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Coincident extremely large sporadic sodium and sporadic E layers observed in the lower thermosphere over Colorado and Utah

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Abstract. On the night of 2 June 2002, the sodium lidar in Fort Collins, CO (40.6 N, 105 W) measured an extremely strong sporadic sodium layer lasting from 03:30 to 05:00 UT with several weaker layers later in the night at 06:00 and 09:00 UT. There is a double layer structure with peaks at 101 and 104 km. The peak sodium density was 21 000 atoms/cm^3 with a column abundance of up to twice that of the normal sodium layer. The peak density was 500 times greater than the typical density at that altitude. The sporadic layer abundance and strength factor were higher than any reported in the literature. The two lidar beams, separated by 70 km at this altitude, both measured 0.6 h periodicities in the abundance, but out of phase with each other by 0.3 h. There is also evidence for strong wave activity in the lidar temperatures and winds. The NOAA ionosonde in Boulder, CO (40.0 N, 105 W) measured a critical frequency (f_oE_s) of 14.3 MHz at 03:00 UT on this night, the highest value anytime during 2002. The high values of total ion density inferred means that Na^+ fraction must have been only a few percent to explain the neutral Na layer abundances. The Bear Lake, Utah (41.9 N, 111.4 W) dynasonde also measured intense E_s between 02:00 and 05:00 UT and again from 06:00 to 08:00 UT about 700 km west of the lidar, with most of the ionograms during these intervals measuring E_s up to 12 MHz, the limit of the ionosonde sweep. Other ionosondes around North America on the NGDC database measured normal f_oE_s values that night, so it was a localized event within North America. The peak of E_s activity observed in Europe during the summer of 2002 occurred on 4 June. The observations are consistent with the current theories where a combination of wind shears and long period waves form and push downward a concentrated layer of ions, which then chemically react and form a narrow layer of sodium atoms.

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1 Introduction

Sporadic sodium layers (Na_s) are narrow (a few km thick) layers, generally on the topside of the sodium layer at ∼90–110 km altitude. There have been many previous observations of Na_s (Kwon et al., 1988; Batista et al., 1989; Senft et al., 1989; Nagasawa and Abo, 1995) and Collins et al. (1996) described the highest abundance Na_S layer reported to date with an abundance of 50% of the normal layer. Previous observations at 40° N in Illinois had suggested that there was a midlatitude deficit of sporadic layers compared to low and high latitudes (Beatty et al., 1988; Senft et al., 1989).

The current best theory for the formation of sporadic sodium layers is that sodium ions are concentrated by wind shears interacting with the electrodynamics to form a narrow ion layer, which is then pushed downwards with the downward phase propagation of most waves and tides (Cox and Plane, 1998; Collins et al., 2002). The chemical lifetime of Na^+ decreases rapidly with decreasing height. When the Na^+ is pushed to an altitude where the chemical lifetime is short enough, the Na^+ is converted into atomic Na, which is then detected as a narrow layer by the lidar. The height of conversion ranges from roughly 103 to 95 km, depending on a number of factors such as atomic oxygen concentration and temperature (Collins et al., 2002).

Sporadic E layers are unusually dense regions of ionization that occur within the E region and reflect radio frequencies varying from 2 to 30 MHz. They have been observed for over 70 years, but are still not fully understood. The best known theory for midlatitude sporadic E by Smith and Miller (1980) proposes that wind shears produced by atmospheric

