Simultaneous atomic and ion layer enhancements observed in the mesopause region over Arecibo during the Coqui II sounding rocket campaign

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Abstract. The NASA Coqui II sounding rocket campaign in Puerto Rico provided the opportunity to obtain a large number of lidar and incoherent scatter radar observations of atomic sodium and ion layers in the upper mesosphere and lower thermosphere. Sodium layer enhancements, coupled with ion layers, were frequently observed in the range of 90-105 km altitude. We found that above 97 km all of the enhanced Na layers were observed to have an associated ion layer, and below that altitude some Na enhancements could occur in their absence. Finally, we show one extraordinary case of a sporadic Na layer that grew to near its peak concentration before the associated ion layer appeared at its altitude.

Introduction

Mesopause atomic layer enhancements (ALEs, a term we use to describe a broad range of such layers including, but not exclusively, sporadic and tidal layers) are frequently observed at both low [Batista et al., 1989; Beatty et al., 1989; Kane et al., 1993] and high [Collins et al., 1996; Hansen and von Zahn, 1990; Heinselman et al., 1998] latitudes by resonance lidars. They occur in the upper two-thirds of the atomic metal layer (90-110 km), and at times from 1300 until 0900 local time (LT) [Clemesha, 1995]. ALEs are generally observed in conjunction with sporadic ion layers (E_s) or tidal ion layers (TILs), but lower altitude ALEs (< 100 km) occasionally appear in the absence of ion layers. Metallic cluster chemistry [Cox and Plane, 1998], metal ion reservoirs in E, layers [Hansen and von Zahn, 1990; Heinselman et al., 1998; Matheus et al., 1993; Tepley and Matheus, 1985], dust [Gelinas et al., 1998], wind shears [Clemesha et al., 1988], tides and gravity waves [Zhou et al., 1993], and turbulence [Zhou and Matheus, 1995] may all contribute to ALE formation.

Sodium resonance lidar observations coupled with incoherent scatter radar (ISR), airglow photometry, all-sky imaging, and in-situ measurements from sounding rockets were carried out during the Coqui II study of the mesosphere and lower thermosphere (February - April, 1998). Here we consider observations made by the lidar and ISR. The purpose was to study Na ALEs observed simultaneously and, in many cases, in common volume with ion layers. We present results that can be used to assess the importance of various proposed mechanisms to better understand these phenomena. We have grouped the layers into two regions: high, meaning 100 km and above, and low (< 100 km), because the high ALEs are more often sporadic and appear to be better correlated with ion layers than the low ALEs.
Instrumentation

Sodium Resonance Lidar

The operation of the Arecibo Observatory Na lidar marked the inauguration of the new Lidar Facility. The transmitter is a Nd:YAG-pumped pulsed dye laser with a mean linewidth of 2.5 GHz and is locked to the Na \( D_2 \) line at 589 nm using a pulsed wavemeter. Its beam divergence of 0.4 mrad produces a 40 m diameter spot at 100 km. The receiver consists of a 0.8 m diameter Cassegrain telescope fiber-coupled to a GaAs photomultiplier. The lidar data are taken with a range resolution of 37.5 m and temporal resolution of 30 s. During the first half of the campaign, (13 February – 8 March), the lidar was directed at a zenith angle of 26.7° and azimuth of 11° east of north, where the rockets would pass through 100 km altitude on their uplegs. From 1 March through 2 April the lidar was vertical, parallel with and roughly 400 m NE of the ISR; an alignment we refer to as “co-aligned.”

Lidar observations began most nights before 2000 LT (UT-4) ending at 0600 the following morning. The ISR operated from 1800 to 0200 LT on the majority of nights, with extended operation on the night of 24-25 February for rocket launches, and from 23-26 March during a World Day run.

430 MHz Incoherent Scatter Radar

The majority of the ISR data taken during this campaign were taken using three modes: an 88 baud, 1 \( \mu \)s/baud code that gives 150 m resolution electron density profiles, a 13 baud, 4 \( \mu \)s/baud Barker code with 600 m resolution, and spectral measurements providing ion velocities, temperatures, and composition [Salzer, 1986]. All electron density results in this paper are from the first two data taking modes, were calibrated with our on-site ionosonde and nearfield corrected. The radar beam diameter at 100 km is roughly 300 m and the time resolution is typically 10 seconds.

Results

Table 1 summarizes ALEs and ion layers observed simultaneously. Na ALEs were observed at altitudes ranging from 91 to 104 km and times starting as early as 1900. The majority of the ALEs were accompanied by ion layers. ALEs observed without ion layers are not included in Table 1.

