

WAVE-ASSOCIATED SPORADIC NEUTRAL LAYERS IN THE UPPER ATMOSPHERE

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Sporadic neutral layers, with thicknesses between a few hundred meters and several kilometers, are observed by lidar in the same height range as ionospheric sporadic E. Ns layers were first observed in sodium, 20 years ago, and more recently have also been seen in potassium, iron and calcium. As in the case of Es there is a strong link with atmospheric waves, and a number of studies have shown evidence for a possible connection with tidal oscillations in the lower thermosphere. Recent observations at São José dos Campos, Brazil, have shown that sporadic sodium layers are frequently observed to occur at the heights of peaks in sodium concentration corresponding to a propagating atmospheric wave. In cases where the vertical wavelength of the propagating wave is short, as many as three complete oscillations can sometimes be seen, and the sporadic layer always occurs at the highest wave maximum, typically in the range 95-100 km. In the case of long-lived events the Ns layer is observed to accompany the downward phase propagation of the atmospheric wave. On the basis of these observations a case is made for the recombination of sodium ions as the source of the observed sporadic layers.

Key words: Ns, Es, Sporadic layers, Sporadic-E, Sodium

CAMADAS NEUTRAS ESPORÁDICAS NA ALTA ATMOSFERA ASSOCIADAS COM ONDAS ATMOSFÉRICAS - *Camadas esporádicas neutras, com espessuras entre algumas centenas de metros e vários quilômetros, são observados por radar de laser na mesma faixa de altura que a E-esporádica ionosférica. Camadas Ns foram observadas pela primeira vez em sódio, 20 anos atrás, e mais recentemente foram observadas em potássio, ferro e cálcio. Como no caso de Es existe uma ligação forte com ondas atmosféricas, e vários estudos mostraram uma possível conexão com oscilações de marés na baixa termosfera. Observações recentes em São José dos Campos mostraram que camadas de sódio esporádicas frequentemente ocorrem nas alturas dos picos da concentração de sódio produzidos por uma onda atmosférica. Em alguns casos, onde o comprimento de onda vertical da oscilação é curto, pode-se identificar até 3 oscilações completas, sendo que a camada esporádica sempre se forma no pico de altura maior. Nos casos de eventos de longa duração, observa-se uma propagação da camada Ns no sentido de alturas menores, acompanhando a propagação de fase da onda atmosférica. Baseado nestas observações propõe-se que a recombinação de íons de sódio seja responsável pela formação das camadas esporádicas.*

Palavras-chave: Ns; Es; Camadas esporádicas; E-esporádica; Sódio

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INTRODUCTION

Sporadic neutral layers (Ns) were first observed in sodium, twenty years ago by Clemesha et al. (1978), and have subsequently also been seen in calcium (Granier et al., 1985, Alpers et al., 1996), iron (Bills & Gardner, 1990, Alpers et al., 1993) and potassium (von Zahn, private communication, 1996). The definition of what constitutes an Ns layer is necessarily somewhat subjective, but it generally involves a layer of metal atoms between a few hundred meters and a few kilometers thick, with a concentration equal to or greater than twice that of the background metal layer which in the case of sodium, for example, has a typical width of around 10 km. An example of a typical Na_s layer observed at São José dos Campos (23° S, 46° W) is shown in Fig. 1. In extreme cases the peak atom concentration can be more than 10 times that of the background. In one case, observed by von Zahn et al. (1988), almost the entire sodium profile was concentrated into a layer only a few hundred meters thick. In the following sections we present some of the principal observed characteristics of Ns layers, and discuss some of the mechanisms suggested as being responsible for their formation. We shall then present some recent observations of Na_s layers associated with wave propagation, and make

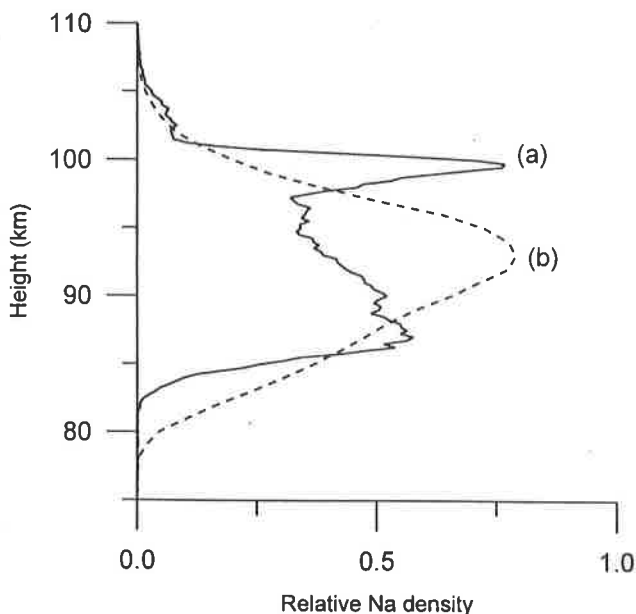


Figure 1 - Typical Ns layer (After Clemesha et al., 1996)

Figura 1 - Camada Ns típica (Fonte: Clemesha et al., 1996)

a case for the recombination of metallic ions as the source of sporadic neutral layers. Note that in this paper we shall use the abbreviation "Ns" to refer to sporadic neutral layers generically, and abbreviations such as "Na_s" to refer to sporadic layers of specific metals.

CHARACTERISTICS OF SPORADIC METAL LAYERS

Composition: Ns layers have been observed in sodium, iron, calcium and potassium, but it is probable that they exist in other metals such as magnesium.

Height: Ns layers are mainly observed at heights above 90 km, in the upper part of the normal layer. Fig. 2 shows the height distribution of Na_s layers observed at São José dos Campos, together with a long-term average for the normal sodium layer. A rather similar distribution was reported by Hansen & von Zahn (1990) for observations made at Andoya (69° N, 16° E), except that these workers saw many more observations above 100 km, mainly in winter.

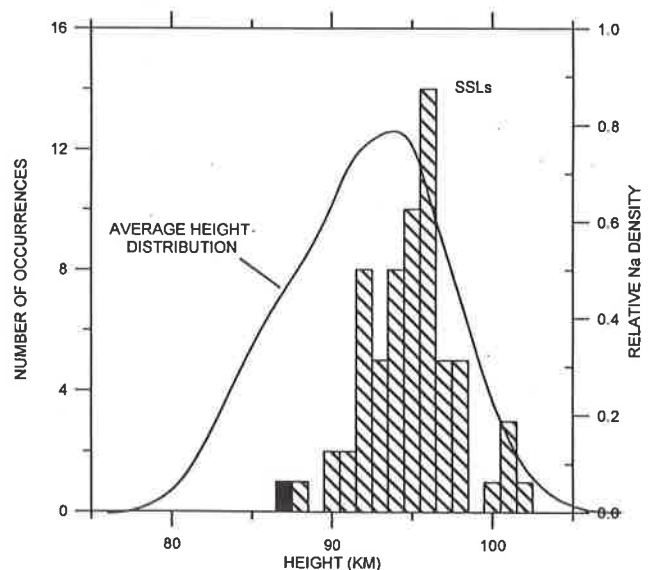


Figure 2 - Height distribution of sporadic sodium layers observed at São José dos Campos (After Clemesha, 1995)

Figura 2 - Distribuição em altura de camadas esporádicas de sódio observadas em São José dos Campos (Fonte: Clemesha, 1995)

Local time of occurrence: The time of occurrence appears to vary considerably with the location of the observations. Hansen & von Zahn (1990) found the layers to be concentrated close to local midnight, leading them to suggest a link with auroral particle precipitation. At São José dos Campos, on the other hand, Batista et al. (1989) found only a small diurnal variation. The distributions reported for these two locations are illustrated in Fig. 3.