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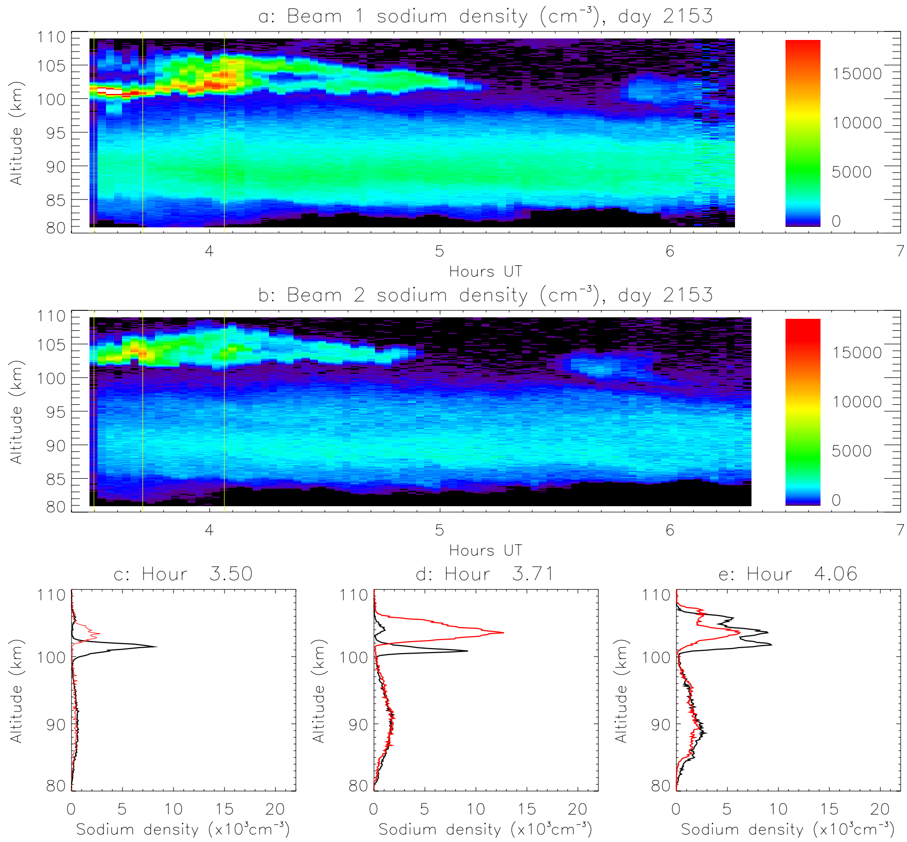

Fig. 1. Sodium density contours for both beams and altitude profiles at three times (marked by yellow lines) for beam 1 (black) and beam 2 (red).

waves interact with magnetic fields to cause ions to converge at one height and then descend with the phase of the wave. Recently, a wind shear-driven dynamo in the E_s layer has been investigated by Cosgrove and Tsunoda (2002). This dynamo is postulated to be driven by a Kelvin-Helmholtz instability that can distort the mid-latitude E_s layer. A strong correlation with sporadic Na layers is expected and has been widely observed (von Zahn and Hansen, 1988; Kirkwood and von Zahn, 1991).

2 Instrumentation

2.1 Sodium lidar

A recent discussion of the narrowband sodium lidar technique and the science enabled is given in (Arnold and She, 2003). This lidar has been operated routinely by Colorado State University in Fort Collins, Colorado (40.6 N, 105 W) since 1991. The lidar measures sodium density, temperature, and zonal and meridional wind from 80–105 km altitude using 2 beams. Beam 1 was pointed 30° east of zenith and beam 2 was pointed 30° north of zenith. This gives about a 70 km horizontal distance between the 2 beams at 100 km altitude. The transmitted power is 0.5 W per beam and the receiving telescope diameter is 0.35 m. The lidar transmits 3 frequencies to sample the thermal width and Doppler shift of the resonance scattering spectra of the sodium layer. The time/height resolutions were 2 min/150 m for sodium density and 15 min/1 km for temperature and wind.

2.2 Ionosondes

The Bear Lake, Utah ionosonde is operated by Utah State University. at 41.9 N latitude and 111.4 W longitude. The Boulder, Colorado ionosonde is operated by NOAA at latitude 40.0 N and longitude 105 W. The ionosondes sweep in frequency and record the time-of-flight and frequency of reflections over a range extending from 70 to 750 km altitude, as well as many other ionospheric parameters. From the critical frequency (f_0E_S), they can infer the electron density. The time-of-flight represents the virtual height which needs to be corrected to obtain the actual height of the layer. However, in the E-region the retardation is small, especially when the E-region is not sunlit so that the virtual and true heights are effectively identical. Operating as an MF (Medium Frequency) radar, the Bear Lake dynasonde also measures the

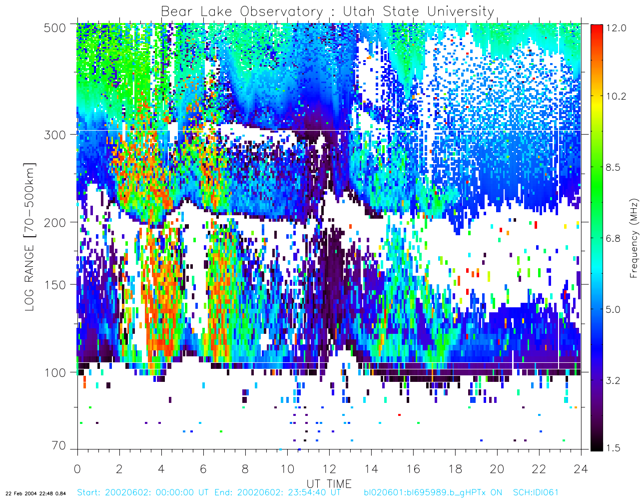

Fig. 2. Contour plot of the Bear Lake ionosonde reflection frequency.

mesospheric winds during the time interval between swept-frequency soundings (Jones et al., 2003).

