Charged dust phenomena in the near-Earth space environment

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1. Introduction

Over 40 metric tons of dust of meteoric origin enters the Earth’s atmosphere every day. This dust settles and creates natural dust layers in the altitude range between 80 and 100 km spanning the Earth’s upper mesosphere to lower thermosphere. As these dust layers are immersed in the ionized portion of the Earth’s atmosphere, they become electrically charged due to the collection of electrons and ions from the Earth’s ionospheric plasma. Noctilucent clouds (NLCs), as viewed from the ground, or polar mesospheric clouds (PMCs), if observed from space, are one fascinating and important seasonal visual manifestation of these dust layers. These are the highest clouds in the Earth’s atmosphere and exist in the coldest regions in our environment, reaching a mean summer minimum temperature of 130 K with temperatures below 100 K having been reported. The summer polar mesosphere becomes cold due to the global meridional circulation pattern from summer to winter with upward adiabatic expansion and cooling in the summer hemisphere and downward compressional warming in the winter hemisphere, both driven by atmospheric gravity waves. So-called polar mesospheric summer echoes (PMSEs) are related radar echoes that are a direct consequence of the sub-visible charged dust producing electron density fluctuations at altitudes above NLC regions. Because of the intimate relationship between these phenomenological signatures and possible long-term global environmental changes, the study of these dust layers is a leading issue in atmospheric space science and may contribute to the important debate on phenomena associated with the rise of greenhouse gases in the modern era (e.g. Thomas et al 1989, 2003, Thomas 1991). Although this has been a vigorous area of research for several decades using ground-based, rocket-borne and satellite measurements, and there remain many unresolved issues regarding the basic physics of natural charged dust layers in this atmospheric region, critical advances have been made within the last decade. In addition, active space experiments have recently started to become important in providing further information on the creation and evolution of the natural dust layer by utilizing ground and space-based techniques. Both active...
creation of artificial dust clouds in the upper atmosphere as well as ground-based high-power radio wave modulation of middle atmospheric dust layers are emerging areas of research that complement passive investigations.

Figure 1 shows a view of PMCs from the Aeronomy of Ice in the Mesosphere (AIM) satellite mission (Russell et al. 2009) from the northern polar region using the cloud imaging and size (CIPS) instrument. PMCs typically extend from the geographic pole to 55° latitude during the summer in both hemispheres. Historically, after 1885, NLCs or ‘shining night’ clouds (which again are the ground-based visual manifestation of PMC) began to appear during Arctic summers (Backhouse 1885, Leslie 1885) and shortly thereafter were determined to be in the 80 km altitude range. It was much later proposed, near the turn of the twentieth century in 1912, that these cloud sightings were due to additional water vapor introduced into the stratosphere by the cataclysmic eruption of Mount Krakatoa two years previously in 1883. Subsequent modeling confirmed that the two year delay time between the eruption and cloud sightings were consistent with transport from the stratosphere to the mesosphere. Over time, this region has evolved into an important laboratory for atmospheric science. There continues to be evidence that these clouds have been increasing in occurrence over the past 100 years due to the anthropogenic effects of increasing methane and carbon dioxide gases, which serve as a source of water vapor and also cooling in the middle atmosphere (e.g. Roble and Dickinson 1989). The increase in occurrence, brightness and latitudinal extent (Taylor et al. 2002, DeLand et al. 2006), which was not understood since their identification in the 1880s, suggests a connection with global change occurring at lower altitudes. This prompted AIM, launched in April 2007, the first space mission dedicated to study the formation and evolution of PMCs.

Although there is vigorous ongoing interest in dust layers in this region of the atmosphere, dust grains in the Earth’s upper atmosphere are associated with other physical effects, having unique observable features that have long been of much scientific and practical interest. Possibly the most important being the subject of meteors, which is directly linked to the Earth’s dust layer as just described. For clarity of definition, the incoming interplanetary object is a meteoroid, whereas the observable optical and radio phenomena as it interacts with the atmosphere is a meteor. If part of the meteoroid survives this interaction with the atmosphere to reach the ground, it becomes a meteorite. On average, over 100 billion meteoroids with masses larger than 1 μg enter Earth’s atmosphere daily. These include shower meteoroids, which are associated with a parent body, as well as sporadic meteoroids, which form the background population.

The existence of the ionized trail of a meteor was recognized by Skellett (1931, 1935) and his collaborators at the Bell Telephone Laboratories, and by Schafer and Goodall (1932), who used a pulsed ionospheric transmitter operating in the wavelength range of 47 m < λ < 190 m during the activity period of the Leonid 1931 meteor shower. Early applications of radio methods in meteor science were described by others, including Hey and Stewart (1947), Lovell (1954), McKinley and Millman, (1949), McKinley (1961) and Millman and McKinley (1963). A head-echo was first recognized and used in England by Hey et al (1947) for determining the meteoroid velocity.

Meteorites form only a very small fraction of the total mass that is captured by the Earth’s atmosphere. Most of the matter is in the form of very fine dust particles. Because of the temperatures reached during entry, a large proportion of these particles evaporate at high altitudes, giving rise to radar signatures, and to the visual phenomenon of shooting stars. Sputtered particles may cause the formation of ionized meteor trails (non-thermal ablation) recorded by radars and may produce observable (high-altitude) meteors, even if the mass loss due to sputtering is small. A region of ionized gas forms near the meteoroid and expands almost instantaneously. The head of the meteor moves with the
speed of the meteoroid. It is followed by the meteor trail (also called the train), that extends behind the meteoroid body. At typical heights between 80 and 120 km, both head and trail, depending on meteoroid mass and entry conditions, can be observed optically as well as by radar backscattering.

Kelley et al (1998) have reported on the detection of a meteor contrail and meteoric dust in the Earth’s upper mesosphere, presenting evidence that the ablated material in the trails of large meteors may coagulate into particles of the order of 50 nm in radius. Meteoroids entering the Earth’s atmosphere are studied by visual means (Hawkes 2002), by radar (McKinley 1961, Pellinen-Wannberg and Wannberg 1994) and by LIDAR (von Zahn et al 2002). Charged dust particles are suspected to influence some meteor observations and be observed by radar scattered signals, but distinguishing between the heavy ion and charged dust signals is still a challenge. The meteor trail echoes are radio waves scattered by free electrons in the trail, which extends for metres to kilometres behind the meteoroid. Rosenberg (2008) suggests that fast ions sputtered from a meteoroid might generate dust-associated waves in the background plasma that are possibly detectable by radar scattering. Figure 2 shows a meteor head and trail very-high-frequency (VHF) radar observation from Close et al (2011) of unusually long duration non-specular echoes using the low-latitude Advanced Research Project Agency (ARPA) Long-Range Tracking and Instrumentation Radar (ALTAIR). The 0.9 m and 36 cm electron density fluctuations that produce the radar scatter last for over 1 min compared with a typical long trail echo of no more than a few tens of seconds. It is proposed that the physics causing this long duration is similar to that producing long-lived electron density fluctuations resulting in PMSE in NLC regions. That is, both of these phenomena result from charged dust particles in the background plasma (e.g Kelley et al 2003).

The role of meteoric dust from ablation is also critical for the creation of sporadic layers composed of Fe, Mg, Na and Ca ions in the E layer of the Earth’s ionosphere (e.g. Visconti 1973, Kirkwood and von Zahn 1991). It has also been proposed that the impact of this dust on collision frequencies, and therefore conductivity, in the electrojet region in the range of 100–120 km may significantly impact the electrojet current and ultimately impact the ionospheric dynamics (Muralikrishna and Kulkarni 2008). Reduction of the electron density due to dust charging has been predicted to cause weakening and even reversal of electrojet currents. This is consistent with observations of blanketing sporadic E layers in conjunction with electrojet current reversals. Another atmospheric phenomenon believed to be impacted by meteoric dust is sprites (Zabotin and Wright 2001). Meteoric dust particles may participate in sprite formation through the quasi-electrostatic field of a lightning stroke firing an arc discharge on a relatively large (25–100 μm) conducting micrometeoroid particle. This effectively transforms its material into a plasma cloud resulting in a streamer developing directly from such a plasma cloud, obviating the electron avalanche stage.