Motion: The heights of Ns layers typically, but not invariably, fall with time. Fig. 4 (a) shows a superposed plot of the height/time histories of Na_s layers observed at São José dos Campos, showing a typically downward trend. At this location the average height of occurrence was also found to decrease during the night, as can be seen from Fig. 4 (b). Batista et al. (1989) found the typical vertical velocity to be about 1 km/s, and Kwon et al., (1988), at Mauna Kea (20° N, 155° W), found rates typically twice this value. There are, however, many individual examples where the layer has been seen to remain constant in height, or even to rise. Horizontal motions appear to have been studied only at São José dos Campos, where Batista et al. (1991), on the basis of observations made using a steerable lidar, found velocities up to 200 m/s, but the higher velocities are probably exaggerated by the assumption of horizontal isotropy involved in the analysis.

Horizontal structure: The steerable lidar measurements of Batista et al. (1991) indicated sizes between 186 km and 2235 km, with an average of 645 km for 10 measurements. As in the case of the measured velocities, the higher values may well be exaggerated by the analysis technique, so the median value of 420 km is probably a better indication of typical horizontal dimensions for Na_s layers at São José dos Campos. Kane et al. (1991) have made airborne observations of Na_s layers with horizontal extents of about 1800 km. Two such layers were observed with similar dimensions, one during a North-South flight, and the other on an East-West flight. Both flights started at Maui, Hawaii (21° N, 156° W).

Seasonal variations: Different seasonal variations have been observed at different sites. Measurements at Andoya (Hansen & von Zahn, 1990) and at São José dos Campos (Batista et al., 1989) show little seasonal variation in the occurrence of Na_s layers, although the Andoya measurements do show many more layers at heights above 100 km in winter than in summer. More recent observations by Nagasawa & Abo (1995), at a site close to Tokyo (36° N, 139° W), indicate a strong seasonal variation with

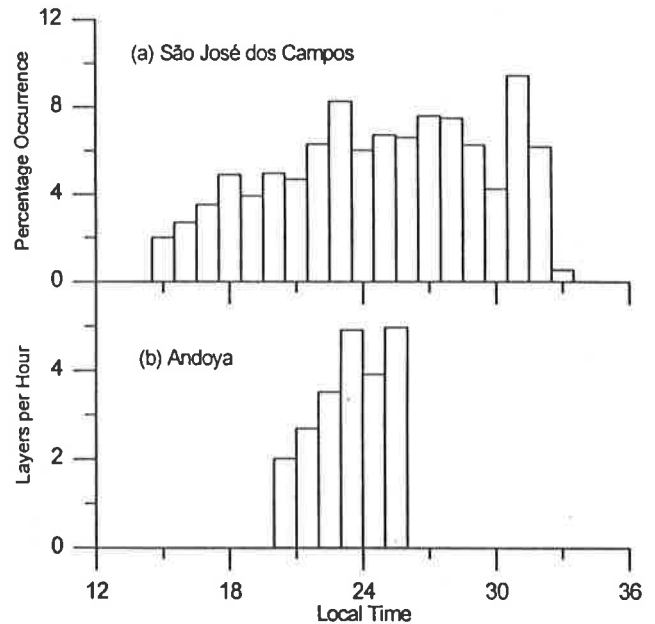


Figure 3 - Occurrence times of Ns layers observed at: (a) São José dos Campos (after Batista et al., 1989); (b) Andoya (after Hansen & von Zahn, 1990)

Figura 3 - Hora de ocorrência de camadas Ns observadas em: (a) São José dos Campos (Fonte: Batista et al., 1989); (b) Andoya (Fonte: Hansen & von Zahn, 1990)

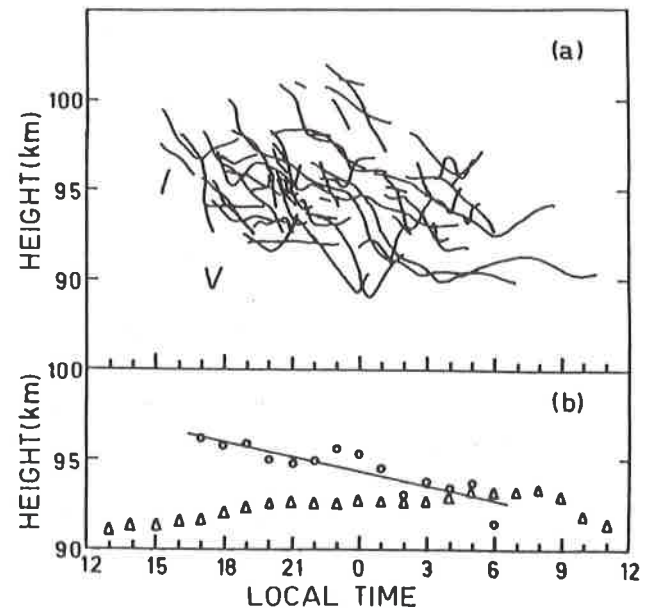


Figure 4 - Vertical motion of Ns layers observed at São José dos Campos (after Batista et al., 1989)

Figura 4 - Movimento vertical de camadas Ns observadas em São José dos Campos (Fonte: Batista et al., 1989)

maximum occurrence in June and July. Observations sufficiently extensive to determine a seasonal variation in Ns layer occurrence have not been made at other sites so, for the time being, we do not have a consistent picture of this variation.

RELATIONSHIP BETWEEN NS LAYERS AND OTHER ATMOSPHERIC PHENOMENA

Correlations between the occurrence of Ns layers and other atmospheric phenomena have been observed in a number of studies. A brief survey of these correlations is given below.

Meteor showers: When Clemesha et al. (1978) reported the first observation of a Na_s layer they suggested that it was the result of the ablation of a single large meteor. In the light of more recent observations this explanation for the origin of Ns layers now seems highly improbable but this does not rule out a possible relationship with meteoric deposition. Only two groups appear to have studied this possibility: Hansen & von Zahn (1990) found that 41 out of 75 Na_s layers observed at Andoya occurred shortly after enhanced meteor activity, but they state that this is not statistically significant; Batista et al. (1989) found some increase in Ns layer occurrence shortly after the Eta-Aquarids in May, the Perseids in August and the Orionids in October. Thus there appears to be some, but certainly not conclusive, evidence for a correlation with meteor showers.

