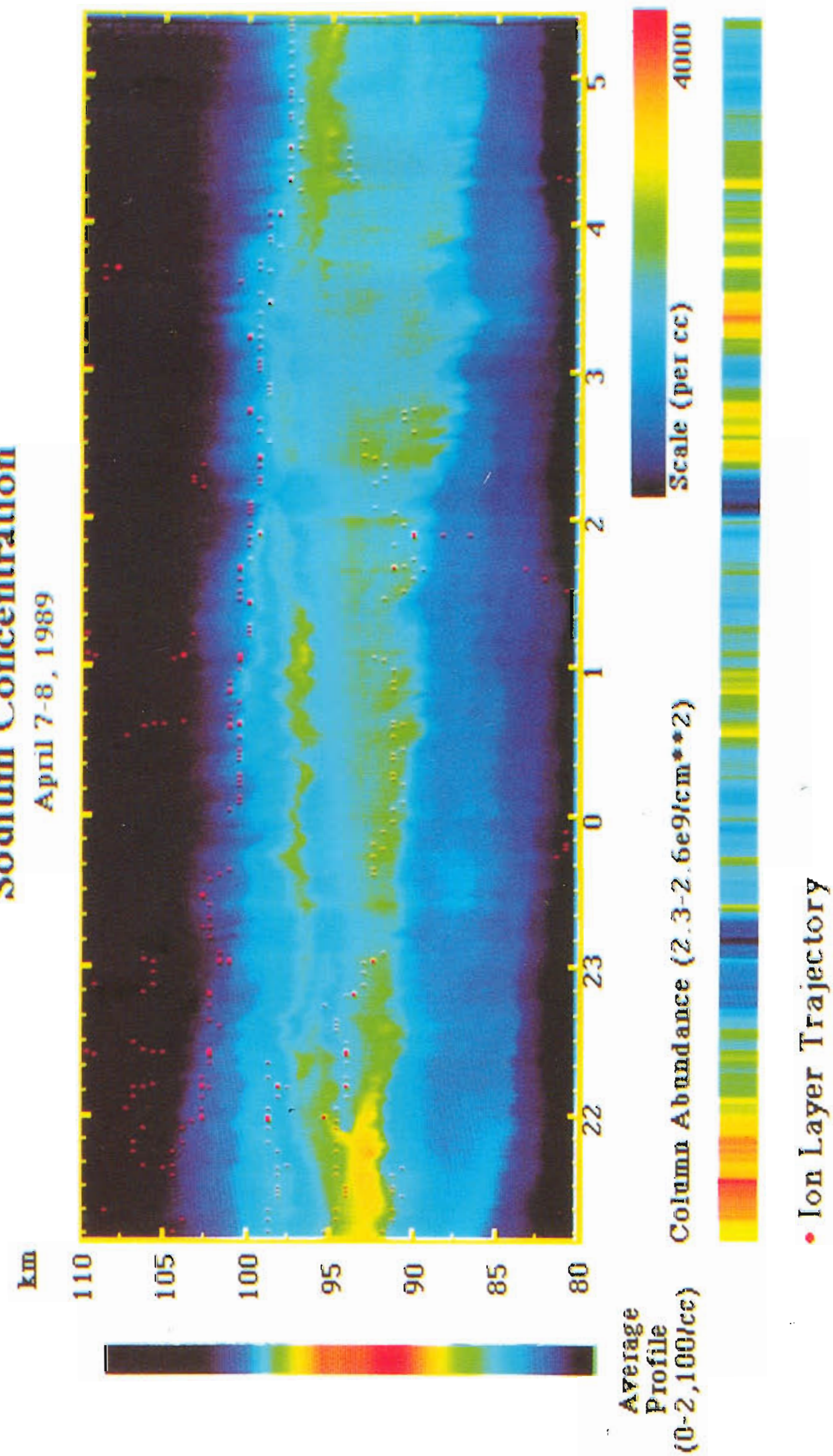

Fig. 7. Similar to Fig. 1 except for the night of 7–8 April. Many fine structures can be observed. Note the wave structure at 97 km around 100 AST has a period of approximately 10 min.

