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Temperature controlled icy dust reservoir of sodium: A possible mechanism for the formation of sporadic sodium layers

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Abstract

Using seven years, from 2006 to 2013, sodium lidar observations over Hefei, China (31.80°N, 117.3°E), we attempt to propose a possible mechanism for the formation of sporadic sodium layers (SSLs or Na_S). We analyze the relationship between low temperature (<150 K) and SSL occurrence and detect a statistically significant link that the low temperature (<150 K) occur in three days before an SSL with an occurrence rate of 93.4% (57/61). The sharp decrease of water vapor concentration nearby before an SSL and the recover after the SSL are also detected frequently. Based upon these evidences and some case studies, we propose an icy dust reservoir in the formation of an SSL. The icy dust could form in the extremely cold mesopause region where the temperature falls below 150 K and it will absorb sodium atoms to form a solid sodium metal film as a sodium reservoir. The icy dust will then sublimate rapidly when meeting with warm air (e.g., 150 K < T < 190 K) and leave behind the solid metal atom film. The remanent sodium film might release vapor sodium atoms finally by some means through high temperature (e.g., >190 K and sometimes even >230 K) and form a sporadic sodium layer. Although not conclusive and highly uncertain, the icy dust reservoir model not only provides a good explanation for the observed characteristics of SSLs; it is also in good agreement with many other observations, such as the simultaneous sporadic sodium and iron layers, the behavior of SSLs on small time scale, the deviation of the sodium density profile of SSLs from the normal one, and the sharply decreased scale height above the peak of the sodium layer. These results further suggest that the icy dust might be a viable option of sodium reservoir for the formation of SSLs.

Keywords: Sporadic sodium layer; Sub-visible icy dust; Temperature

1. Introduction

The sporadic sodium layer (SSL or Na_S), also called sudden sodium layer, was first detected more than 30 years ago (Clemesha et al., 1978). Since then, many SSLs have been reported and several possible mechanisms have been proposed to the formation of this gorgeous phenomenon. In 1978, Clemesha et al. suggested that the huge quantity of sodium atoms in SSLs come from direct meteor injections (Clemesha et al., 1978), but this mechanism was soon rejected since the occurrences of SSLs were independent from meteor events (Clemesha et al., 1988; Hansen and Von Zahn, 1990). Moreover, meteors only affect a small area and they can hardly explain the broad scales with a horizontal extent over 1000 km for some SSLs (Clemesha et al., 1988).

In the late 1980s, Von Zahn et al. (1987) proposed that the sodium atoms in SSLs are released from dust or smoke

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through the impact of auroral particles (Von Zahn et al., 1987), but this proposal was soon rejected because of its many shortcomings (Clemesha et al., 1988). The amount of meteor dust particles in mesosphere is also not sufficient to produce the great quantity of sodium atoms in normal SSLs (Cox et al., 1993), and the sodium layer density is in fact sometimes reduced during auroral events (Heinselman et al., 1998; Tsuda et al., 2013).

Further, there is little doubt that temperature has an effect on sodium density with higher temperatures corresponding to higher sodium abundance (Clemesha et al., 2010; Zhou et al., 1993). In a more complex and temperature dependent mechanism (Zhou et al., 1993; Zhou and Mathews, 1995), which is supported by some observed connections between SSLs and enhanced temperature (Gardner et al., 1991; Gardner et al., 1993; Gardner et al., 1995; Nesse et al., 2008), the local heating from gravity and tide waves was proposed for triggering the formation of sodium atoms. Another sophisticated model is based upon the increasing number of observations in recent two decades of the association between sporadic neutral layer (N_S) and the famous mesosphere lower thermosphere (MLT) phenomenon called sporadic E layer (E_S) (Alpers et al., 1994; Batista et al., 1989; Dou et al., 2009; Dou et al., 2010; Gong et al., 2002; Hansen and Von Zahn, 1990; Kwon et al., 1988; Miyagawa et al., 1999; Nagasawa and Abo, 1995; Shibata et al., 2006; Von Zahn and Hansen, 1988). From laboratory studies, it is shown that sporadic sodium layers can be formed by a descending sporadic E layer in which the sodium ions have different lifetime between 100 km and 90 km (Cox et al., 1993; Cox and Plane, 1998). The E_S could also provide an electron layer to recombine with the sodium ions pre-concentrated by wind shear and thus form SSLs (Beatty et al., 1989; Clemesha et al., 1999; Collins et al., 2002; Cox and Plane, 1998; Daire et al., 2002; Gardner et al., 1993; Kane et al., 1991; Nesse et al., 2008; Sridharan et al., 2009; Williams et al., 2006).