Dusty (or complex) plasma physics has evolved into a relatively mature field of study over the past several decades (e.g. Shukla and Mamun 2002, Shukla and Eliasson 2009). In the past, these principals have been collected and applied to dusty space plasmas in the Universe on several occasions (e.g. Whipple et al 1985, Goertz 1989, Merlino and Goree 2004, Mann et al 2011). The objective of this paper is to collect recent advances in dusty plasmas specifically applied to the Earth’s atmospheric dusty space plasma region. It is important to note this dust plasma configuration is quite unique from many dusty plasma scenarios as it exhibits strong and relatively complex coupling between the dust, plasma and background neutral atmosphere, which in essence controls the plasma dynamics and observable plasma structuring. Some clues to this were first observed from mysterious radar scatter (PMSE) in the VHF and UHF range from the index of refraction fluctuations, due in turn to electron density fluctuations that could exist at Bragg scales (half radar wavelength) much smaller than the spatial scale for neutral air fluctuations to become dissipated by viscosity (viscous subrange). Resolution of this puzzle has led to some fundamental concepts in dusty plasmas
in the near-Earth space environment (Kelley et al 1987, Kelley and Ulrick 1988). As just noted, these concepts are becoming increasingly important for the interpretation of meteor observations as well. To this end, several current research agendas involving dust layers in the near-Earth space environment will be considered. First, the creation of the dusty plasma in the near-Earth environment will be discussed. The connection of these dusty plasmas with exotic observational phenomena will be described, accompanied by the concepts and criteria for dusty plasmas. Description of the important physical processes required to characterize the charged dust region will then be discussed. These primarily involve the charging, collision, conductivity and diffusion processes. A discussion of basic models that may be used for investigating a spectrum of processes and phenomena including electrodynamics and plasma physics is presented. Next applications are discussed, including the investigation of density, electric field and potential fluctuations with and without coupling to the neutral atmosphere, dusty plasma waves and both space-based and ground-based active experiments. Finally an assessment of future research directions will be provided.

2. The near-Earth space environment as a dusty plasma

2.1. Basic criteria for dusty plasmas

The Earth’s ionosphere is well described as a plasma (e.g. Kelley 2009). This discussion will therefore be limited to the Earth’s ionosphere, roughly between 80 and 1000 km above the earth’s surface. However, for the purposes of this work, some description in terms of a dusty (or complex) plasma is necessary (Shukla and Mamun 2002, Shukla and Eliasson 2009). The field of dusty plasmas has become a vigorous and established area of research for a number of decades now. Basic concepts on criteria for a dusty plasma that distinguish it from a more conventional plasma will be briefly provided here. Some basic concepts of the creation and characterization of the dusty space plasma will also be provided in the following sections as well.

A dusty plasma is described as a conventional electron and ion plasma with embedded micrometre or submicrometre-sized particulates that are charged. There are neutral particle species included as well. The charged dust particles are massive relative to the plasma and neutral species and may be of the order of 10⁶ or heavier than the ions and exhibit a distribution in particle size. The mixture of a conventional plasma and charged dust may be described as a ‘dusty plasma’ or ‘dust-in-plasma’ depending on the relative spacing of the charged dust particles. Denoting the interparticle spacing of the dust as \( a \), the dust particle radius as \( r_d \) and the plasma Debye length as \( \lambda_D \), the condition for ‘dust-in-plasma’ is \( r_d \ll \lambda_D < a \). In this case, the dust particles are considered as a collection of individual isolated screened particles. The condition for a dusty plasma is \( r_d \ll a < \lambda_D \), in which the dust particles may exhibit collective behavior (e.g. wave motion). The distinction between the two regimes may have important consequences for radar scatter as an important example to be discussed in section 4.5.

Depending on the dust particle size, the particles may be singularly or multiply charged and the charge state may be positive or negative. The charge on the dust particles may also vary in time unlike in a conventional plasma and may lead to dust charge fluctuations (e.g. Jana et al 1993, Tsytovich and de Angelis 1999) as well as fluctuations in density, potential, electric fields, etc. The charging process will be discussed in more detail in sections 2 and 3. Assuming a single plasma ion species, the macroscopic neutrality condition with no external disturbances present is given by

\[
q_d n_d = q_i n_i - Q_i n_0 \quad (1)
\]

where \( q_d \) is the ion (electron) charge, \( n_{i(e)} \) is the ion (electron) equilibrium density, \( Q_i \) is the dust charge (which may be positive or negative) and \( n_0 \) is the equilibrium dust density. For negatively charged dust particles, under certain circumstances, significant reduction in electron density in the mesosphere may occur, which is commonly referred to as an electron ‘bite-out’ (Reid 1990) and will be considered in more detail later. Another related fundamental parameter is the percentage of charge on the dust particles. This parameter is often called the Haynes number and is given by

\[
h = \frac{Z_d(n_d)}{n_i} \quad (2)
\]

where the equilibrium charge state is denoted by \( Z_d = Q_d/e \) where \( e \) is the unit charge. The Debye or electrostatic shielding length is given by

\[
\lambda_D = \frac{\lambda_{De} \lambda_{Di}}{\sqrt{\lambda_{De}^2 + \lambda_{Di}^2}} \quad (2)
\]

where \( \lambda_{De(i)} = \sqrt{k_B T_{e(i)} e^2 n_{e(i)} e^2} \) is the electron (ion) Debye length where \( k_B \) is Boltzmann’s constant, \( T_{e(i)} \) is the electron (ion) temperature, \( \varepsilon_0 \) is the permittivity, and \( n_{e(i)} \) is the equilibrium electron (ion) density. The shielding distance with negatively charged dust is primarily controlled by ions and that with positively charged dust is primarily controlled by electrons. A final important characteristic describing dusty plasmas is the relative size of the dust Coulomb potential energy to the thermal energy with the dust temperature denoted by \( T_d \). This is referred to as the Coulomb coupling parameter and is given by

\[
\Gamma_c = \frac{Q_d^2}{a k_B T_d} \exp \left( -\frac{a}{\lambda_D} \right) \quad (3)
\]

All the dusty plasmas under consideration here are weakly coupled with \( \Gamma_c \ll 1 \). The other regime \( \Gamma_c \gg 1 \) is strongly coupled and may exhibit dust crystals (e.g. Chu and Lin 1994, Thomas et al 1994).

2.2. Creation of dusty plasmas in the near-Earth space environment

There are several observational phenomena, primarily in the Earth’s mesopause, the 80–90 km range, associated with the existence of dust particles in the near-Earth space environment. As noted earlier, two examples are NLCs (or PMCs

\[
\rho_0 = \rho_0 \quad (1)
\]

where \( \rho_0 \) is the electron (ion) Debye length, \( i_0 \) is the electron (ion) equilibrium density, \( Q_i \) is the dust charge (which may be positive or negative) and \( n_0 \) is the equilibrium dust density. For negatively charged dust particles, under certain circumstances, significant reduction in electron density in the mesosphere may occur, which is commonly referred to as an electron ‘bite-out’ (Reid 1990) and will be considered in more detail later. Another related fundamental parameter is the percentage of charge on the dust particles. This parameter is often called the Haynes number and is given by

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if observed from space) and PMSEs, which are interrelated. NLCs, which are the highest clouds in the Earth’s atmosphere, consist of optically visible water vapor (dust) particles in the range of 10–100 nm and of density 10–5000 cm$^{-3}$. As NLCs scatter less than 1% of light incident on them, they are only visible when the sun shines from below and the sky above is dark, making them night luminescent. They were first reported in 1885 by Backhouse (1885). PMSEs are radar echoes from electron density fluctuations at the Bragg scale due to electron charging onto the irregular dust density associated with said NLCs. They have been observed roughly in the range from 3 MHz to 1 GHz with the first observations reported by Ecklund and Balsley (1981). There have been a number of extensive reviews of PMSEs and NLCs in the past (e.g. Cho and Kelley 1993, Cho and Rottger 1997, Rapp and Lubken 2004). A third phenomenon associated with mesospheric dust layers is sudden (or sporadic) atom layers (SALs). These have also received considerable attention with rocket, radar and LIDAR investigations as mesospheric dust is proposed as a source and/or sink for these layers that may be of the order of 1 km thick, develop in minutes and last for minutes to hours (e.g. Gelinas et al 1998, Lynch et al 2005, Gelinas et al 2005) near 95 km.