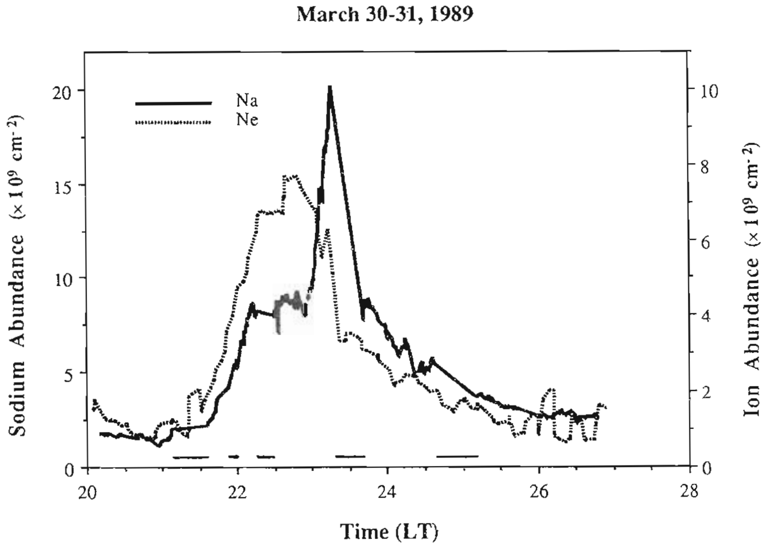

Fig. 2. Column contents for both sodium and ions over the 90–100 km altitude range. The SSLs occur at 2140 and 2300 AST and coincide with the jumps in layer height seen in Fig. 1. Note that the large SSL event that occurs at 2300 AST corresponds to an abrupt decrease in ion content. Typical peak concentrations of sodium are 3400 per cc at 2100 AST, 18,000 per cc at 2230 AST and 43,200 per cc at the peak of the SSL event. Peak ion concentrations of about 19,000 per cc are observed near 2300 AST. The times of missing lidar data are indicated by the line segments above the time axis. The column content during these periods is obtained by linear interpolation.

'jumps' in height. These results clearly demonstrate the close correspondence between the location of the ion layer peaks and the peak of the sodium layer until about 0000 AST. The ion layers near 93 and 105 km altitude are usually present, and we refer to them as Tidal Ion Layers. The ion layer that appears at 2100 AST near 96 km altitude is a sporadic layer or true sporadic *E*. This layer and the lower ion layer merge at the beginning of the SSL event, and while the lower layer reforms at 2300 AST, the ion layer associated with the peak of the SSL separates from the SSL and ultimately merges with the upper TIL. Notice that as the lower TIL first merges with and then separates from the sporadic *E* layer, the SSL splits and jumps in height. The lower TIL also corresponds to a relatively weak local maximum or layer in the sodium concentration.

Each of the ion layers in these results is presumably associated with a region of ion convergence in the wind system. However, the complexity of the layering event in Fig. 1 surely rules out pure tidal effects. Mathews *et al.* (1993) define these zones of closely spaced, multiple ion layers as Complex Layer Structures (CLS). The CLS presumably arises from multiple regions of ion convergence within a 'superposition' of tides and acoustic-gravity waves which may also be undergoing non-linear interaction. Mathews *et al.* (1993) also offer additional information on sporadic ion layer and Tidal Ion Layer (TIL) processes as well as results for the entire AIDA campaign.

Another view of the linkage between the sodium and ion processes is presented in Fig. 2, where we give the total column contents or abundances of sodium (solid line) and ions (dashed line) over the range of 90–100 km altitude. We see that the sodium and ion column contents started to increase at about 2140 AST, when the lower ion layer started moving upward and the sodium layer, which became the SSL, started to form at the height of the sporadic *E* layer. The sodium column content increased, over 40 min, from 1.5×10^9 to 8×10^9 cm^{-2} and then leveled off until the second SSL event started at 2300 AST. The absolute column contents are similar over this period.