3 Observations

When the lidar was started after dark on 2 June 2002 for a day/night campaign, a strong sporadic sodium layer was already present in both beams. In Fig. 1, we show the sodium density for beam 1 and beam 2 as a function of UT time and altitude. The sporadic layer was apparent at about 103 km altitude lasting for about 1.5 h. Both beams showed a double layer structure most of the time. The sporadic layer lasted until about 05:00 UT with a weaker reappearance from 05:30 to 06:12 UT. The Boulder and Bear Lake ionosondes were both operational that night. The NOAA Boulder ionosonde measured an f_oE_s of 14.3 MHz at 03:00 UT on this night, the highest value during 2002. The Bear Lake, Utah dynasonde also measured intense Es between 02:00 to 05:00 UT and again from 06:00 to 08:00 UT about 700 km west of the lidar, with most of the ionograms during these intervals measuring f_0E_s up to 12 MHz, the limit of the ionosonde sweep. Other ionosondes within North America included in the NGDC database measured normal f_oE_s values that night, so it was a localized event within North America. There was high activity reported in Europe, however. Figure 2 shows the height of reflection for different ionosonde transmitted frequencies at Bear Lake. The two areas of high frequency returns are apparent from 02:00–05:00 and 06:00–08:00 UT.

Figure 3 shows the evolution of the peak Na density, Na abundance, ionosonde critical frequency, and peak altitudes of the sporadic Na, normal Na, and sporadic E layers. The peak density was 21 200 sodium atoms/cm^3 at 102 km for beam 1, versus 12 700 cm^{-3} for beam 2. The Boulder f_oE_s peaked at 14.3 MHz at 03:00 UT with smaller peaks at 04:30 and 05:00 UT. The abundance showed a large oscillation with a period near 0.6 h. The oscillation in the two beams was out of phase, which may indicate that the horizontal wavelength of the wave perturbation was about 140 km, but this depends strongly on the direction of wave propagation. The abundance of the sporadic layer was roughly equal to the normal layer on average, with excursions up to twice the abundance of the normal sodium layer. The strength factor is often used in the literature and is defined as the ratio of the peak sporadic layer density to the typical density at the altitude. The normal sodium density at 102 km is 3040 cm^{-3}, giving a strength factor of over 500 for beam 1. As far as we know, this was the highest strength factor reported in the literature.

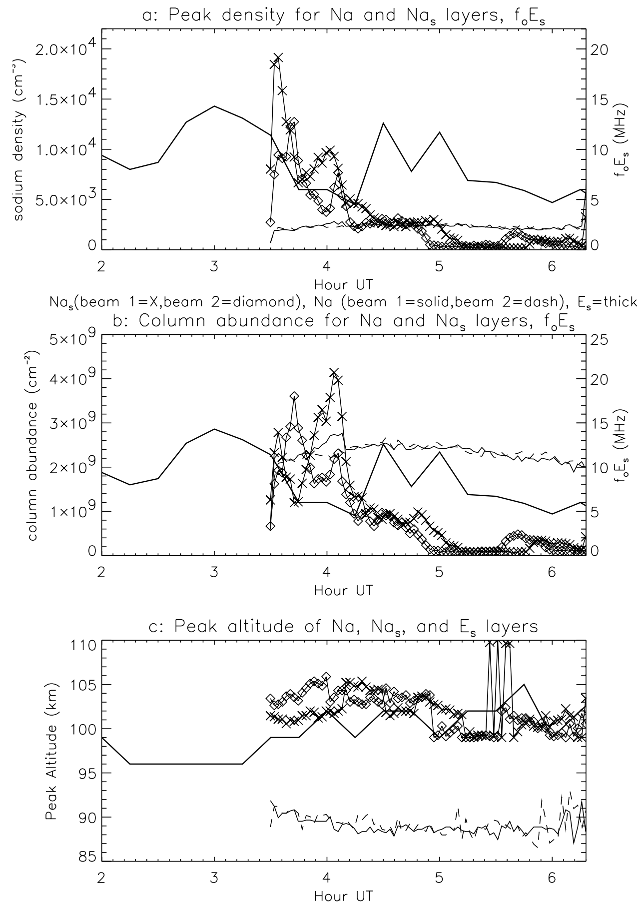

Fig. 3. **(a)** Peak sodium density for the sporadic and normal layers for beam 1 (x) and beam 2 (diamonds). The thick line is f_oE_s. **(b)** Same as (a) for column abundance. **(c)** same as (a) for peak altitude.