The microphysics of the origin of the dust layer in the mesosphere was investigated in detail by the two seminal works of Rosinski and Snow (1961) and Hunten et al (1980). The work of Rosinski and Snow considered the condensation of meteor trail vapors into secondary particulate matter in the meteor ablation zone and made estimates of the size distribution. The process of the condensation was coagulation due to collisions between molecules. It was also noted that if water vapor existed at these altitudes, then larger particles could be formed by adsorption onto the secondary particles to create aggregates of nuclei surrounded by ice, possibly leading to NLCs. The work of Hunten et al extended the work of Rosinski and Snow by considering in detail the height and size distribution of the condensation products of the meteoroid ablation process and their further evolution through coagulation, sedimentation and diffusion. These were termed ‘smoke’ particles, and are currently often called Hunten particles or meteoric smoke particles (MSPs) in the literature. Hunten et al used the broader terminology ‘dust’ for any solid particle entering the atmosphere at the time. The results of the work were that the smoke particle radii were in the low nanometre (nm) size range with densities of several 1000 cm$^{-3}$ and could exist in the altitude range from 30 km to 110 km. Further application of the results to the formation of NLCs and metal layers were also noted.

The microphysics have also been investigated further more recently by a number of authors (Turco et al 1982, Jensen and Thomas 1988, Reid 1990, Klostermeyer 1998, Plane 2000, Berger and Von Zahn 2002). Solar occultation infrared measurements have confirmed that the dust particles mainly consist of water ice in the summer polar mesosphere (Hervig et al 2001, Eremenko, et al 2005) and Hervig et al (2009) reported the first measurements of mesospheric smoke particles from a satellite. The formation of the dust particles in the Earth’s summer polar mesopause requires water ice nucleation and condensation as described by Rapp et al (2013) and summarized in figure 3. Water ice nucleation is possible from 80 to 90 km above the Earth’s surface as the temperature in this altitude range drops below the water vapor frost point during the summer. The nucleation process is likely to be of a heterogeneous nature involving water ice molecules attaching to pre-existing nuclei. It has been proposed the condensation nuclei may include large condensation proton hydrate clusters, carbon particles (i.e. soot), sulfuric acids (volcanic ash), sodium bicarbonate and hydroxide and MSPs with the latter being the most likely candidate. Meteoric particles consist of metallic compounds and silicon oxides and therefore polymerization
is a probable cause for particle growth by water molecule attachment. Formation of meteoric smoke particles happens after near-complete ablation of meteoroids in the altitude range of 75–115 km and leads to particle sizes of 1–2 nm and densities of a few 1000 cm$^{-3}$ as stated earlier (Hunten et al. 1980). The critical radius for water ice particle nucleation under typical mesospheric conditions is believed to be near $r_D = 1.3$ nm. These particles of meteoric origin are difficult to measure and there is a relatively broad spread in the densities reported by various authors at this radius from $10^1$ to $10^3$ cm$^{-3}$. Validation of the characteristics of MSPs via sounding rocket in the tropical mesosphere was made by Gelinas et al. (2005) by measurement of the charged population of these meteoric particles of the order of 100 cm$^{-3}$ and inferring the uncharged population of 1000 cm$^{-3}$ as predicted by Hunten et al. (1980).

The first detection of charged icy dust particles associated with PMSEs and NLCs was reported by Havnes et al. (1996a, 1996b) during the DUSTY series of sounding rocket experiments. A key result was that significant quantities of charged dust exist in the PMSE and NLC regions, sufficient to modify the background electron density with depletions and steep gradients due to electron charging processes.

As described in figure 3, the initial nucleation occurs near the top of the layer, with growth, sedimentation, etc taking place at a lower altitude. This is the primary source region of sub-visible PMSE dust particles. The bottom of the layer, where temperature begins to increase, contains a much lower density of larger (several tens of nm or larger), visible NLC particles. The temperature minimum in the summer mesopause is typically in the 100–150 K range.

Figure 4 shows the results of first measurements of charged dust in the near earth space environment. Figure 4(a) is the first measurement of charged dust made by Havnes et al. (1996a) during the Dusty I campaign in the polar mesosphere. Figure 4(b) is the first measurement in the tropical mesosphere by Gelinas et al. (1998). It is important to note the measurement by Gelinas et al. (1998) is of meteoric smoke particles proposed by Hunten et al. (1980) that are available as condensation nuclei for the larger water ice dust particles associated with PMSE and NLC observed during measurement of Havnes et al. (1996a).

Unfortunately, a nomenclature issue may arise as one may speak of the ‘dust’ particles of meteoric origin that may serve as condensation nuclei or the water ice ‘dust’ particles. Since this work will consider a plasma physics perspective, ‘dust’ will refer to either the Hunten or ice particles for notational simplicity, however, the context will be clarified as necessary.

It can be shown that the medium just described may satisfy criterion for being a dusty plasma. Using typical mesospheric parameters of $n_e \approx 10^9$ m$^{-3}$, $T_e \approx 150$ K, and $n_D \approx 10^8$ m$^{-3}$ for the region of sub-visible charged ice particles of size range 1 nm to 10 nm that are assumed to be the source region for PMSE. This implies $\lambda_D \approx 3$ cm, $a \approx 0.2$ cm and therefore $n_d < a < \lambda_D$ is well satisfied. In the lower part of the layer of visible particles (i.e. the NLC region) where inter-particle spacing increases, it may be difficult to maintain this criterion and the dust-in-plasma condition may possibly be more appropriate.

The scenario for generation of the upper atmospheric dust layer just described depends on ablation and re-coagulation of meteoric dust material in the tens of grams range as theoretically proposed by the early works of Rosinski and Snow (1961) and Hunten et al. (1980). This ultimately produces dust particles in the nm size range in the atmospheric dust layer. Recently a new mechanism has been proposed as an alternative to these ideas by Kelley (2015). Owing to the detection of interplanetary dust in the solar wind by the Cassini spacecraft, it is proposed that meteoric dust material is coated with a monolayer of these nm interplanetary dust particles. The existence of such a coating has been argued in the past due to the fact that comets survive close encounters with the sun and such a dust coating would provide insulation. Once the coated meteoric material enters the upper atmosphere, the monolayer of nm-scale dust is stripped off, falls and provides a source for the dust layer. As an example, an estimate shows
that a fairly sizable 500 g meteor could carry a monolayer of 10^{15} 1-nm dust particles. The flux of these nm-sized particles into the upper atmosphere from the meteor flux in the size range from 10 nm to 1 cm as proposed by Hunt et al. (1980) can be estimated to be of the order of 10^6 m^-2 s^-1. This flux would fill the empty dust layer in 4 months. The outflux from the dust layer near 90 km can be estimated to be of a similar magnitude using current measurements of charged dust density and the terminal fall velocity of the dust. This of course would produce a stable dust layer with the characteristics of current observational evidence. Further work is ongoing to refine this new model.