The most unusual and, as far as we know, unique aspect of the 30–31 March event occurred after the initial SSL event with the occurrence of a second, much more intense—though certainly related—sodium enhancement. The second SSL, which occurred at about 2300 AST, was marked by the sodium column content increasing abruptly, over about 20 min, from 8×10^9 to 20×10^9 cm^{-2}. As seen in Fig. 1, the second enhancement was linked, as was the first event, to a rapid shift in the height of the sodium layer. This shift was from about 95 to 97 km and occurred in only a few minutes. This shift was matched by a similar shift in the ion layer height. Clouds then blocked the lidar beam for about 30 min, during which time the sodium content peaked and then decreased to the prior level and continued decreasing.

Unlike the first SSL event, the second event was marked by a simultaneous decrease in ion content. One proposed chemical scheme producing neutral atomic sodium involves the creation of negative ions (VON ZAHN and MURAD, 1990) and would yield an increase in sodium concentration with a corresponding decrease in electron concentration. However, as noted above, until about 2250 AST the sodium and ion contents were highly correlated even in small details. This double SSL event is also discussed by KANE *et al.* (1993).

2.2. *The* 5–6 *April* 1989 *event*

In Fig. 3 we give the sodium concentration and ion layer trajectory results for 5–6 April 1989. This figure is similar to Fig. 1 except that the peak sodium concentration is a factor of 10 smaller. As in Fig. 1, the sodium layer location and motions are closely matched by those of the ion layers. These results are remarkable in that a strong acoustic-gravity wave (AGW) or buoyancy oscillation with a period of 10.4 min is clearly seen in the envelope of the sodium layer. The periodicity is also shown in the spectral analysis reported by SENFT *et al.* (1993). Note that, unlike the 30–31 March results, no abrupt shifts in layer height are manifested.

Figure 4, which is similar to Fig. 2, gives the 90–100 km column content of ions (dashed line) for the entire night of 5–6 April, as well as the corresponding sodium column content (solid line) for that period during which lidar data were available. A small—relative to the 30–31 March events—SSL occurred at 0300 AST and was characterized by an increase of sodium column content from 1.5×10^9 to 3.4×10^9 cm^{-2}. This increase occurred over a period of about one hour and corresponded to a similar increase in the ion column content. Comparison of Figs 2 and 4 shows that the two nights are in fact rather different in character, with 5–6 April showing smooth rather than abrupt shifts in the height of the peak of both the sodium and ion layers. The preliminary view of all SSL events during AIDA indicates that the 5–6 April results are typical except for the presence of the large wave perturbation of the ionosphere and neutral atmosphere. It should be noted that a large sporadic E event occurred between 2130 and 0030 AST and could well have been accompanied by an SSL although no lidar information is available.

2.3. *The* 4–5 *and* 7–8 *April events*

Compared with the spectacular events observed on the nights of 30–31 March and 5–6 April, the results from 4–5 and 7–8 April may seem to be less interesting. However, study of these nights, which bracket the 5–6 April event, aids in understanding the 'special' events. The observational results for the nights of 4–5 and 7–8 April are shown in Figs 5–8, which follow the formats used in Figs 1 and 2. We note that many details shown in these figures resemble the large enhancements and vertical oscillations shown above, although on a much smaller scale.

The sodium concentration and ion layer trajectory results for 4–5 April, shown in Fig. 5, are very similar to those of the event that occurred on 30–31 March. That is, a CLS (Complex Layer Structure) is evident. Before 2200 AST the 95 km TIL coincides with a weak, extended sodium layer. At 2230 AST the lower ion layer is disrupted or shifted upward by about 4 km, where another ion layer forms as does a SSL. As seen in Fig. 6 this shift in ion layer height, like the one on 30–31 March, is accompanied by increases in both ion and sodium column abundances. Although the ion content increased much more than the sodium content (note the differences in scale), the sodium content change anticipated the change in ionization. This result is different from that of the 30–31 March event. However, note that in this case the sporadic E layer that formed at the height of the SSL again moved upward and joined the 103 km TIL, while another TIL formed at the height of the SSL—just above the height of the earlier TIL—at 0000 AST.