The altitudes of the peak densities for the normal and sporadic layers are shown in Fig. 3. The altitude of the normal sodium layers in the two beams was typical and ranged from 90 to 88 km. The sporadic sodium layer showed a double layered structure and was higher than the sporadic E layer from 3.5–05:00 UT. The height of the sporadic E layer had descended from 120 km to 96 km the evening before (not shown).

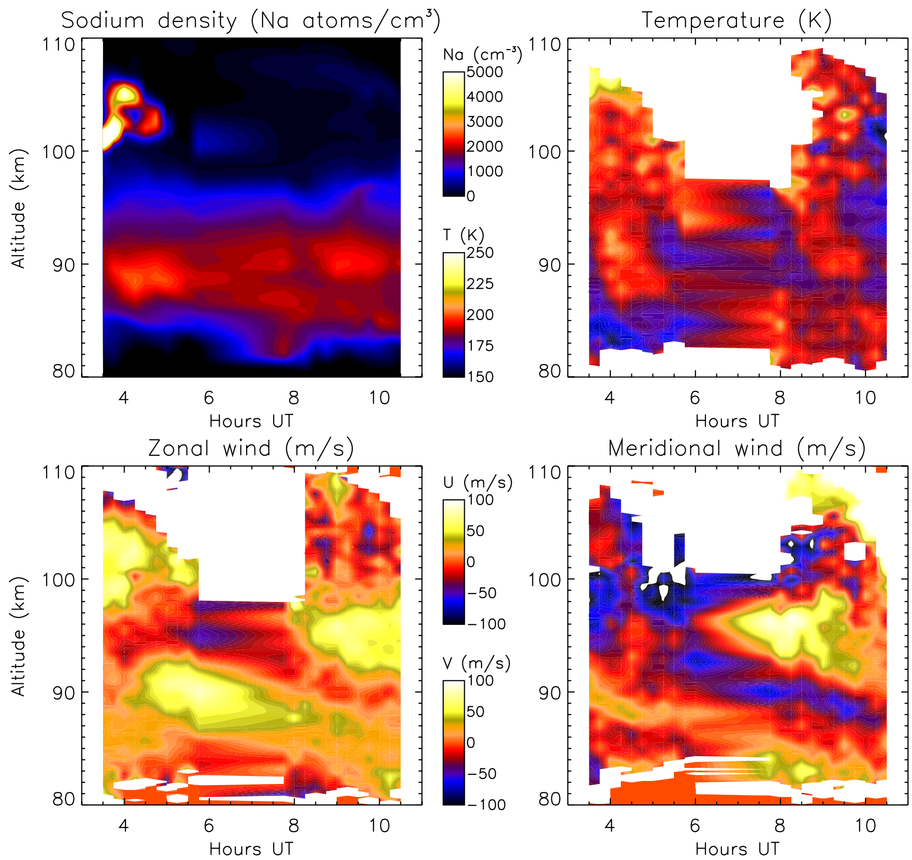

Fig. 4. Contour plots of density, temperature, and zonal and meridional winds with 15 min and 1 km resolution.

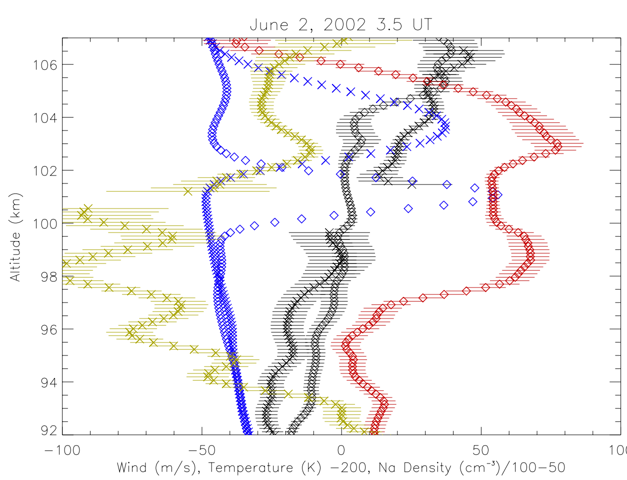

Fig. 5. Profiles of density (blue), temperature (black), and zonal (red) and meridional (green) winds with 15 min and 1 km resolution at 3.5 UT for beam 1 (x's) and beam 2 (diamonds).