2.3. Fundamental physical processes in the dusty plasma

2.3.1. Charging. Charging is a fundamental process in a dusty space plasma and a number of models have been utilized for charged dust regions in the near-Earth space environment. Several of these will be briefly reviewed here. The most fundamental is the orbit-limited motion (OML) approach described and used by a number of authors (Bernstein and Rabinowitz 1959, Havnes et al. 1990, Shukla and Mamun 2002). This model may be used to estimate the equilibrium charge on the dust particles as well as to consider the dynamical charging process, which will be discussed in more detail subsequently. Assuming the primary currents are only from the electron and ion fluxes onto a dust particle for the moment, then the equilibrium of these two currents

\[ I_e + I_i = 0 \]  

will determine the equilibrium charge state. As an example, the currents for an attractive electron and repulsive ion interaction with a dust grain (ultimately yielding negative dust), are given by

\[ I_e = q_n \pi r^2 \sigma_{e,m} \exp(-q_e \varphi_d/k_B T_e) \]  

\[ I_i = q_n \pi r^2 \sigma_{i,m} (1 - q_i \varphi_d/k_B T_i) \]  

where the mean electron (ion) speed is \( v_{\text{me}}(\text{mean}) = \sqrt{8 k_B T_e(\text{mean})/\pi m_e(\text{mean})} \). The floating potential in terms of the dust charge (which may be obtained from the potential/charge relationship for a spherical capacitor) is given by

\[ \varphi_d = \frac{Q_d}{4 \pi e_0 \sigma_d}. \]  

The importance of the simultaneous numerical solution of expressions (4)–(7) for \( Q_d \) is that a nm-sized dust particle carries no more than a few negative charges. Negative charging is due to the higher electron thermal velocity. For typical mesospheric ions of roughly 50 proton masses (50m_p) and assuming for simplicity, equal electron and ion density (small dust density) and temperature \( T \), the floating potential from equation (4) is determined as \( e\varphi_d/k_B T \approx -4.0870 \). This expression with equation (7) may be used to roughly estimate the dust charge number variation with radius, which indicates that dust particles of the order of 10 nm will attain a few negative charges assuming mesospheric temperatures of near 150 K. Larger particles indicative of artificially created dusty space plasmas, in the range of 1 \( \mu \)m, existing at higher altitudes and temperatures with lighter ion species such as O^+\( (16 m_p) \), imply \( e\varphi_d/k_B T \approx -3.615 \). In this case, \( Z_d \) may be in the range of 100 to 1000 negative charges. Finally, it should be noted (and for the rest of the discussion) that magnetic field effects on the charging currents are neglected here. This is a reasonable approximation in applications when the electron and ion gyro-radii are larger than the dust grain size and Debye length but the effect may tend to charge a dust particle more negative (e.g. Lange 2016). A modified OML approach should be used otherwise (Tsytovich et al. 2003).

As the particles in the mesosphere only attach a small number of particles, it may also be effective to consider a rate of attachment for electrons and ions to the dust particles rather than currents as described in equations (5) and (6). This rate of attachment may be defined by dividing the currents by the charge of plasma species, \( s \), in equations (5) and (6); i.e. the rates of attachment for the OML model would be

\[ \nu_{\text{OML}} = I_s/q_s. \]  

An important quantity that can be obtained from equation (8) is the estimate of time period for a dust particle to charge (negatively) from the electron current. Taking \( Q_d = 0 \) initially (which implies \( \varphi_d = 0 \)), this charging time period is given by

\[ \tau_s = 1/\nu_{\text{OML}} \approx (n_s \pi r^2 \sigma_{e,m})^{-1}. \]  

As an example, for mesospheric parameters, this simplified expression gives roughly \( \tau_s \approx 1 \) s (e.g. Lie-Svendsen et al. 2003, Chen and Scales 2005).

Other models have been utilized for investigating charging of dust particles in the mesosphere. Two primary ones include the model of Draine and Sutin (1987) and Natanson (1960). These are expressed in terms of attachment rates for discrete particle charging rather than continuous currents as the OML model stated above and include induced dipole forces for attachment by neutral particles. The Draine and Sutin model for the rates of attachment of the plasma species \( s \) (electrons or ions) to dust particles is given by

\[ \nu_s = n_s \pi r^2 \sigma_{v,m} \nu(Q_d) \]  

with the species sticking coefficient given by \( s_s \). The function \( \nu(Q_d) \) depends on whether the interaction with the plasma species is for a neutral, attractive or repulsive dust particle. For neutral dust this induced image potential contribution is

\[ \nu(Q_d = 0) = 1 + \frac{\pi}{2a} \]  

For an attractive interaction

\[ \nu(Q_d) = \left( 1 - \frac{b}{a^2} \right) \left( 1 + \frac{2}{\sqrt{a - 2b}} \right) \]  

and for repulsive interactions

\[ \nu(Q_d) = \left( 1 + \frac{1}{\sqrt{4a + 3b}} \right)^2 \exp\left( -\frac{b/2a + 1}{1 + b/2a} \right) \]  

where \( a = 4 \pi e_0 \sigma_d k_B T/q_s^2 \) and \( b = Q_d q_s \). The sticking coefficients may be approximated by \( s_e \approx 0.5 \) and \( s_i \approx 1 \) (e.g. Biebricher et al. 2006).
The Natanson (1960) rates are often used and these attachment rates can be written as

\[ \nu_N = n_s \pi r_d^2 \nu_m \left(1 + \frac{e^2}{8e_0 k_B T_n} \right) \]  \hspace{1cm} (13)

for neutral particles,

\[ \nu_N = n_s \pi r_d^2 \nu_m \left(1 + \frac{|Z_d|e^2}{4\pi e_0 k_B T_n} \right) \]  \hspace{1cm} (14)

for attractive interaction between plasma species and dust particles and for repulsive interaction

\[ \nu_N^a = n_s \pi r_d^2 \gamma^2 \nu_m \exp \left[ -\frac{|Z_d|e^2}{4\pi e_0 \gamma k_BT_n} \left(1 - \frac{1}{2\gamma(\gamma^2 - 1)} |Z_d| \right) \right] \]  \hspace{1cm} (15)

where \( Z_d \) is the number of unit charges on the dust particle and \( \gamma \), which is the scaled distance where Coulomb and induced dipole attractive forces balance, is determined by solving \((2\gamma^2 - 1)\gamma(\gamma^2 - 1) = Z_d\). For example, \( \gamma \) is in the range of 1.62 to 1.22 for \(|Z_d|\) in the range from 1 to 7 unit charges.

All three of the sets of the attachment rates above (Natanson, OLM, and Draine and Sutin) have been effectively used by various authors (e.g. Rapp and Lubken 2001, Dimant and Milikh 2004, Biebricher et al 2006) for dust charging applications in the mesosphere, although the Natanson rates are more typical for the mesosphere primarily due to the small grain sizes and low/neutral charge states. All three approaches are expected to have limitations for small particles approaching 1 nm. Comparisons of the three charging models for particular mesospheric applications show qualitatively similar results (e.g. Chen and Scales 2007, Mahmoudian and Scales 2013). As will be discussed in more detail later, the Natanson coefficients have been modified by Robertson and Sterrnovsky (2008) to include the induced dipole force as well as the Coulomb force for attractive particles, motivated by recent in situ measurements that are not in line with the standard attachment coefficients. Ion collection is enhanced substantially by a factor of 2 for the smallest particles. For mesospheric particles smaller than 100 nm, it can be shown that the effect of collisions on the charging rates is small (Robertson and Sterrnovsky 2008).