Figure 7 displays the observational results for the night of 7–8 April. Although both the sodium and ion layers show the usual bulk downward motion, many small structures are present within the sodium layer. Similar structures are present in all the data, but the low peak sodium concentration in effect enhances the small-scale features in this figure. Of particular interest is the wave structure near 96 km that occurred from 2300 to 0140 AST. This wave structure has a period of about 10 min, which is approximately the same as the one on the night of 5–6 April. The similarity of oscillations in altitude and period for the two nights hints that they may be due to the same process. We suggest a buoyancy oscillation of the local atmosphere. This night is unusual not only because of the low sodium concentrations but also because the

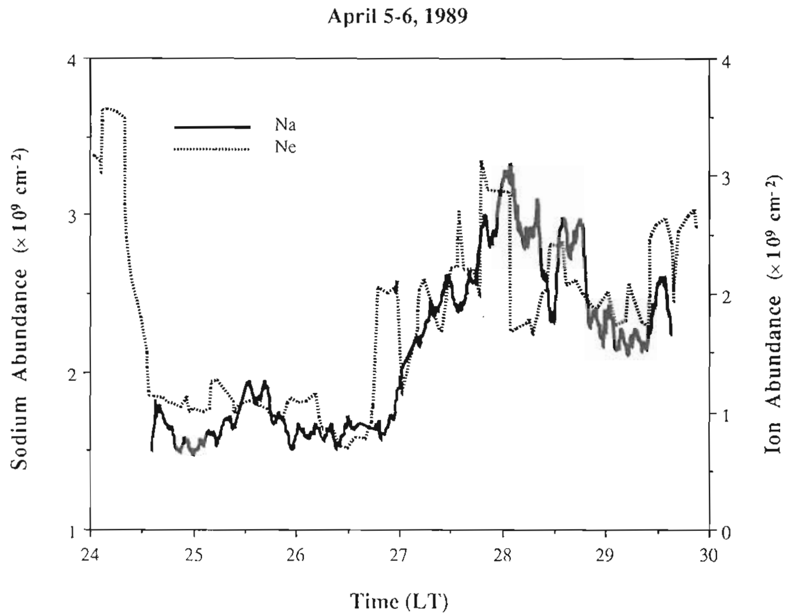

Fig. 4. Similar to Fig. 2 with a small SSL event occurring at 0300 AST. Note that column densities for this night are significantly lower than those for 30–31 March, as given in Fig. 2. A peak sodium concentration of 6000 per cc occurs near 0400 AST.

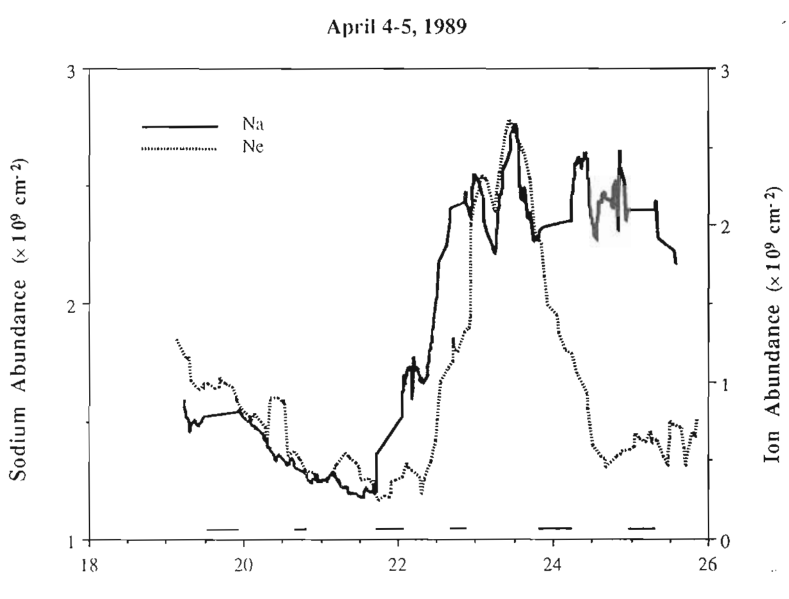

Fig. 6. Similar to Fig. 2 except for the night of 4–5 April. Note that sodium and ion concentrations show remarkable correlation before 2230 AST. The times of missing lidar data are indicated by the line segments above the time axis. The column content during these periods is obtained by linear interpolation.