Figure 1. Na density and plasma frequency (proportional to the square root of the electron concentration) observations for three nights of co-aligned operations during Coqui II. The horizontal axis is local time and the vertical axis is altitude. Panel (a), from 18 March, shows lower altitude simultaneous ALE and \( E_s \) layers. Of interest on this night is that the onset of the Na layer at near 2240 LT and 96 km preceded that of the \( E_s \) layer by almost an hour. Panel (b) is from 22 March. It shows a simultaneous \( N_s \) and \( E_s \) event which occurred between 2130 and 2230 at 103 km. Visible at the top edge of the \( E_s \) layer are the descending ion layers which are linked to the sporadic layer. Panel (c), from 23 March, has examples of high (101 km at 2100) and low (96 km at 0130) coupled \( N_s \) and \( E_s \) layers, as well as a tidal ALE with no TIL that lasted throughout the observation period.

High Atomic Layer Enhancements

During 23 nights of simultaneous lidar and ISR operations, 6 ALEs were observed at 100 km or above. All were accompanied by ion layers. Five were observed while the ISR and lidar were co-aligned. One distinguishing aspect of these coupled layers was the strength of the ion layers and the high peak electron to peak sodium abundance ratio, \( N_s/[Na] \) as shown in Table 1.

Figure 1b shows a strong Na ALE, at 103 km and 2145 on 22 March. This is a classic sporadic (\( N_s \)) layer [Clemesha, 1995] accompanied by an \( E_s \) layer. This layer appeared out of a background Na concentration of less than 40 atoms \( \text{cm}^{-3} \), and the concentration rose to over 1400 atoms \( \text{cm}^{-3} \) in about 10 minutes. It remained near its peak level for close to 20 minutes before falling gradually to the background level in about 40 minutes. Figure 2 shows the time histories of the \( N_s \) and \( E_s \) layers at the altitude of 103 km where the peak abundances occurred. The electron concentration jumped over 2 orders of magnitude to form the \( E_s \) layer, which was fed by a descending layer. As the \( E_s \) layer evolved,
# Table 1. List of coincident Na and E layers

<table>
<thead>
<tr>
<th>ALE/ion layer Alt.</th>
<th>Date</th>
<th>Pk. Time (LST)</th>
<th>Duration</th>
<th>(N_e)</th>
<th>[Na]</th>
<th>(N_e/\text{[Na]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>104/104 km⁰</td>
<td>3/21</td>
<td>2030</td>
<td>1920-2100</td>
<td>21,000</td>
<td>400</td>
<td>50</td>
</tr>
<tr>
<td>103/103 km² S⁰</td>
<td>3/22</td>
<td>2145</td>
<td>2130-2230</td>
<td>72,000</td>
<td>1400</td>
<td>50</td>
</tr>
<tr>
<td>102/99 km³ S⁰</td>
<td>3/28</td>
<td>2045</td>
<td>&lt; 2030-2110</td>
<td>29,000</td>
<td>1200</td>
<td>20</td>
</tr>
<tr>
<td>101/101 km³ S⁰</td>
<td>3/23</td>
<td>2100</td>
<td>2045-2100</td>
<td>29,000</td>
<td>800</td>
<td>40</td>
</tr>
<tr>
<td>101/98 km³ S⁰</td>
<td>3/2</td>
<td>0015</td>
<td>2345-0415</td>
<td>78,000</td>
<td>5300</td>
<td>10</td>
</tr>
<tr>
<td>99/99 km</td>
<td>3/2</td>
<td>2130</td>
<td>&lt; 1900-0100</td>
<td>29,000</td>
<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>98/97 km³ T⁰</td>
<td>3/31</td>
<td>0115</td>
<td>&lt; 0030- &gt; 0200</td>
<td>29,000</td>
<td>5000</td>
<td>6</td>
</tr>
<tr>
<td>97/100 km³</td>
<td>2/22</td>
<td>2130</td>
<td>2100-0100</td>
<td>18,000</td>
<td>2000</td>
<td>9</td>
</tr>
<tr>
<td>96/96 km² S²T³</td>
<td>3/18</td>
<td>0045</td>
<td>2240-0115</td>
<td>25,000</td>
<td>4600</td>
<td>5</td>
</tr>
<tr>
<td>96/95 km² S⁰</td>
<td>3/23</td>
<td>0130</td>
<td>0110-0330</td>
<td>650</td>
<td>2000</td>
<td>0.3</td>
</tr>
<tr>
<td>96/91 km, S²T³</td>
<td>2/16</td>
<td>2145</td>
<td>2115-2300</td>
<td>42,000</td>
<td>1800</td>
<td>20</td>
</tr>
<tr>
<td>96/95 km, S⁰</td>
<td>2/20</td>
<td>2300</td>
<td>2215-0000</td>
<td>400</td>
<td>7000</td>
<td>0.6</td>
</tr>
<tr>
<td>95/94 km, T³</td>
<td>2/15</td>
<td>2300</td>
<td>2230- &gt; 0000</td>
<td>12,000</td>
<td>2400</td>
<td>5</td>
</tr>
<tr>
<td>91/90 km, S²T³</td>
<td>3/2</td>
<td>2145</td>
<td>2050-2215</td>
<td>52,000</td>
<td>3000</td>
<td>20</td>
</tr>
</tbody>
</table>

\(^a\)Lidar and ISR were co-aligned.  
\(^b\) S = Sporadic Atom Layer  
\(^c\) T = Tidal Atom Layer  
\(^d\) Started sporadic, became tidal but without a TIL  
\(^e\) Ratios are rounded to 1 significant digit
the Na concentration was close to its maximum value when the electron concentration began to rise. We saw a similar sequence for the 101 km altitude ALE and \( E_s \) at 2100 on 23 March (see Figure 1c).