Out of these mechanisms, none could explain all the observed characteristics for the formation of SSLs (Batista et al., 1989; Batista et al., 1991; Clemesha, 1995; Cox et al., 1993; Nesse et al., 2008). Increasing amount of evidences indicated that the SSLs in various latitudes and altitudes have different characteristics (Friedman et al., 2000; Hansen and Von Zahn, 1990; Kane et al., 1993) and could be formed by different mechanisms (Cox et al., 1993; Gardner et al., 1995; Zhou et al., 1993; Zhou and Mathews, 1995). For example, the short-duration SSLs below 90 km might be formed from advection of meteor trails (Beatty et al., 1988), but the SSLs above 98 km, which have a strong correlation with the E_S, could be directly recombined from the E_S (Gardner et al., 1993; Hansen and Von Zahn, 1990; Kane et al., 1993). Most of SSLs in normal altitude (90–98 km), however, have much greater peak density and longer duration; and they do not seem to be derived directly from the E_S because the density of sodium ions in E_S is too low (Kane et al., 1993; Von Zahn et al., 1987). The correlations between the SSLs and E_S at normal altitude are also much weaker than those above 98 km (Friedman et al., 2000; Hansen and Von Zahn, 1990; Kane et al., 1993; Kwon et al., 1988). Furthermore, the large peak density compared with Na total column abundance indicates that the SSLs sodium atoms must come from some reservoir (most likely to be dust or smoke) not normally detectable to the lidar (Gu et al., 1995). Therefore, a possible sodium reservoir, which could store and release massive sodium atoms, is expected for SSLs at normal altitude.

The recently observed anti-correlation between the density of mesosphere sodium layers, as well as other metal layers such as K and Fe, and the mesospheric ice particle phenomena in the summer time of high latitudes, such as the polar mesospheric cloud (PMC, at about 85 km, observed by satellite; also called noctilucent cloud (NLC) when it was observed by the ground) and the polar mesospheric scatter echoes (PMSE, at about 88 km) (Lubken and Hoffner, 2004; Plane et al., 2004; She et al., 2006; Thayer and Pan, 2006), suggests a mechanism for the depletion of metal species by these icy dust particles in mesosphere. The mesosphere icy dust particles are able to adsorb metal atoms on the surfaces (Bellan, 2008; Fan et al., 2007; Plane et al., 2004; Raizada et al., 2007; Thayer and Pan, 2006) and pack metal ion clusters or compounds as nuclei (Olofson et al., 2009; Plane, 2000). So the icy dust particles can store sodium species very efficiently.

Recently, the dust reservoir model received attention again in the support of many new observations. For example, in situ measurements and ground base lidar results showed that a 5 km thick positively charged dust layer was simultaneous with an observed sporadic sodium layer (Gelinas et al., 1998). After that, the strong correlations between charged dust density profile and neutral metal atom profile were also observed, suggesting that dust particles served as a reservoir for atomic metal (Gelinas et al., 2005).

In this study we propose a modified icy dust model. The icy dust particle is expect to provide a possible adequate sodium reservoir for the formation of large SSLs at normal altitudes (with a peak altitude between 90 and 98 km) of subtropical area where the mesopause temperature between 95 and 100 km is lower than those at other latitudes of the same regions. We will discuss the possibility of such icy dust reservoir above the 95 km in subtropical area, the role of icy dust reservoir in the formation of SSLs and the triggering mechanism.

2. Observations and results

2.1. Typical-normal altitude-large (TNAL) SSLs events observed by USTC lidar

The Detailed information of the University of Science and Technology of China (USTC) lidar in Hefei (31.8°N, 117.3°E) has been described in previous studies and many