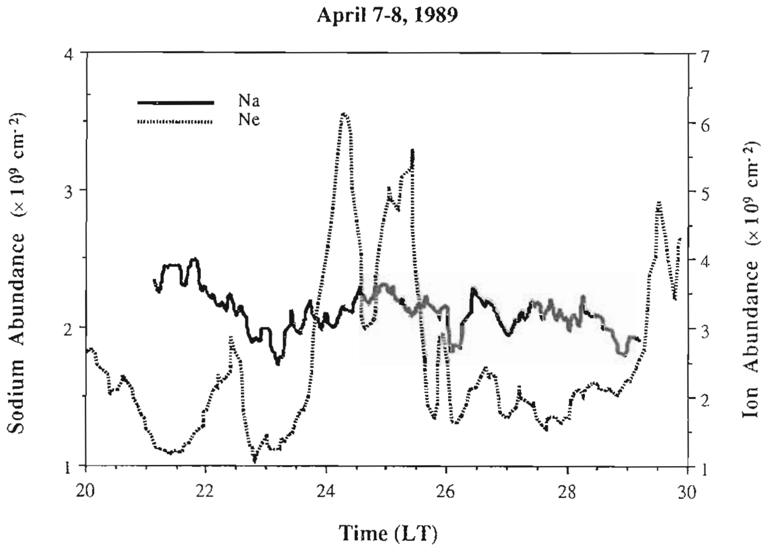

Fig. 8. Similar to Fig. 2 except for the night of 7–8 April. This is the only night that ion abundance variations are not highly correlated to the sodium abundance variations.

ion and sodium processes are largely uncoupled, as indicated by the column contents shown in Fig. 8. While all the other nights are characterized by the sodium and ion column abundances showing the same trends, the increase in ion concentration for this night is not accompanied by the same increase in sodium abundance. That is, a SSL did not occur and while the ion layer trajectories are somewhat complicated before 2200 AST, there are no converging ion layers. Hansen and von Zahn (1990) report observations of sporadic E without an accompanying SSL, but not vice versa. Note that the TILs do define 'edges' in the sodium layer.

2.4. *Some AIDA averages*

We have given some specific results from the AIDA campaign. These results strongly suggest a link between the sodium and ion processes. In an effort to give something of an overview of the AIDA results and to further test the link between sodium and ion processes, we give in Fig. 9 the average, for the 90–100 km altitude range, sodium and ion concentrations plotted vs time, from the entire AIDA campaign. The sodium average in Fig. 9 must be regarded with some care because the lidar data were not nearly so continuous as the ISR data. Thus, for example, the peak near 2300 AST in Fig. 9 is strongly weighted by the large SSL event on 30–31 March. However, the general trends exhibited by these averages are of interest. For example, the local maxima in average sodium concentration at 2300 AST and, possibly, at 0400 AST correspond to the local maxima in ion concentration that occur at nearly the same times. The ion concentration maxima correspond to the arrival at 100 km altitude of TILs that are descending at the tidal phase speed.

The correspondence between sodium and ion average concentration maxima and minima (2100 and 0200 AST) suggests a link in the two processes. Since the ions are being transported downward through the atmosphere and the sodium layer is essentially stationary, the link is apparently tied to the arrival of the ions (e.g., Na^+) or of the associated electrons. Electron processes involving sodium could include significant electron currents interacting with meteoric dust and smoke as releasing neutral sodium and/or some chemical reaction scheme directly involving electrons. Additionally, the temperature at the ion convergence zone should be a local maximum. Zhou *et al.* (1993) suggest a strong positive temperature dependence in the net production of sodium.