A related concept to dust charging is photoemission, which results from a flux of photons incident on the dust particle surface releasing photoelectrons and ultimately resulting in positive dust particles. This occurs when the photon energy is larger than the photoelectric work function. An additional current may be added to equation (4), assuming positively charged dust and approximated by (Rosenberg 1996)

\[ I_p = -q_s \pi r_d^2 \varphi_0 Q_{ab} Y_p \exp \left( \frac{\varphi_s \varphi_0}{k_B T_p} \right) \]  \hspace{1cm} (16)

where \( I_p \), \( Q_{ab} \), and \( Y_p \) are the photon flux, efficiency of absorption for photons, the yield of photoelectrons and the photon average temperature. For negative grains, it can be shown that an approximation is \( I_p = -\pi r_d^2 \varphi_0 Q_{ab} Y_p \). These currents can be converted into an emission rate as in equation (8), i.e.

\[ \nu_p = \frac{I_p q_s}{e} \]. The importance of photoemission depends on the application in the near-Earth space environment. There has been some disagreement on the importance in the mesosphere in comparing theory and observations (e.g. Dimant and Milikh 2004, Hvisual et al 2003). However, calculations by Rapp (2009) indicate that photoemission is unlikely to be important for mesospheric ice particles but may possibly be important for MSPs with a sufficiently small radius (1 nm) and made of metallic compounds (e.g. FeS2, SiO) leading to photoelectrons. This is proposed as a possible explanation for the observed existence of both positive and negative dust particles in the mesosphere. Photoemission effects may be more consequential for active space experiments where larger dust particles (~1 \( \mu \)m) are produced (Bernhardt et al 2012).

Another charging process that may have relevance to mesospheric dust is due to hyperthermal electrons, which are a small population of electrons produced during auroral activity (Rosenberg et al 2012). This is a small population of secondary electrons, relative to the background electron population density \( n_e \) with density \( n_s \), drift speed \( V_H \) and thermal speed (energy) \( V_H \) such that \( n_d/n_e \ll 1 \) and \( V_H/V_d \ll 1 \), which may be observed during precipitation activity such as enhanced D layer absorption (Margot-Chaker and McNamara 1984). The additional attachment rate has been provided in Rosenberg et al (2012)

\[ \nu_H = n_t \gamma V_d \nu_m \left(1 - \frac{q_s \varphi_s}{k_B T_H} \right) \]  \hspace{1cm} (17)

where \( s_H \) is the sticking coefficient. Such an additional current may increase negative dust charging and allow shorter spatial scales (i.e. UHF PMSEs) to persist for longer periods of time (assuming 10 nm or larger dust particles), consistent with observations.

2.3.2. Collisions. Important collisional processes consist of those between electrons, ions and dust particles with the neutral background. The collisions of ions with the neutral background in the mesosphere is often calculated with the expression assumed valid for neutral particles smaller than 0.5 nm in radius (Hill and Bowhill 1977)

\[ \nu_{ea} = 2.6 \times 10^{12} n_a \left(0.78 \frac{28}{m_e + 28} \sqrt{\frac{1.74 m_e + 28}{28 m_e}} + 0.21 \frac{32}{m_e + 32} \sqrt{\frac{1.57 m_e + 32}{32 m_e}} + 0.01 \frac{40}{m_e + 40} \sqrt{\frac{1.64 m_e + 40}{40 m_e}} \right) \]  \hspace{1cm} (18)

where \( m_e \) is the mass of ion species \( s \), \( m_a \) is the atomic mass unit and \( n_a \) is the neutral density. The dust-neutral collision frequency can be described by an expression similar to that for hard sphere collisions (Epstein 1924) given by Schunk (1977)

\[ \nu_{dn} = \frac{8 \pi}{3 \sqrt{\frac{m_e}{m_d} + m_e \sqrt{\frac{2k_B T_d}{\mu_d}}} \left(\frac{r_d}{\mu} + e_d \right)^2} \]  \hspace{1cm} (19)
where $m_n \approx 29 m_e$ is the approximate mean molecular mass of air, $r_{De}$ is the dust (neutral) radius (where $r_e \approx 0.2$ nm), and the reduced mass is $\mu_n = m_m m_n (m_m + m_n)$. The electron-neutral collision frequency is given by

$$\nu_{en} = n_e \sigma_{en} \nu_e$$

(20)

where the cross-section $\sigma \approx \pi r_e^2$. Typical dust-neutral, ion-neutral and electron-neutral collision frequencies in the mesopause region are $\nu_{en} \approx 10^3$ Hz, $\nu_{in} \approx 10^7$ Hz and $\nu_{en} \approx 10^9$ Hz, which are to be compared with the dust, ion and electron plasma frequencies of $\omega_{pe} \approx 10$ Hz, $\omega_{in} \approx 10^4$ Hz, and $\omega_{en} \approx 10^6$ Hz (e.g. Lie-Svendsen et al. 2003, Robertson 2007). This indicates that normal ion and dust plasma modes are typically overdamped in the mesospheric dusty plasma region.

2.3.3. Conductivity. Charging and collisional processes involving dust also have important effects on currents in dusty space plasmas. This can be seen from the basic expression relating the plasma current density from ions and electrons in a magnetic field and the driving electric field $J = eE$ where the conductivity tensor is given by (e.g. Chen 1984)

$$\tilde{\sigma} = \begin{pmatrix} \sigma_0 & \sigma_{H} & 0 \\ \sigma_{H} & \sigma_0 & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix}$$

(21)

and $\sigma_0$, $\sigma_0$ and $\sigma_H$ are the parallel, Pederson and Hall conductivities, which are given by

$$\sigma_0 = n_e \frac{e^2}{m_e \nu_{in}} - n_e \frac{e^2}{m_e \nu_{en}}$$

$$\sigma_H = n_1 \frac{e^2 \nu_{in}}{m_1 (\nu_{in}^2 + \nu_e^2)} - n_1 \frac{e^2 \nu_{en}}{m_e (\nu_{en}^2 + \Omega_e^2)}$$

where $\Omega_{e(i)}$ is the electron (ion) gyrofrequency. The heavy charged dust mobility is taken as negligible in this case. Under these circumstances, it can be seen that the dust may impact the current in at least two ways. The first is the reduction of electron density through the charging process just described. For negative dust charging, the electron density is reduced to $n_e = n_1 - Q_d n_d$. The second impact of the dust is on the collision frequencies, which are impacted by electron and ion collisions with neutral dust particles. The collision frequencies used are adjusted to the total collision frequencies of electrons and ions with both dust and background neutrals, that is, $\nu_e = \nu_{en} + \nu_{id}$ and $\nu_i = \nu_{in} + \nu_{id}$. These collision frequencies with dust may be roughly approximated with $\nu_{e(i)} \approx \pi r_d^2 \nu_{e(i)}^2$. As an example, it has been proposed that both aspects of the impact of dust on currents through the conductivity have a number of important implications for electrojet currents in the E layer between 90 and 120 km including reduction and possible reversal of the currents (Muralikrishna and Kulkarni 2008).

