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Diagnosis of Charged Dust Layers in the Near-Earth Space Environment

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ABSTRACT
Polar Mesospheric Summer Echoes (PMSEs) are very strong radar echoes produced by electron density fluctuations at half the radar wavelenght (Bragg scatter condition) in the altitude range 80-90 km. The temporal behavior of PMSE response to high-frequency pump heating can be employed to diagnose the charged dust layer. Specifically, the rise and fall time of radar echoes as well as relaxation and recovery time after heater turn-on and off are distinct parameters that are functions of radar frequency. The main purpose of this study is to use the temporal evolution of PMSEs during active modification using high power radiowaves to study the fundamental physics of dust charging in space and to develop a new remote sensing technique for measuring ionospheric parameters in the near-Earth space environment.

Keywords: polar mesospheric clouds, active space experiments, PMSE, Remote sensing

INTRODUCTION
Noctilucent clouds (NLCs) from ground observations, or polar mesospheric clouds in the case of space observations, have first been recorded in 1885 (Backhouse, 1885). Particles responsible for NLCs usually grow sufficiently that they can be observed by lidars (Baumgarten et al., 2008), spaceborne cameras (Russell et al., 2009), and rocket-borne photometers (Gumbel and Witt, 2001). Analysis has shown that visible NLC particles typically have the characteristic sizes in the range 20–100 nm (Baumgarten et al., 2008). Polar mesospheric summer echoes (PMSEs) are strong radar echoes produced by particle clouds which are formed at mesopause altitudes 83–88 km (Rapp and Lubken, 2004). The electron irregularities are produced as a result of charging onto the irregularity structures in the subvisible particle density (Inhester et al., 1994). These subvisible particles are located a few kilometers above the NLCs and smaller in size in comparison with those creating NLCs (Robertson et al., 2009). The PMSEs were first observed using the 50 MHz VHF radar at Poker Flat, Alaska but have subsequently been detected using a number of different radio sounding frequencies including 1.29 GHz, 933, 224, 53.5, 8, 7.6, 4.9, 3.3, 2.43 MHz (Cho and Rottger, 1997). PMSE particles are dusty ice particles and are a combination of dust and ice (Brattli et al., 2009, and the special issue devoted to the measurements of ice particles) which for the remainder of this paper will be referred to as simply dust particles.

In recent years, ground-based observation techniques have drawn considerable interest in the space science community although it may be lacking in spatial and time resolution. More direct investigations which resolve these issues are possible by sounding rocket. However, with these in-situ methods, the short time frame of the experiments becomes a problem as many of the most interesting mesospheric phenomena occur over a longer time interval. Recently, experimental observations have shown that PMSEs may be modulated by radio wave heating of the irregularity source region with a ground-based ionospheric heating facility. It is clear from these past investigations that the temporal behavior of PMSEs during ionospheric heating shows promise as a diagnostic for the associated dust layer. Therefore, PMSE heating experiments a promising alternative approach that can be implemented to diagnose the PMSE source region at much lower cost. The first modulation of PMSE with radio wave heating was reported by Chilson et al. (2000), where it was shown that backscatter could be reduced in intensity as the heater is switched on, and thereafter return to its original strength when the heater was switched off. This behavior was also observed in other PMSE heating experiments and led to a powerful tool to investigate the

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physical processes at mesopause altitudes (Belova et al., 2001, 2003; Havnes, 2004; Mahmoudian et al., 2011; 2012 a,b).

Forefront problem in the field and Problems to study

a. Dust Charging Process in Space

Recent rocket payloads have studied the properties of aerosol particles within the ambient plasma environment in the polar mesopause region and measured the signature of the positively charged particles with number densities of 2000 cm^{-3} for particles of 0.5–1 nm in radius (Robertson et al., 2009). At this time there appears to be significant uncertainty as to the charging process producing the positive dust particles and these are not consistent with the standard charging theory. The measurement of significant numbers of positively charged aerosol particles is unexpected from the standard theory of aerosol charging in plasma. Nucleation on the cluster ions is one of the most probable hypotheses for the positive charge on the smallest particles.
Our studies have shown that there may be opportunity for investigation of charging processes by utilizing high-frequency (HF) PMSE heating measurements, since charging timescales become more relevant than diffusion timescales. Figure 1 shows a comparison of the electron fluctuation amplitude (again related to radar cross-section) and the average dust charge Z_d. It is assumed that the irregularity scales correspond to a radar frequency of 8 MHz. It is evident that the charge and fluctuation amplitude have very similar behavior and much can be learned about the charging from radar return. Therefore, enhancement of irregularity amplitude after heater turn-on in the HF band is the direct manifestation of the dust charging process in the space. Further active experiments of PMSEs should be pursued in the HF band to illuminate the fundamental charging physics in the space environment and get more insight into this unique medium.