**Low Atomic Layer Enhancements**

Low ALEs can have different characteristics than high ALEs. They can be sporadic and will often be associated with TILs, or they may even exist in the absence of ion layers. During Coqui II, more than 15 low ALEs were detected. For this report we considered 11: 9 that had ion layers associated with them (see Table 1), and 2 that did not and were observed while the lidar and ISR were co-aligned. Of these 11, 6 could be characterized as tidal (meaning they exhibited a steady, prolonged descent of \( \leq 1 \) km/hr). Of the 2 that were seen in the absence of ion layers, one was tidal. Using these features, we classify the Na layers into three types: non-tidal with a coincident ion layer, tidal with an ion layer, and with no ion layer.

Non-tidal layers had a lot of variety. Some descended at rates up to 4 km/hr, much faster than the tidal layers. They also showed a large range of \( N_e/[Na] \) ratios, from near 1 to 100. A non-tidal ALE is seen in Figure 1c. The panels for 23-24 March show the formation of an \( E_s \) layer and a \( N_e \) ALE just after 0100 near 96 km. The ALE displays an upward drift and waves with a 15 minute period, and the \( E_s \) layer has neither apparent drift nor waves.

A tidal layer is seen in Figure 1a, for 18-19 March.

An ALE and an ion layer formed about 2315 near 97 km and drifted downward at 1 km/hr for about 2 hours, peaking at around 0045 before dissipating. This layer is complicated by a narrow, non-tidal ALE, discussed below, which preceded the strong layer.

In Figure 1c, the Na and ISR data for 23-24 March show an example of an ALE without an associated ion layer. This is a tidal layer that lasted throughout the night, drifting from 97 km to 89 km over a period of 8 hours. From 2230 to 0000 the layer dissipated and later reformed. There was \( E_s \) and ALE activity during this period, but none of it was associated with the tidal layer. On 18 March, another ALE, this time a sporadic layer without an ion layer, formed at 96 km at 2240 as shown in Figure 1a. Its evolution is obscured by both the appearance of the tidal ALE mentioned above, which overlapped with the \( N_e \), and clouds between 2330 and 0015.

**Discussion and conclusions**

A variety of ALEs were observed by the Arecibo Observatory Na resonance lidar during the Coqui II campaign over a large range of altitudes, from 91 to 104 km, and most were accompanied by ion layers.

Among the high layers, the \( N_e \) layer of 22 March stood out. It was a strong layer that appeared at 103 km, and its concentration quickly grew to that of the bulk layer. Along with it, a descending ion-layer-fed \( E_s \) layer formed and appeared to drive the production of Na atoms. Note that at the peak abundance altitude, the \( E_s \) layer began to grow after the Na concentration had nearly reached its peak. The growth rate of the ALE, the observation of descending layers feeding the \( E_s \) layer, and their short lifetimes argue for local formation of the layers rather than a drift into the field-of-view. If the layers did develop overhead, this observation is contrary to previous observations by this group and others showing the presence of \( E_s \) as leading that of \( N_e \) in time [Beatty et al., 1989; Heinselman et al., 1998]. Its ratio \( N_e/[Na] \approx 50 \) is in good agreement with the assertion of Hansen and von Zahn [1990]. A similar phenomenon was observed in a \( N_e \) layer on 23 March. The fact that the ALE developed before the corresponding \( E_s \), together with the fact that all high ALEs were accompanied by strong \( E_s \) layers is an apparent contradiction that adds further complexity to the search for an explanation of ALEs.

We saw no relation between airglow observations of mesopause winds near 100 km or temperatures near 100, 94 or 87 km, and the formation of ALEs. On nights
where the winds diverged from the mean patterns [Bird et al., 1993] no increase in layer formation was observed.

The Coqui II sounding rocket campaign provided the opportunity for an extensive survey of enhancements in the mesopause atomic metal layer. Most of these enhancements would fit accepted definitions of sporadic layers (c.f. Clemesha [1995]; Hansen and von Zahn [1990]). There were, however, layers that exceeded the background Na concentration by factors of 1.5 or more, but did not appear suddenly nor cover a narrow vertical range. Thus, we coin the term atomic layer enhancement, or ALE. This term includes many of the enhanced tidal and sporadic layers observed, whether accompanied by or in the absence of ion layers. The data do not provide us with clear evidence for an explanation of ALEs, but it is a unique data set that may eventually help us to unravel their mystery.

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References


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