The zonal and meridional winds showed strong and complicated wave fields with possibly both downward and upward phase progression (Figs. 4, 5). The winds had a strong southward flow of 80 m/s from 95–100 km and an eastward flow of 60 m/s from 98–104 km due to a large vertical wavelength wave. This large scale wave produced large wind shears and downward phase progression which some theories suggest are related to sporadic E layer formation (Smith and Miller, 1980; Kirkwood and von Zahn, 1991). The meridional wind also had a 2 km vertical wavelength wave of 25 m/s amplitude. This wave was present in the temperature but not in the zonal wind, suggesting meridional propagation. This wave likely caused the double peak in the sporadic sodium layer. The temperature data had lower wave activity with shorter period waves more apparent. There was no large temperature enhancement associated with the sporadic Na layer. The temperature just increases smoothly with latitude into the thermosphere in a typical fashion. The sodium density had variations at several periods, ranging from 1 h to 5 h.

4 Discussion and conclusions

The ionosonde critical frequency can be related to electron density, N_e, with the formula: N_e=1.24×10$^4 f_p^4$ (cm^{-3}), with f_p denoting the plasma frequency in MHz. For the maximum frequency measured by the Boulder ionosonde of 14.3 MHz at 03:00 UT, N_e=2.5×10^6 electrons/cm^3. The limiting frequency at Bear Lake of 12 MHz corresponds to 1.7×10^6 e$^-$/cm^3. The frequency was 11.4 MHz or 1.6×10^6 e$^-$/cm^{3}at 3.5 UT when the sodium density reached its peak in beam 1. The ratio of N_e to Na density was 75 for beam 1 at 3.5 UT and 35 for beam 2 at 3.75 UT, assuming the sporadic layers are horizontally uniform and we should compute the ratio at the same time. If instead we think the variations are wave induced and we should use the peak electron and sodium densities regardless of time, the ratio was 118 for beam 1 and 197 for beam 2. If we assume the total ion density was equal to the electron density and that the atomic sodium was produced from sodium ions, the sodium ions then constituted between 0.5% and 3% of the total ions on this night. In the literature, it has often been assumed that sodium ions comprise about 5–35% of the total ions (Kopp, 1997). Even though this was a very large sporadic sodium layer, the sporadic E layer was even larger, so there should have been an abundance of sodium ions present that could be converted to neutral sodium. Several previous reports have suggested that there were not enough sodium ions available to produce the larger Na_S layers observed (Kane and Gardner, 1993), but that probably was not the case here.

The peak densities in the sporadic sodium layers on this night were large but not unprecedented. The layers were very thick, so the total abundance was the largest we have measured in over 10 years over Fort Collins. The peak electron density as inferred from f_oE_s was very high, though, so if the sodium ion density follows the electron density, there is likely a sufficient reservoir of Na^+ for the formation mechanism proposed by Cox and Plane (1998). There was a significant meridional wind shear, but not an unusually high temperature or large temperature shear during the sporadic layer event. There were significant wave perturbations at periods ranging from 0.6 to 5 h and vertical wavelengths as short as 2 km. This night represented an extreme case, but the observations are still consistent with the current theories for the formation of sporadic E and sporadic sodium layers from ions concentrated into narrow layers by the wind shear mechanism.

This sodium layer was larger than any of the sporadic layers detected in six years of observations (2000–2006) in campaign mode at 69° N by the Weber sodium lidar at the ALOMAR observatory in northern Norway. We did see a number of medium strength sporadic sodium layers at ALOMAR during the summer of 2002 (Williams et al., 2006, 2004; She et al., 2006). A preliminary investigation of the CSU data looked at 46 days with 696 total hours from April to June 2002 and June to August 2003. Of these days, sporadic layers were present on 30 days. We saw 36 separate sporadic layers lasting 134 total hours, so 65% of days and 19% of hours had sporadic layers. This is a much higher occurrence rate and a larger peak abundance than was seen in the many hours of observation by the sodium lidar in Illinois in the 1980s (Senft et al., 1989), possibly indicating a large interannual or decadal variability in the sporadic layer occurrence rate. More recent observations in Japan by Nagasawa and Abo (1995) at 35° N and by Gong et al. (2002) at 31° N showed a similar occurrence rate as in Colorado in summer 2002–2003. To understand the interannual, seasonal, and latitudinal variations better, we will need to calculate the occurrence rate for the rest of the more than 9000 h of data from the CSU lidar taken between 1990 and 2006.

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