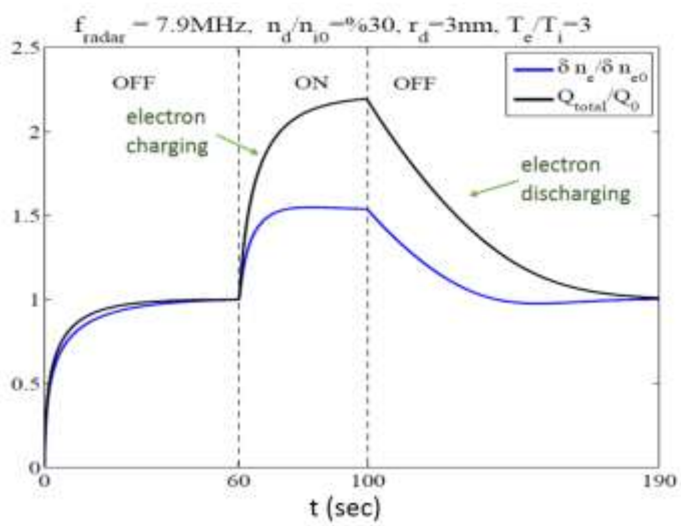

Figure 1. Calculation of the comparison of average dust charge and electron fluctuation associated with HF radar scatter indicating similar temporal behavior.

b. Developing a new remote sensing technique

Using ground-based ionospheric heating facilities to produce an artificial enhancement in electron temperature is shown as a rich source of diagnostic information for charged dust layers in the earth's upper atmosphere. The dependency of the backscatter signal strength after the turn-on and turn-off of the

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radio wave heating to the radar frequency is a unique phenomenon that can shed light on the unresolved issues associated with the basic physics of the natural dust layer. The recent work by Mahmoudian and Scales (2012a) has attempted to provide further physical insight into the physical processes associated with temporal evolution of the electron irregularities during the turn-on of the radiowave heating and can be seen to be complementary to past work that has considered the physical processes after the turn-off of radio wave heating. The new analytical model developed by Mahmoudian and Scales (2012a) is able to describe the temporal evolution of electron irregularities during the early phase of the heating cycle. The simplified analytical models here provide quite reasonable agreement with full computational results. It turns out that active PMSE heating experiments involving multiple observing frequencies at 7.9 (HF), 56, and 224 MHz (VHF) may contribute further diagnostic capabilities, since the temporal evolution of radar echoes is substantially different for these frequency ranges. Measuring radar echoes at multiple frequencies provides us with enough information to estimate important plasma and dust parameters. Analytical expressions for observable parameters associated with the radiowave turn-on, τ_{max}, τ_{min}, δn_e^{max}, δn_e^{min}, $\Delta\delta n_e$, and τ_d (Figure.2) during active perturbation of PMSEs are derived here that may provide information on the dust layer such as dust density altitude profile, dust density irregularity amplitude, dust charge state variation, and degree of electron temperature enhancement during radio wave heating (Mahmoudian an Scales, 2012a).

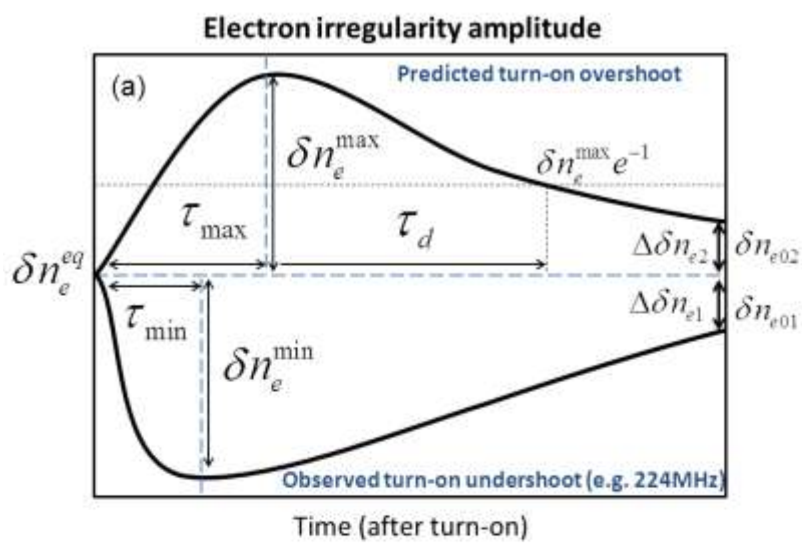

Figure 2. Schematic of electron irregularity behavior subsequent to the turn-on of radio wave heating. Observables lead to the diagnosis of the dust layer.

CONCLUSION

Modification of PMSEs by radio wave heating has significant potential for remote sensing of dust parameters in the mesosphere once suitable computational models have been developed. The main focus of this study was on the temporal behavior of irregularities after radio wave heating turn-on and turn-off to diagnose dusty space plasmas at mesopause altitudes. Characteristics of the dusty space plasma, such as dust density and radius, charge state and plasma heating ratio, can be obtained from the temporal behavior of the irregularities observed by radars. Most past active experiments have concentrated on VHF PMSE. It is clear from the recent studies that lower-frequency PMSE, including HF PMSE, has substantial potential as a diagnostic tool during active modification experiments. Since the dust charging dominates during pump turn-on in the HF band it causes an enhancement of radar echoes. Further

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experiments should be pursued since fundamental charging physics may be revealed which is critical to understanding dusty space plasmas.

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