2.3.4. Diffusion. Diffusion processes in a dusty space plasma are fundamentally important in the evolution of electron density fluctuations coupled to turbulence in the background neutrals, as will be discussed in more detail shortly. Diffusion smoothes the electron and ion density fluctuations at small spatial scales and understanding the impact of charged dust on the diffusion process is critical for understanding in situ spacecraft measurements and radar scatter produced by the electron density fluctuations. Concepts of diffusion in such a plasma environment were first successfully applied to experimental observations by Kelley et al. (1987) and Kelley and Ulwick (1988). Owing to the presence of the heavy dust in the background electron-ion plasma, it is multiconstituent and the diffusion may most appropriately be described as multipolar diffusion, which is an extension of ambipolar diffusion in an electron-ion plasma (Hill 1978a, Hill et al. 1999, Rapp and Lubken 2004). Multiconstituent ambipolar diffusion is also an alternate terminology that has been used. A brief description of this diffusion process is as follows. The simplified circumstance of electrons, positive ions and negative dust with no charging effects and equal temperature $T$ will be considered. Under the assumption that the spatial scales of the neutral background turbulence structuring is larger than the electron Debye length, then quasineutrality can be assumed, implying zero net current and approximate charge neutrality. Plasma diffusion equations can then be derived by the standard procedure (e.g. Chen 1984). Fluxes for each species are substituted into the continuity equations and in this case they yield diffusion equations that are nonlinear due to addition of the charged dust. Upon linearization, diffusion equations for the fluctuations in the electron density, $n_{ec}$, and the sum of positive ions and dust, $n_{id} = n_1 + n_d$, become (Hill 1978a)

$$\frac{\partial n_{ec}}{\partial t} = \frac{D_1 - D_2}{2} \nabla^2 n_{id} + \left[ D_1 + \frac{D_1 + D_2}{2} (1 + 2h) \right] \nabla^2 n_{ec}$$

(22)

$$\frac{\partial n_{id}}{\partial t} = \frac{D_1 + D_2}{2} \nabla^2 n_{id} + \left[ D_1 + \frac{D_1 - D_2}{2} (1 + 2h) \right] \nabla^2 n_{ec}$$

(23)

The diffusion coefficient of plasma species $s$ is denoted by $D_s = k_B T_s / m_s \nu_{Di}$. As these are coupled linear differential equations, eigenvalues that correspond to two diffusion modes may be obtained from standard mathematical techniques. The two corresponding diffusion coefficients $D_{1,2}$ can be easily be calculated to be

$$D_{1,2} = \frac{1}{2} \left[ D_1 + (D_1 + D_2) (h + 1) \right]$$

$$\pm \frac{1}{2} \left[ D_1^2 (h + 2)^2 + 2D_2D_3 (h - 2)(h + 1) + D_3^2 (h + 1)^2 \right]^{1/2}$$

(24)

where $D_1$ corresponds to the positive sign on the square root and $D_2$ the negative sign. Physically the two coefficients correspond to two diffusion modes. The first described by $D_1$ involves the interaction between the electrons and positive ions and the second described by $D_2$ involves the interaction between the electrons and negative dust. The interactions are due to the multipolar (or multiconstituent ambipolar) electric field. The importance of this is that the slowest of these diffusion modes controls the lifetime of electron density fluctuations. This lifetime is enhanced due to the heavy charged dust by introducing the slow diffusion mode (i.e. much smaller
diffusion coefficient) associated with $D_2$. It should be noted that by neglecting the dust ($D_d = 0$ and $h = 0$) then $D_1 = 2D_i$ which is the standard ambipolar diffusion result for an electron–ion plasma of equal temperatures (e.g. Chen 1984) and is reasonably adequate for characterizing fluctuations on timescales that are short relative to any substantial dust motion (e.g. Lie-Svendsen et al 2003). The parameter that describes the slowing of the electron (particle) diffusion relative to neutral (velocity) diffusion is the Schmidt number, which is the ratio of the neutral (air) kinematic viscosity $\nu_a$ to the slow mode electron diffusion coefficient $D_2$ and is given by

$$S_c = \frac{\nu_a}{D_2}$$

(25)

(e.g. la Hoz et al 2006). Therefore, enhancement in the Schmidt number corresponds to longer lifetimes of fluctuations on a shorter spatial scale. This is a fundamental concept in such a dusty plasma environment with strong coupling to neutral particle dynamics. Further details of the application of this parameter to interpretation of the behavior of electron density fluctuations and radar observations will be provided in section 4.2. A final important parameter is the diffusion time, which is given by $\tau_D \approx (\lambda/2\pi)^2/D$ for sinusoidal plasma fluctuations of wavelength $\lambda$ (Chen 1984). Assuming 3 m fluctuations (common for VHF Bragg scatter radar measurements), the ambipolar (or fast) diffusion time is roughly of the order of 1 s or less and the slow diffusion time is of the order of hundreds of seconds (e.g. Lie-Svendsen et al 2003, la Hoz et al 2006).

### 2.4. Creation of artificial dusty space plasmas

Rocket engine firings often occur in the upper atmosphere and may produce a number of observable signatures (Bernhardt et al 2012). These include electron density reductions, optical emissions and generation of plasma waves. Early work on modeling microphysics leading to the production of dusty ice particles by rocket engines through exhaust cooling and condensation and the associated ionospheric modification through pickup of electrons was provided by Bernhardt et al (1980). Such active production of dusty space plasmas may be used to access the impact of artificial dust layers on various communication systems in the UHF, S and L frequency bands. Also, as described in section 2.2, as natural dust layers produce radar scatter, possibilities exist for further insight into radar scatter theories from natural dusty plasma turbulence. The type of rocket exhaust believed to be most effective for artificial generation of dusty space plasmas is solid rocket motors. These generate particulates of aluminum oxide ($\text{Al}_2\text{O}_3$) that may capture ionic electrons, and it is argued to effectively create a heavy negatively charged dust cloud (or so-called dirty plasma) through the chemical reaction

$$\text{Al}_2\text{O}_3 + e^- \rightarrow \text{Al}_3\text{O}_2$$

(26)

which produces heavy negative molecules. The rocket exhaust is typically 2–3 km s$^{-1}$ relative to the spacecraft velocity of 8 km s$^{-1}$. The temperature is quite low, of the order of 120 K. The progression of the exhaust interaction with atmospheric neutrals proceeds through the following phases: (1) a snowplow leaving a depleted region behind the exhaust gas; (2) collisional heating; and (3) chemical reactions. The plasma interaction with the exhaust includes ion–molecule charge exchange, electron–ion recombination and optical emissions from chemiluminescence.

Creation of an artificial dusty plasma was undertaken with the first charged aerosol release experiment (CARE I). The experiment released approximately 111 kg of $\text{Al}_2\text{O}_3$ and also 200 kg of other exhaust gas vapors at 280 km altitude (Bernhardt et al 2011, 2012). The particles ranged from 100 nm to 10 $\mu$m in size, with a peak in the size distribution at 1 $\mu$m. Along with the $\text{Al}_2\text{O}_3$ ‘dust’, 200 kg of molecules are created that undergo ion-molecule interactions. The instrument package allowed the effects of the charged particulate dust from the hypersonic ion beam created by the exhaust vapors to be distinguished. The primary signature of the artificially created dust layer on CARE 1 was the visible signature due to the particulates scattering sunlight. Figure 5 shows the artificial dust layer created by the CARE 1 experiment.
A CARE II experiment was launched on September 16, 2015 at 19:06 GMT, from Andoya, Norway, with a more extensive set of instrumentation to carefully assess the plasma environment during the dust release. A dust cloud of Al2O3 particulates was created utilizing 37 small rocket firings to inject 68 kg of material. This was also accompanied by 133 kg of molecules including CO2, water vapor and hydrogen. Measurements were made with plasma probes and electric field booms on the deployable instrument payload. Multi-frequency beacon transmissions from the rocket payload were used to monitor ionospheric disturbances with ground receivers. Ground-based radars and optical instruments also monitored the dust release. Analysis of the observations is currently ongoing. It can be validated here that such active experiments may produce a dusty plasma. For instance, assuming typical F-layer parameters near the peak electron density of \( n_e \approx 10^4 \text{m}^{-3} \), and \( T_e \approx 1000 \text{K} \), then \( \lambda_0 \approx 3 \text{mm} \). Assuming the Al2O3 dust density is only 1% of the electron density (i.e. \( n_d \approx 10^{10} \text{m}^{-3} \)), implies an interparticle spacing of \( a \approx 0.5 \text{mm} \) and therefore \( a_0 < a < \lambda_0 \), satisfying the criterion. From another perspective, it has long been proposed that space shuttle exhaust could produce dusty space plasmas (e.g. Bernhardt et al 1995). Recently, Kelley et al (2010) have more closely linked space shuttle launches at solstice to direct creation of NLCs, PMSEs and sporadic E layers using LIDAR, UHF radar and wide-angle cameras. These observations have similar characteristics to such observations made in the past, showing that a solstice shuttle launch produced NLCs and sporadic iron layers (Stevens et al 2003, 2005). Modeling of the chemistry showed that enhanced water vapor due to the shuttle exhaust necessitates both the atom and ion (Fe) layers. Finally an important outcome of the observations is that the impact of the transport of the exhaust plume to the poles is ultimately argued to be due to thermospheric turbulence effects (Kelley et al 2009).