Sporadic-E layers: A correlation between the occurrence of Ns and Es was first noted by Clemesha et al. (1980) and has subsequently been confirmed by many studies (von Zahn & Hansen, 1988; Alpers et al., 1993; Mathews et al., 1993; Nagasawa & Abo, 1995). Fig. 5, from Nagasawa & Abo (1995) shows that Na_s layers were typically seen about 20 minutes after the observation of Es on an ionosonde located 12 km from the lidar site. On the other hand the relationship is far from being 1 to 1. On a number of occasions Ns layers have been seen without the observation of Es on a nearby ionosonde (Alpers et al., 1993). In the same experiment, however, the last named workers observed very similar vertical profiles of Fe and Fe^+ in a sporadic layer. It can be concluded that Ns is undoubtedly related to sporadic-E although, at a given location and time, the presence of one does not necessitate the existence of the other.

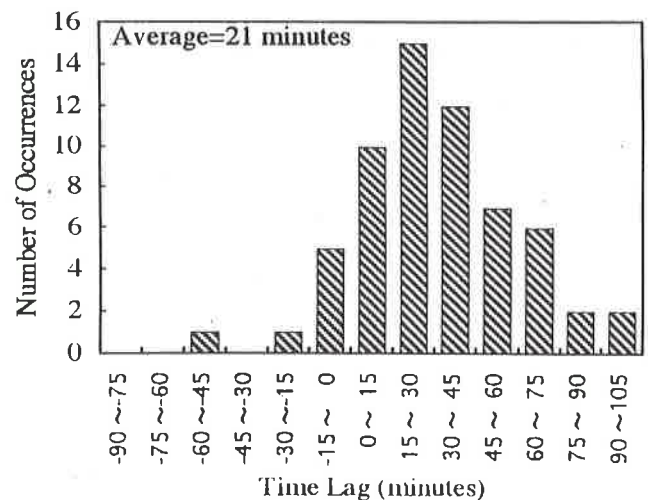


Figure 5 - Statistics of time of occurrence of Ns layer with respect to Es layers (after Nagasawa & Abo, 1995)

Figura 5 - Estatística da hora de ocorrência de camadas Ns relativa à ocorrência de camadas Es (Fonte: Nagasawa & Abo, 1995)

Winds: Observations of the vertical profile of horizontal winds have been made simultaneously with the observation of Ns layers in a number of cases. Alpers et al. (1993) did not see a close relationship between Ns layers and wind-shear, but on one occasion Gardner et al. (1995) found a very similar height-time history for a Na_s layer and the height of maximum vertical shear in the horizontal wind, the Na_s layer occurring about 2 km above the height of maximum shear. The relationship between sporadic-E layers and wind-shear is complicated by the presence of electric fields and, if Ns layers result from the neutralization of metallic ions, this complication would extend to the Ns layers as well.

Temperature: A relationship with atmospheric temperature has been observed in a number of experiments. Alpers et al. (1993) found sporadic iron layers to occur close to the minimum of the vertical temperature profile, and Hansen & von Zahn (1990) found the same behavior for sodium. On the other hand, Gardner et al. (1993) observed a Na_s layer to closely follow the height of maximum temperature associated with a gravity wave (see Fig. 6, reproduced from Gardner et al., 1993). On another occasion Gardner et al. (1995) saw no correlation between the height of an Ns layer and the temperature profile.

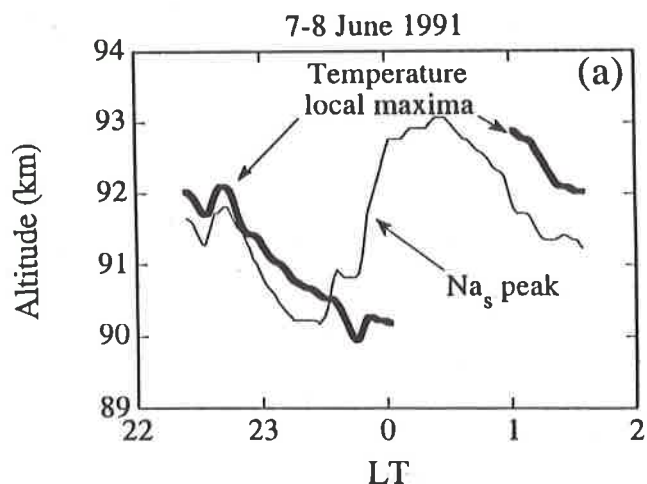


Figure 6 - Time histories of the height of a sporadic Na layer and the height of a local temperature maximum (after Gardner et al., 1993)

Figura 6 - Variação temporal da altura de uma camada esporádica de sódio e da altura do máximo local de temperatura (Fonte: Gardner et al., 1993)

MECHANISMS SUGGESTED FOR THE GENERATION OF NS LAYERS.

A number of different mechanisms have been suggested as being responsible for the generation of Ns layers.

Recombination: An obvious possibility is that Ns layers are produced by the neutralization of metal ions. This is an attractive hypothesis because it can explain the formation of thin layers and the relationship to Es. Sporadic neutral layers would result from the neutralization of thin metallic ion Es layers produced by the well-established wind-shear mechanism (Whitehead, 1961), in which electrodynamic forces, produced by tidal or gravity wave induced motion of ions relative to the geomagnetic field, causes their accumulation at certain locations in the wind field. In the case of sodium this mechanism has generally been rejected because most ion mass spectrometer measurements show Na^+ concentrations much smaller than the observed Ns layer densities. This is not the case for Fe, where Fe^+ concentrations appear to be sufficient to explain the occurrence of sporadic Fe layers. Alpers et al. (1993), in an experiment in which rocket measurements of ion composition were made simultaneously with lidar observations of Fe, found a ratio of 1.75 between Fe^+ and