3. SUMMARY AND CONCLUSIONS

The results presented here provide significant additional evidence for the relationship between the ion–electron (plasma) processes and neutral sodium processes. Both sodium and ion layers are seen to descend at the phase velocity of the tidal wind in general. This suggests that the 'background' sodium

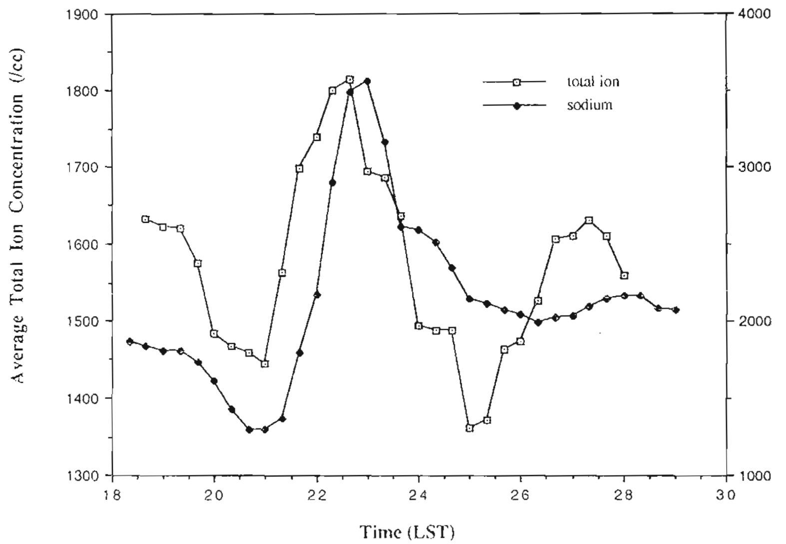

Fig. 9. The sodium and ion concentrations averaged over 90–100 km are plotted as a function of time and averaged over all data available from AIDA scene II (see fig. 1 of MATHEWS *et al.*, 1993; companion paper). The same trend of variation in sodium and ion abundances is clearly seen.

layer is coupled to tidal processes as are the ion layering processes. One possible mechanism would be temperature dependency of the sodium chemistry. However, sporadic sodium events and sporadic *E* layers are observed when the normal downward motion of the layers is interrupted. We suggest that the upward motion of the ion layers is due to the intervention of acoustic-gravity waves, a theory discussed by ZHOU (1991).

We confirm the BEATTY *et al.* (1989) conclusions that the SSLs and sporadic *E* layers occur at essentially the same heights and undergo the same motions. However, the differences between the 30–31 March and the 5–6 April SSL and sporadic *E* events suggest that this relationship has several facets. For example, the 90–100 km column content of both sodium and ions was substantially larger on 30–31 March than on 5–6 April. Both the sodium layer and the TILs showed abrupt shifts in height on 30–31 March and 4–6 April that did not occur on 5–6 April. Also the coincidence in the height of the SSL and sporadic *E* layer was not quite as close on 30–31 March as on 5–6 April. Both of these results suggest that small horizontal scale (recall that the lidar and radar beams were separated by about 20 km at these heights) irregularities were present on 30–31 March. This again points to the importance of complex dynamics in producing sporadic *E*, usually within a Complex Layer Structure (CLS) event, and sporadic sodium layers.

In general, SSL events were characterized by corresponding increases in both ion and sodium column content. However, the large SSL event on 30–31 March occurred as the ion column content decreased. The SSL then dissipated rapidly also. The dissipation of the SSL could have occurred as a result of negative ion formation with a corresponding release of neutral sodium as suggested by VON ZAHN and MURAD (1990). However, this could also be explained by the 'temperature' effects of a small-scale, intense wave process and differing sodium production and loss time constants. Additionally, the anti-correlation could also be explained, at least in part, by the 20 km separation between the lidar and radar beams.

In the case of the 30–31 March SSL event, we suggest that large electron currents, needed to maintain charge neutrality (ions are collisionally tied to the neutral atmosphere) and which must accompany 'edges' of advecting ion layers, free neutral sodium from meteoric dust and smoke in the manner suggested by VON ZAHN *et al.* (1987). Indeed, magnetometer results from San Juan at the time of this event are suggestive of some response to the SSL-associated large sporadic *E* event.

The total issue of the sporadic sodium layer/sporadic *E* link remains open. However, the relationship is firmly established as is, in our view, the role of complex dynamics—dynamics which include tidal and AGW processes.

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