3. Models

A spectrum of computational models have been proposed and utilized to investigate plasma processes in the near-Earth space environment including the effects of charged dust particles. Some recent models include full particle-in-cell (PIC) as well as purely fluid models (e.g. Winske et al 1995, Lie-Svendsen et al 2003, Havnes 2004, Biebricher and Elbing et al 2012). These have been used for studying a variety of processes including: density, electric field and potential structures; diffusion processes; responses of electron density fluctuations during active ground-based radiowave heating; active creation of dusty space plasmas; and dusty plasma waves and instabilities. A 1D unmagnetized model will be described here that employs a hybrid approach with fluid electrons and ions and PIC Monte Carlo Collision (PIC-MCC) dust particles, which allows for flexibility in incorporating dynamical charging models for the dust as well as dust mass distributions (Scales 2004, Chen and Scales 2005, Mahmoudian and Scales 2013). It may be used for investigating the physical processes just noted. A simplified version is described as follows.

The ions are treated with continuity and momentum equations

\[
\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_i) = Q - L + \frac{dn_i}{dt}_{\text{charging}} \tag{27}
\]

\[
\mathbf{v}_i = \frac{1}{m_i} \left( \frac{q_i}{m_i} \mathbf{E} - \frac{1}{n_i m_i} \nabla p_i \right) + \mathbf{V}_a. \tag{28}
\]

Here \( n_i, \mathbf{v}_i, m_i, q_i \) are the ion density, velocity, mass, and charge, \( Q \) and \( L \) are the ionospheric production and loss, and \( dn_i/dt_{\text{charging}} \) is the ion loss due to charging onto the dust particles. Also in equation (28), \( \mathbf{V}_a \) is a driving neutral particle velocity, \( \nu_{ia} \) is the ion–neutral collision frequency, \( \mathbf{E} \) is the electrostatic field, and \( p_i \) is the ion pressure. For a deterministic discrete state dust charging approach, the ion loss term due to dust charging can be written as \( dn_i/dt_{\text{charging}} = \nu_{ia} n_i \) where the total effective charging rate may be calculated using a chosen set of ion attachment rates in section 2.3.1 from \( \nu_e = \sum_{Z} \mathcal{N}(Z) \nu'(Z) \) where \( \nu'(Z) \) is the ion attachment rate at discrete charge state \( Z \) and the dust density (normalized to \( n_i \)) at charge state \( Z \) is described by the dynamical equation

\[
d\mathcal{N}/dt = \nu'(Z - 1) \mathcal{N}(Z - 1) - (\nu'(Z) + \nu'(Z)) \mathcal{N}(Z) + \nu'(Z + 1) \mathcal{N}(Z + 1)
\]


The model described here uses an alternate approach by collecting charge on individual simulated dust particles, and has several advantages to be discussed including possibilities for stochastic charging. The dust particles are treated with the PIC-MCC method (e.g. Birdsell 1991) in which individual particles are dynamically advanced in time with the Lorentz force equation

\[
\frac{d\mathbf{x}_{ij}}{dt} = \frac{Q_{ij}}{m_{ij}} \mathbf{E}_{ij} \tag{29}
\]

\[
\frac{d\mathbf{v}_{ij}}{dt} = \mathbf{v}_{ij} \tag{30}
\]

where \( \mathbf{x}_{ij}, \mathbf{v}_{ij}, m_{ij}, \) and \( Q_{ij} \) are the individual dust particle position, velocity, mass, and charge. The latter two quantities \( (m_{ij},Q_{ij}) \) vary in time according to prescribed models as will be described later. \( \mathbf{E}_{ij} \) is the weighted electric field at the particle position. It should be noted that a variety of other dust particle forces may be incorporated in equations (28) and (29) as necessary for the particular application, such as the gravitational force \( \mathbf{g} \). A variety of possibilities for charging models exist for the dust particles. Continuous as well as discrete stochastic approaches have been employed (e.g. Chen and Scales 2005, Biebricher and Havnes 2012, Mahmoudian and Scales 2013) due to the variety of particle sizes for various applications as discussed in section 2.3.1. It may be argued that smaller dust that acquires only a few charges may be more accurately described with a discrete stochastic charging model. However, the PIC model utilizes super-particles in which one simulation particle represents many actual plasma particles.
and thus can be considered to carry an average charge when using a continuous charging model. Comparisons of continuous and discrete stochastic charging models have been shown to produce quite similar qualitative results for dust particles larger than 5 nm (e.g. Chen and Scales 2005, Mahmoudian and Scales 2013). Therefore, one possibility of the charging model is to employ the simplest version of the continuous OLM model described in section 2.3.1,

\[ \frac{dQ_{ij}}{dt} = I_{ij} + I_{ij} \]  

(31)

here \( I_{ij} \) and \( I_{ij} \) are the electron and ion currents to the individual dust particles. Assuming negative (or neutral) dust particles, then the currents can be written as

\[ I_{ij} = q_{e}n_{e} \pi r_{d}^{2} \nu_{me} \exp(-q_{e} \varphi_{ij}/k_{B}T_e) \]  

(32)

\[ I_{ij} = q_{i}n_{i} \pi r_{d}^{2} \nu_{mi}(1 - q_{e} \varphi_{ij}/k_{B}T_i) \]  

(33)

and for positive dust particles, the currents can be written as

\[ I_{ij} = q_{e}n_{e} \pi r_{d}^{2} \nu_{me}(1 - q_{e} \varphi_{ij}/k_{B}T_e) \]  

(34)

\[ I_{ij} = q_{i}n_{i} \pi r_{d}^{2} \nu_{mi} \exp(-q_{e} \varphi_{ij}/k_{B}T_i) \]  

(35)

where \( r_{d} \) is the individual dust particle radius,

\[ \nu_{mi}(i) = \frac{8k_{B}T_{mi}(i)}{\pi m_{i}(i)} \]. 

The individual dust particle floating potential is given by

\[ \varphi_{ij} = \frac{Q_{ij}}{4\pi \varepsilon_{0} r_{d}^{2}}. \]  

(36)

Other charging models that have been utilized for various applications by other authors (e.g. Dimant and Milikh 2004, Robertson and Sternovsky 2008, Biebricher et al. 2012) can easily be incorporated into the aforementioned framework either through continuous currents or with discrete charging rates (Chen and Scales 2007, Mahmoudian and Scales 2013). Implementation of stochastic discrete charging models using PIC-MCC will be described in section 4.1. Finally, possibilities also exist for easily incorporating other currents due to modified electron distribution functions resulting from geophysical activity such as the impact of a hyperthermal electron population associated with D layer absorption or photoemission as discussed in section 2.3.1.

Possibilities for dust mass (or equivalently dust radius considered here as \( r_{d} \sim m_{d}^{1/3} \)) distributions include uniform or Gaussian. A uniform dust radius distribution is of the form

\[ f(r_{d}) = \frac{1}{r_{d_{\text{max}}} - r_{d_{\text{min}}}} \]  

(37)

where \( r_{d_{\text{max}}} \) and \( r_{d_{\text{min}}} \) are the maximum and minimum dust radius. A Gaussian dust radius distribution may be expressed by (Berger and von Zahn 2002)

\[ f(r_{d}) = \frac{1}{\sqrt{2\pi} \sigma_{r_{d}}} \exp\left[-(r_{d} - r_{d_{0}})^{2}/2\sigma_{r_{d}}^{2}\right] \]  

(38)

where \( r_{d_{0}} \) and \( \sigma_{r_{d}} \) are the mean and standard deviation of the dust radius.