Fe in a sporadic layer. On the other hand, in the same experiment a sporadic Fe layer was observed for more than an hour without sporadic-E being observed by an ionosonde installed at the same site as the lidar. The possibility that high altitude Na_s layers, where the total sodium required is small, could be produced by neutralization of ions has been discussed in some detail by Hansen & von Zahn (1990) and Kane et al. (1993), and these workers make a convincing case for the ion recombination mechanism for Ns layers observed above 100 km. On the other hand, Collins et al. (1996) have reported the observation of a large Na_s layer centered on 109 km, in which the total abundance of sodium was, according to these authors, too large to have been produced by this mechanism. Despite the difficulty of the lack of sufficient Na ions, this mechanism still appears to be worthy of further study. The observation of a Ns layer without a corresponding Es layer does not necessarily constitute a fatal objection because the layer could have formed some time before its observation, by which time the most of the ions could have recombined. It should also be remembered that few mass spectrometer measurements of ion composition have been made in the lower thermosphere. Kopp (1997) has reviewed such measurements, and out of 5 experiments one, made during the Perseid meteor shower, showed a peak Na^+ concentration of 10^4 cm^{-3} , sufficient to explain most Na_s layers. Another rocket experiment, reported by Kirkwood & von Zahn (1993), also measured a peak Na^+ concentration of about 10^4 cm^{-3} . Thus it seems that sufficiently high sodium ion concentrations to explain the formation of Na_s layers can exist in thin layers associated with sporadic-E. A second objection to the ion recombination mechanism, frequently quoted in the literature, is that the recombination rates for metallic ions are too slow to explain the observed growth rates of Ns layers. As pointed out by Clemesha (1995), the observed rapid growth rates could well represent not the formation of neutral metal atoms, but the advection of a cloud of neutrals of limited horizontal extent over the observing site, so the required growth rates could be fairly modest. It should also be pointed out that Plane (paper presented at the Equatorial Atmosphere-Ionosphere Interactions Symposium of the 1997 IAGA meeting) has shown that dissociative recombination of molecular ions formed by reactions between metallic ions and atmospheric molecules are very fast at heights below 100 km.

Direct meteor deposition: In the first report of a sporadic sodium layer, Clemesha et al. (1978) suggested

that the origin of the excess sodium must be direct deposition from the ablation of individual large meteors. In a later paper, Clemesha et al. (1988) suggested a mechanism whereby an initially thick layer, caused by meteor deposition could be converted into a thin layer by wind-shear. In the light of more recent measurements direct meteor deposition seems unlikely. Kane et al. (1991) have pointed out that their airborne measurements show that Ns layers can exist over horizontal extents of several thousand km, and the direct meteor deposition mechanism is inconsistent with this observation. It is also difficult to see why this mechanism should lead to the behavior reported in the previous section, and the association of Ns layers with a displaced background layer, as reported in Clemesha et al. (1996).

Atmospheric aerosols: von Zahn et al. (1987) suggested that the sporadic sodium layers which they observed at Andoya could be caused by the liberation of sodium from aerosol particles by auroral particle bombardment. Although there is no experimental evidence for the existence of such aerosols, Hunten et al. (1980) have suggested that "smoke" particles, produced during the ablation of meteors, could play an important role in the atmospheric sodium layer. Two problems with this mechanism are that it will not work for middle and low latitudes, and that Es and Ns layer formation is not well correlated with particle precipitation (Kirkwood & Collis, 1989).

A variation on the aerosol mechanism, proposed by Beatty et al. (1989), is that Ns layers could be produced via the formation of cluster ions generated by collisions between Es ions and dust particles. In yet another variation on this theme, Kirkwood & von Zahn (1991) have suggested that charged dust particles could be lifted to Es layer heights by electric fields, and that the interaction between the high-density plasma in the Es layer and the aerosol particles would result in the release of free sodium. In favor of these mechanisms is the necessary correlation with sporadic-E, in agreement with the experimental evidence, and the fact that the incoherent scatter measurements at Arecibo occasionally indicate the presence of layers of negative ions of large mass which could be charged dust particles or large cluster ions. It is also possible to imagine that such a mechanism might produce thin dust layers at a height where the electrodynamic forces counterbalance sedimentation. On the other hand, there is no direct evidence for the existence of dust particles at the heights in question, and

the mechanism whereby free metal atoms could be liberated from these particles is poorly understood.

Chemical sources: von Zahn & Murad (1990) have suggested that the process $\text{NaHCO}_3 + e \rightarrow \text{Na} + \text{HCO}_3^-$ could be a source for sporadic Na layers. This mechanism was proposed following the suggestion by Murad & Swider (1979) that the formation of NaHCO_3 could be an important sink for atmospheric sodium, and the determination by Ager III and Howard (1987) of a high rate coefficient for the reaction $\text{NaOH} + \text{CO}_2 + \text{M} \rightarrow \text{NaHCO}_3 + \text{M}$. On the other hand, none of the atmospheric models for the sodium layer indicate that there would be anywhere near enough NaHCO_3 at the required heights to explain the formation of sporadic sodium layers. Furthermore, this mechanism does not explain one of the primary characteristics of Ns layers, their small vertical extent, nor is it consistent with the relationship with atmospheric waves reported in this paper. Rajasekhar & Plane (1993) have made a detailed study of the chemistry involved in this mechanism, and do not make a convincing case for its viability.

Temperature dependent mechanisms: Zhou et al. (1993) have suggested that Ns layers might be caused by temperature fluctuations produced by gravity waves and/or tides. In a later paper Zhou & Mathews (1995) suggest that this mechanism might operate through turbulent heating consequent upon gravity wave breaking. They point to the large seasonal variation in sodium abundance as evidence for a strong temperature dependence in the sodium chemistry. There appear to be two major problems with this mechanism: firstly, recent models of the sodium layer (Helmer & Plane, 1993) indicate very little temperature dependence of the sodium concentration on the topside of the layer; secondly, simultaneous measurements of the vertical temperature profile and Ns layers do not show a consistent relationship between the two (Alpers et al., 1993).

Redistribution of the background layer: Kirkwood & Collis (1989) have suggested that sporadic sodium layers could be caused by redistribution of the background layer by large amplitude vertical winds associated with gravity waves, the existence of which is suggested by incoherent scatter measurements. There are two fatal flaws in this mechanism: 1) all the experimental evidence indicates that Ns layers result from additional atoms, not a redistribution of the existing layer; 2) for the mechanism to work, the mixing ratio of the minor constituent must increase with height on the topside of the layer, but all the experimental evidence shows that it decreases.

NS LAYERS AND WAVE PROPAGATION

There is a great deal of evidence for a connection between Ns layers and atmospheric waves, some of which has been briefly referenced above. The measurements of Gardner et al. (1995), Hansen & von Zahn (1990), Hecht et al. (1993) and Gardner et al. (1993) all show the existence of a relationship between the vertical motion of Ns layers and atmospheric wave propagation in terms of temperature or winds. A good example of a Na_s peak tracking the height of maximum temperature in a propagating wave is shown in Fig. 6. Unfortunately no very consistent picture has emerged from these studies.

Clemesha et al. (1996) showed that the shape of the background sodium layer during the occurrence of Na_s layers at São José dos Campos is different to that of the average layer. During the occurrence of Na_s the background layer typically peaks below 90 km, whereas the average layer has its peak at around 93 km. Fig. 1 shows an example of this. A possible explanation of this shift of sodium to lower heights is that Na_s layers are related to tidal activity, and that the shift represents a given phase in the tidal oscillation. The effect of atmospheric tides on the background sodium layer has been studied in some detail by Batista et al. (1985). That Ns layers might be related to tidal oscillations has been emphasized in a recent paper by Zhou & Mathews (1995), who comment that "The evidence for the generation of SSLs by tides seems to be very strong. The strong local time dependence of SSLs (Kwon et al., 1988; Hansen & von Zahn, 1990) and, more compellingly, the large horizontal extent exhibited by SSLs (Kane et al., 1991) clearly suggest that tides play a very important role". Zhou & Mathews (1995) suggest that Ns layers could result from heating in thin turbulent layers generated by the breaking of gravity waves or tides. With respect to the role of tides, they point to the correlation between Ns layer occurrence and sporadic-E, and to the fact that some forms of the latter appear to be produced by the accumulation of ionization in thin layers via tide-related windshear. In our 1996 paper (Clemesha et al., 1996) we concluded that there was insufficient information for us to decide whether the change in shape of the main layer during the occurrence of Na_s is the result of tidal/gravity wave modulation, or whether it is the result of a loss of sodium on the topside of the layer. In the following paragraphs we present new observations, showing a strong link between Ns layer formation and the propagation of atmospheric waves.

In 1996 we made a number of observations at São José dos Campos with higher time and height resolution than we had used in the past. During these observations, with 250 m resolution in height and 3 minutes in time, a number of Na_s layers were observed. Fig. 7 (a) shows the height-time history of the sodium layer observed at São José dos Campos on the night of June 13/14, 1996. In order to show more clearly the strong wave propagation present in these observations the data have been filtered by taking a 2 km/10 min running mean. Fig. 7 (a) shows the presence of a propagating wave with 6 km vertical wavelength and an apparent period of 12 hours. Fig. 7 (b), an unfiltered average profile for 2337 to 2343 LT, shows the presence of a strong Na_s layer located at the upper wave maximum. The significant point about this observation is that the Na_s layer occurs exactly at the peak of a coherent wave structure which lasts for at least 9 hours. That this is not an isolated

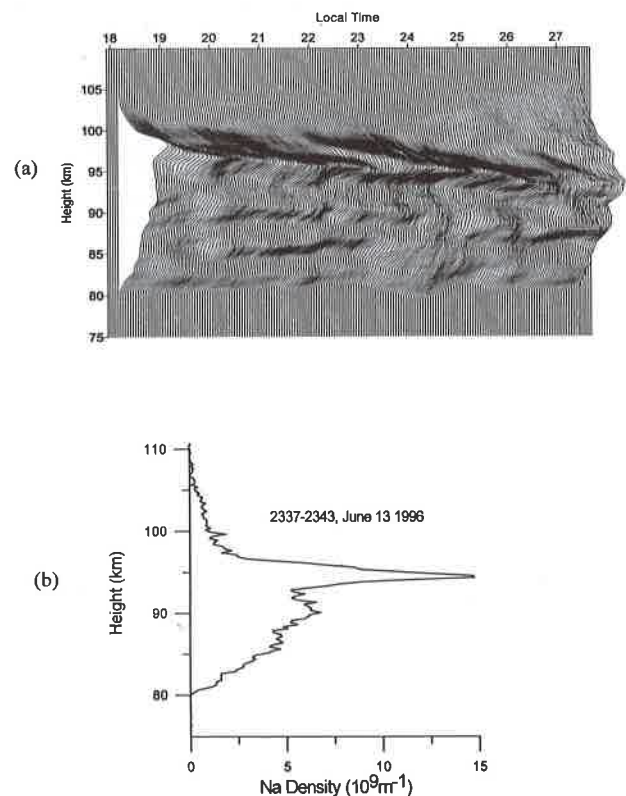


Figure 7 - (a) Time history of vertical distribution of Na for June 13-14, 1996; (b) Na_s layer observed at 2340 LT.

Figura 7 - (a) Variação temporal da distribuição vertical de sódio, 13-14 de junho de 1996; (b) camada Ns observada às 2340 hora local.

coincidence is shown by the further examples of this type of behavior given in Figs. 8 and 9. In each case a Na_s layer occurs at a peak in a long-lived oscillation in the sodium layer. It appears that similar behavior has been observed at other locations: Hansen & von Zahn (1990), for instance, report an example of a Na_s layer apparently tracking the height of peak Na density in a gravity wave observed at Andoya, and Gardner et al. (1993) observed a sporadic iron layer which closely tracked the height of what they consider to be a gravity wave-induced perturbation of the atmospheric sodium layer.

Not all Na_s layers observed at São José dos Campos are associated with wave propagation, as can be seen from Fig. 10, where a short-lived Na_s layer shows no obvious relationship to wave activity in the sodium layer. On the

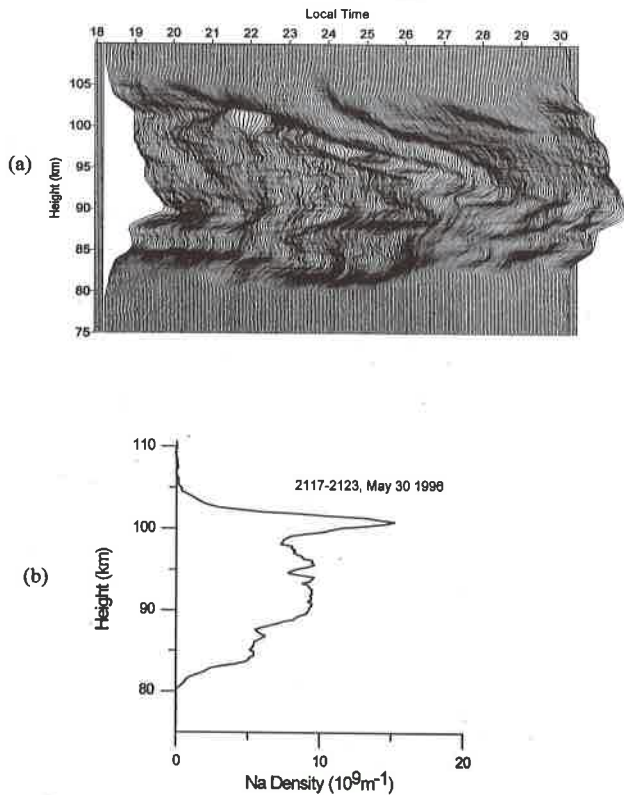


Figure 8 - (a) Time history of vertical distribution of Na for August 6-7, 1996; (b) Na_s layer observed at 2248 LT.

Figura 8 - (a) Variação temporal da distribuição vertical de sódio, 6-7 de agosto de 1996; (b) camada Na_s observada às 2248 hora local.

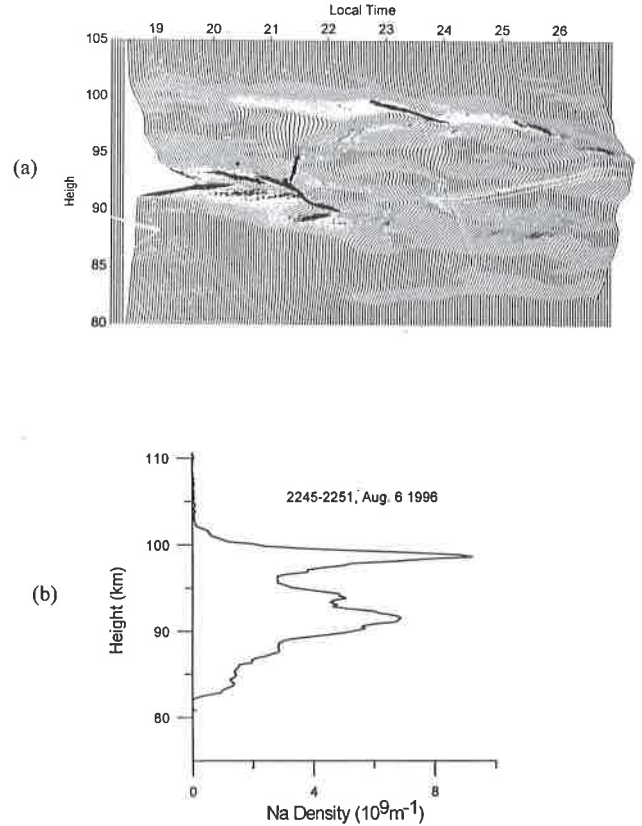


Figure 9 - (a) Time history of vertical distribution of Na for May 30-31, 1996; (b) Na_s layer observed at 21:20 LT.

Figura 9 - (a) Variação temporal da distribuição vertical de sódio, 30-31 de maio de 1996; (b) camada Na_s observada às 21:20 hora local.

other hand, the occurrence of Na_s layers close to the peak of a propagating wave in the sodium layer does seem to be a common feature in our observations. An example of this appeared in one of the earliest publications on sporadic sodium layers (Fig. 2 from Clemesha et al., 1980). It is often difficult to decide whether a peak in the sodium layer represents a sporadic layer, or simple modulation of the sodium distribution by an atmospheric wave. This is well illustrated in Fig. 11, where we reproduce two Na profiles, one from Gardner et al. (1986) and the other from Gardner et al. (1993). One of these was presented as showing the presence of a sporadic sodium layer, and the other as showing gravity wave modulation of the background sodium layer. At least at first sight it appears that there is no clear division between a simple wave modulation of the layer, where the principal effect is the interaction between

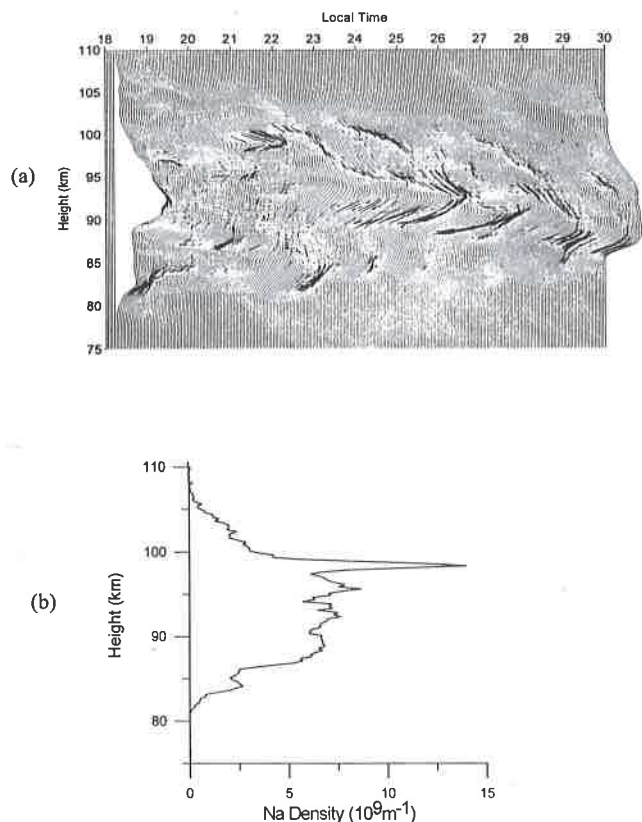


Figure 10 - (a) Time history of vertical distribution of Na for May 31-June 1, 1996; (b) Na_s layer observed at 2042 LT.

Figura 10 - (a) Variação temporal da distribuição vertical de sódio, 31 de maio - 1 de junho de 1996; (b) Camada Na_s observada às 20:42 hora local.

the vertical displacement associated with a wave and the vertical gradient in mixing ratio of the minor constituent, and an additional mechanism that appears to amplify the modulation on the upper side of the layer.

DISCUSSION

The question which must now be asked is what sort of mechanism is consistent with the observed behavior? The well-documented relationship between the occurrences of Ns and Es layers, together with the generally accepted wind-shear mechanism for the formation of some types of sporadic-E, already suggests that wave propagation might be one of the causative factors in the formation of Ns. The new results presented here make this relationship even more

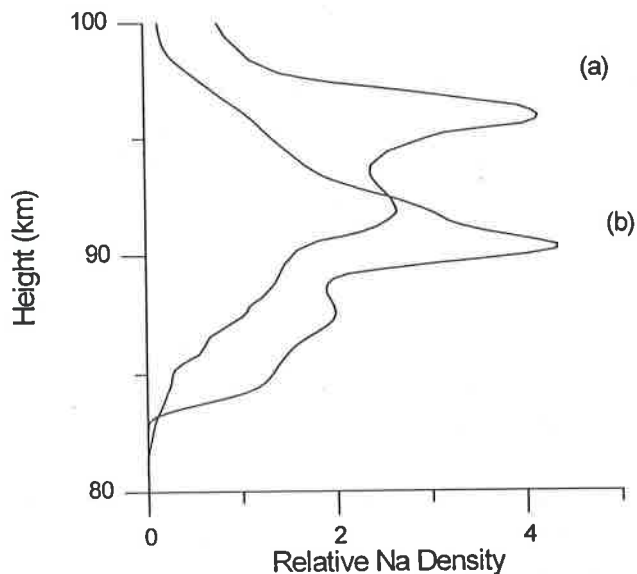


Figure 11 - (a) Sodium profile replotted from Gardner et al. (1986); (b) Sodium profile replotted from Gardner et al. (1993).

Figura 11 - (a) Perfil de sódio tirado de Gardner et al. (1986); (b) Perfil de sódio tirado de Gardner et al. (1993).

evident. Among the mechanisms consistent with this relationship, the most probable appears to be the formation of Ns layers via the neutralization of metallic ions. The aerosol mechanisms of Beatty et al. (1989) and Kirkwood & von Zahn (1991) both suffer from the defect of being highly speculative, lacking both direct evidence for the existence of the required dust particles and a detailed knowledge of the mechanisms involved. As discussed earlier, although there are difficulties with the ion recombination mechanism as an explanation for the formation of Ns layers, these are not necessarily insuperable. Since metallic ions near the mesopause are almost certainly of meteoric origin, it is entirely reasonable to suppose that their concentrations vary widely in space and time, as do those of the meteoric metals. Thus it could well be that sufficient ions could exist over restricted areas to explain the production of Ns layers by recombination. Not only could this mechanism explain the formation of thin layers, via the wind-shear mechanism, but it could also explain the unexpectedly large amplitude of gravity waves observed on the topside of the sodium layer.

If the neutralization of windshear concentrated ions is indeed the source of Ns layers, then the question arises as

why the layers should form at the same height as the peak in the propagating wave. Simple wave induced modulation of the density of a layered minor atmospheric constituent occurs mainly as a result of vertical wave motions in the presence of a mixing ratio gradient (Chiu & Ching, 1978). Under most circumstances the direct modulation of atmospheric density by the wave field is much smaller than this effect. As a result, peaks in the density of the minor constituent occur at the points in the wave field where the vertical displacement is a maximum in the direction of decreasing mixing ratio. On the topside of the layer, which is where Ns layers are observed, this means that the peaks should form close to where the maximum upward displacement occurs. According to the windshear theory of Es formation (Whitehead, 1961), ion layers should form at the nodes in the component of the wind structure perpendicular to the Earth's magnetic field. However, even in the case of long-period gravity waves, where the simple polarization relations for gravity waves apply, the relationship between the heights at which these nodes occur and the heights of maximum vertical displacement, where local maxima in the wind modulation of the layer are expected, depends on the direction of wave propagation with respect to the magnetic field. In the case of short-period gravity waves and tides, where there is no simple relationship between the wave field components, the situation is even more complex. Thus we must conclude that there is no reason for windshear concentrated ion layers to occur at any fixed height with respect to the wave peaks induced in the background layer by the vertical wind. Why, then, should the observations show that Ns layers most frequently occur at a wave peak? It is our belief that this happens because not only the Ns layers, but also the wave peaks themselves, are the result of the neutralization of windshear concentrated ions. The main evidence in support of this suggestion is the unexpectedly large amplitude of waves observed on the topside of the sodium layer.

As mentioned above, wave modulation of a minor constituent layer in the atmosphere is mainly the result of the vertical displacement of air parcels in the presence of a gradient in the mixing ratio of the minor constituent. In such a process the original mixing ratio of the air parcel is conserved. The depth of modulation produced by this mechanism depends on the strength of the mixing ratio gradient and the magnitude of the displacement. The process is most effective where the vertical gradient in the minor constituent concentration is in the opposite direction

to the gradient in atmospheric density, i. e., on the bottomside of a minor constituent layer. To see whether this mechanism is capable of explaining a given modulation of the layer we need to plot the layer profile as mixing ratio, rather than density. We have done this for a typical wave observed in the sodium layer in Fig. 12. Fig. 12a shows the vertical distribution of sodium density in a strongly wave-modulated layer observed at 1950 LT on June 12, 1996. In the same figure we show the average profile observed over 12 hours, between 1800 on June 12 and 0600 on June 13. Both profiles have been low pass filtered with a vertical cutoff wavelength of 2 km. At first sight the profile for 1950 appears to show a simple wave modulation of the average background layer. Fig. 12b shows the same profiles in terms of mixing ratio, determined by dividing the sodium densities by a typical atmospheric density profile for this height region. From Fig. 12b it is immediately clear that the wave modulation on the topside of the layer cannot be explained in terms of vertical displacements in the presence of a mixing ratio gradient. The peak in the 1950 LT profile located close to 98 km shows a mixing ratio greater than anything present in the average profile, and the minimum at 103 km would require a vertical displacement of about 7 km for it to be produced by the vertical motion of an air parcel. Since the vertical wavelength of the oscillation appears to be about 7 km, this is clearly impossible. Below the peak of the layer the situation is quite different. Only small vertical displacements are required to explain the wave modulation, and it is reasonable to suppose that the wave observed in this region is indeed produced by the mixing ratio gradient mechanism.

The existence of wavelike structures in the upper part of the sodium layer, with amplitudes too large to be explained in terms of wave-associated vertical winds in the presence of mixing ratio gradients, leads us to postulate that such structures are the results of neutralization of windshear concentrated sodium ion layers. This explains why there is no clear division between wave-modulation of the topside of the sodium layer and Ns layers. The latter frequently appear to grow out of the former. Although sporadic neutral layers are relatively infrequent at our location, descending wavelike structures with amplitudes similar to that of the example shown in Fig. 12 occur often. Whether or not these structures result in the formation of what would conventionally be called a sporadic layer would depend on the amplitude and, perhaps more importantly, the coherence of the wave responsible. In summary, we

suggest that the following process takes place: sodium ions, trapped at the descending nodes in the winds associated with tides and/or gravity waves, are neutralized by processes of the sort described by Plane (paper presented at the Equatorial Atmosphere-Ionosphere Interactions Symposium of the 1997 IAGA meeting), leading to the

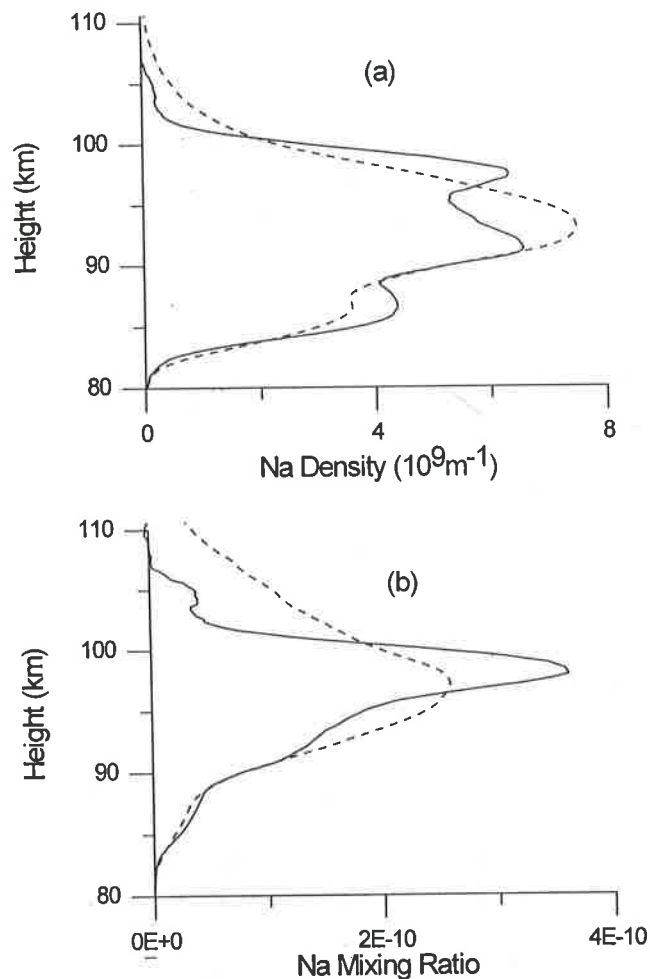


Figure 12 - Sodium profiles for June 12, 1996. The solid lines show the profile measured at 1950 LT, and the broken lines show the average profile for 1800 LT on June 12 to 0600 LT on June 13. In (a) the profiles are plotted as sodium density; in (b) they are plotted as mixing ratio.

Figura 12 - Perfis de sódio para 12 de junho de 1996. A curva sólida mostra o perfil observado às 1950 LT, e a linha tracejada mostra o perfil médio para o período 1800, hora local, do dia 12 de junho a 0600, hora local, do dia 13. No painel (a) os perfis são plotados em unidades de densidade; em (b) são plotados em razão de mistura.

formation of descending peaks in sodium density. When the amplitude and coherence of the waves are appropriate, this process leads to the formation of the narrow layers of very high density known as sporadic layers. It should be pointed out that N_s layers should not be expected to be invariably associated with ion layers, because low eddy diffusion coefficients could lead to the neutral layer continuing to exist long after the ion layer has dissipated. The most frequent occurrence of N_s layers at heights between 90 and 100 km is consistent with Plane's suggestion that metallic ions are neutralized by the dissociative recombination of molecular ions formed by reactions between the metallic ions and atmospheric molecules, a process whose efficiency increases rapidly with decreasing height. With regard to the low Na⁺ ion densities observed in the appropriate height range it must be remembered that the number of mass spectrometer measurements available is small and that, out of 6 reliable measurements, two showed sodium ion layers with concentrations comparable to that of Na atoms in sporadic layers.

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CAMADAS NEUTRAS ESPORÁDICAS NA ALTA ATMOSFERA ASSOCIADAS COM ONDAS ATMOSFÉRICAS

Camadas esporádicas neutras (Ns), com espessuras entre algumas centenas de metros e vários quilômetros, são observadas por radar de laser entre as alturas de 90 e 110 km, a mesma faixa de altura onde se observam as camadas ionizadas ionosféricas de E-esporádica (Es). Camadas Ns foram observadas pela primeira vez em sódio, 20 anos atrás, e mais recentemente foram observadas em potássio, ferro e cálcio. Como no caso de Es existe uma ligação forte com ondas atmosféricas, e vários estudos mostraram uma possível conexão com oscilações de marés na baixa termosfera.

Apesar da existência de muitos dados experimentais, ainda não existe uma explicação geralmente aceita para a formação das camadas Ns. A primeira explicação, oferecida na época da primeira observação de uma camada Ns, foi que a camada formou-se a partir da entrada na atmosfera de um meteoro. Observações mais recentes, indicando que as camadas podem ter dimensões horizontais de mais que 1000 km, enfraquecem esta explicação. Outros mecanismos, envolvendo a liberação de átomos a partir de partículas de aerossóis ou sua produção via reações químicas, carecem de subsídios concretos em relação aos processos físicos envolvidos.

Observações recentes em São José dos Campos mostraram que camadas de sódio esporádicas freqüentemente ocorrem nas alturas dos picos na concentração de sódio produzidas por uma onda atmosférica. Em alguns casos onde o comprimento de onda vertical da oscilação é pequeno, pode-se identificar até 3 oscilações completas, sendo que a camada esporádica sempre se forma no pico de altura maior. Nos casos de eventos de longa duração observa-se uma propagação da camada Ns no sentido de alturas menores, acompanhando a propagação de fase da onda atmosférica.

A modulação de camadas atmosféricas por ondas normalmente acontece onde há um gradiente vertical na razão de mistura do constituinte minoritário que constitui a camada. Nesta situação, a existência de ventos verticais associados com a onda causa o deslocamento de parcelas de ar até alturas onde a razão de mistura difere da razão no seu ponto de origem. Uma vez que a razão de mistura é necessariamente conservada, esta diferença resulta em uma modulação pela onda da densidade da camada em uma determinada altura. Na parte superior da camada de sódio o gradiente da razão de mistura é relativamente pequeno, e o mecanismo descrito acima é ineficiente. Neste trabalho mostramos que é impossível produzir não apenas as camadas esporádicas por este processo mas, em muitos casos, também a observada "modulação" por ondas. Em função da observada relação entre camadas Ns, camadas Es, e ondas atmosféricas, reexaminamos a possibilidade da

recombinação de íons de sódio ser responsável pela formação das camadas esporádicas.

No passado, a recombinação de íons de sódio como mecanismo para a produção de camadas esporádicas foi geralmente rejeitada. Esta rejeição se baseia no fato que a maioria das medidas da concentração de íons, feitas por espectrômetro de massa a bordo de foguete de sondagem, mostra concentrações de íons de sódio bem menores que a concentração típica de átomos de sódio nas camadas esporádicas. Outra razão pela rejeição deste mecanismo está relacionada com a observação de que as camadas Ns freqüentemente aumentam em amplitude muito mais rapidamente do que possa ser explicado pelos mecanismos de neutralização de íons metálicos conhecidos. Esta última objeção, porém, não leva em conta o fato que todas as observações de camadas esporádicas feitas até agora foram unidimensionais, de tal maneira a ser impossível distinguir entre variações verdadeiramente temporais, e variações resultantes da translação horizontal de uma camada contendo variações horizontais. A existência de fortes gradientes horizontais nas camadas Ns já foi demonstrada em vários estudos experimentais.

O número de experimentos que mediram a concentração de íons de sódio na faixa de altura relevante é reduzido. De um total de 6 experimentos que resultaram em perfis confiáveis, 4 indicaram concentrações de sódio de uma ou mais ordens de grandeza menor que as concentrações tipicamente encontradas para sódio neutro. Do outro lado, em dois experimentos, foram observadas camadas estreitas de íons de sódio com concentração em torno de 10^{10} m^{-3} , comparável com a concentração de átomos de sódio nas camadas Ns. Esta taxa de ocorrência de camadas de íons não é incompatível com a taxa de ocorrência de camadas Ns. A existência de observações de camadas esporádicas de sódio com concentrações ainda maiores, em torno de $5 \times 10^{10} \text{ m}^{-3}$ também não é incompatível com as medidas por espectrômetro de massa, uma vez que estas altíssimas concentrações são observadas apenas em raras ocasiões.

Concluímos que a origem das camadas Ns é a mesma das camadas Es: o bem-aceito mecanismo de concentração de íons pelo cisalhamento dos ventos horizontais na presença do campo geomagnético. A camada esporádica neutra seria simplesmente o resultado da recombinação de íons de sódio, provavelmente através da formação intermediária de íons moleculares que, subseqüentemente, sofrem um processo de recombinação dissociativa. Este mecanismo é compatível com o forte relacionamento observado entre camadas Ns e Es, a relação entre camadas esporádicas e ondas atmosféricas, e seu observado movimento vertical.