Collisions of the dust with neutrals is incorporated with a Langevin approach in which the velocity vector is randomly scattered every time step and the magnitude conserved (Winske and Rosenberg 1998). The collision frequency is given as

\[ \nu_{ij}(t + \Delta t) = \nu_{ij}(t) \exp(-\nu_{\text{dia}}\Delta t) + \nu_{ei}(1 - \exp(-\nu_{\text{dia}}\Delta t)) + \nu_{\text{dust}}(1 - \exp(-2\nu_{\text{dia}}\Delta t))^{1/2} N_{t} \]  

(39)

where \( N_{t} \) a uniform random number on (0 1) and \( \nu_{\text{dia}} \) and \( \nu_{\text{dust}} \) are the dust neutral collision frequency and thermal velocity, respectively. The neutral driving velocity is given by \( V_{n} \). The electron density is calculated from a condition of quasi-neutrality

\[ n_{e} = n_{i} - Z_{d} n_{d}. \]  

(40)

The electron velocity, which is not directly required in the calculation, is of the same form as that of (28)

\[ \nu_{e} = \frac{1}{m_{e}} \left( \frac{q_{e}}{m_{e}} \hat{E} - \frac{1}{n_{m_{e}}} \nabla p_{e} \right) + V_{n} \]  

(41)

Finally the electric field is calculated from a condition of current density closure in one dimension

\[ \hat{J} = \sum_{s} q_{n} n_{s} \nu_{s} = 0. \]  

(42)

This yields for the electric field

\[ \hat{E} = \frac{q_{e} D_{e} \nabla n_{e} + q_{i} D_{i} \nabla n_{i} - \hat{J}_{d}}{q_{e} \mu_{e} n_{e} + q_{i} \mu_{i} n_{i} + Q_{\text{dust}} q_{d}} \approx \frac{k_{B}T_{e}}{e} \hat{\nabla} (\log(n_{e})) \]  

(43)

where \( D_{s} = q_{s} k_{B} T_{s} \mu_{s} \) and \( \mu_{s} = q_{s}^{2}/m_{s} \mu_{s} \) are the diffusion and mobility coefficients of species \( s \), and \( \hat{J}_{d} \) is the dust current density calculated from the PIC dust particles. Owing to the small electron mass, the later expression in (43) is usually a good approximation for the electric field.

The computational cycle consists of initialization of all species densities and velocities. The electric field may then be calculated from (43). The dust and ion velocities may be advanced (as well as dust charge) and then their densities updated. The cycle is then repeated with calculation of the electric field. It is noted that an alternate approach to that just described, rather than using current closure for the electric field calculation (i.e. equations (42) and (43)), is to use Poisson’s equation, which requires a full time integration solution of an electron continuity equation (e.g. Biebricher and Havnes 2012). This approach has advantages and disadvantages, however. The applications to be discussed here are well described by the model just provided. As noted by Hill (1978a), if the spatial scales of the plasma fluctuations due to the neutral fluctuation driving force is of the order of the Debye length or smaller, the plasma will be non-neutral rather than quasineutral and Poisson’s equation rather than current closure is preferred.

2D models that consider magnetic field (\( B \)) and additional physics including electron inertia and other important ion wave phenomena (e.g. dust ion acoustic, drift and shear-driven waves) including kinetic effects (utilizing PIC) have been described and utilized elsewhere (e.g. Bordikar and Scales 2012, Fu and Scales 2013). These are relatively
straightforward extensions of the previously described model by including magnetic field forces in the momentum and particle Lorentz force equations (assuming charged particle gyroradii are much larger than the dust grain size) and will not be discussed in detail. An advantage of such models is the ability to consider the electrodynamics of localized dust cloud creation and associated processes due to shear and density gradient driven processes at the cloud boundary for expansion across a magnetic field. Also, low-frequency dust acoustic waves generated by cross-field electron currents analogous to the Farley-Buneman instability in an electron–ion plasma have been investigated (Scales and Chae 2003). These configurations may occur during active aerosol releases in the space environment and meteor trails.

4. Applications

4.1. Plasma density, potential and electric field structures

4.1.1. Small scale fluctuations. One of the most basic effects of charged dust on the space plasma environment is the alteration of the plasma density, potential and electric field structure due to the dust charging process. Assuming an irregular dust background density, this will result in irregular densities in electrons and ions through the dust charging process. This is important for a number of reasons. It of course may provide electron density fluctuations that scatter ground-based radar signals and allow remote sensing of the dust layer. For instance, in the polar mesosphere, this ultimately leads to the peculiar polar mesospheric summer and winter radar echoes (e.g. Ecklund and Balsley 1981, Cho and Kelley 1993, Cho and Rottger 1997, Rupp and Lubken 2004), which continue to be an important and intense area of investigation in the space science community after over 30 years. For substantially high dust densities, significant reductions in the electron density may result over large spatial regions, which are referred to as electron bite-outs (e.g. Reid 1990, Jensen and Thomas 1991). The impacts of dust clouds on potential and density structures have been considered in some detail in the mesosphere with the model of Lie-Svendsen et al (2003). Active space experiments that release dust clouds at higher altitudes in the ionosphere are also proposed and observed to produce a plethora of modifications on the background plasma environment (Bernhardt et al 2012). As will be described in the following, measurement of the structure of the plasma density, potential and field structures may ultimately lead to diagnostic information on the dust particles.

First, consider a simplified stationary (in time) dust density fluctuation composed of sinusoids embedded in the background plasma described by the 1D model of the previous section with periodic boundary conditions of the form

$$n_d(x) = n_{d0}\left(1 + \sum_m b_n d_{m0} \sin(2\pi mx/\ell + \phi_n)\right)$$

(44)

where $n_{d0}$ is the background dust density and $b_n d_{m0}$ is the dust density fluctuation amplitude of mode $m$ where $b_n d_{m0} n_{d0} \ll 1$ and a value of 0.2 in the mesosphere is not unreasonable. Also $\ell$ is the system length and $\phi_n$ is a random phase to replicate a simplified turbulent spectrum. The wavelength of mode $m$ is determined by $\lambda = \ell/m$. Charging onto this irregular dust density by electrons and ions produces fluctuations in the electron and ion density. Parameters to be used are those typical of the earth’s polar mesosphere and are described in table 1.

Figure 6 shows the relative phasings of the electron and ion fluctuations ($b n_e$, $b n_i$), assuming a single sinusoid in equation (44) for simplicity, in the presence of two dust fluctuation ($b n_d$) spatial scales, calculated with the model of section 2. Parameters associated with figure 6 are $n_d = 10^9$ m$^{-3}$, $r_d = 10$ nm, $n_{d0} m_{d0} = 0.6$ and only negative dust particles are considered. The shorter spatial scale is 0.7 m and the longer is 20 m. The fluctuations show anti-correlation (180° phase shift) of the electron and ion fluctuations for short spatial scales and correlation (in phase) for the longer spatial scales. The relationship between the fluctuations in the short wavelength regime may be described using basic perturbation analysis (e.g. Robertson 2007, Scales and Chen 2008). Assuming Boltzmann electrons and ions (instantaneous diffusion regime), the electron and ion fluctuations, $b n_e$ and $b n_i$ may be related to the electrostatic potential fluctuation $\delta \phi$ by

$$\frac{\delta n_e}{n_{e0}} \approx -\frac{T_i}{T_e} \frac{\delta n_i}{n_{i0}} \approx -\frac{e\delta \phi}{k_B T_e}.$$  \hspace{1cm} (45)

The relation between the electron and dust fluctuations can be shown to be

$$b n_e \approx -Z_d n_{d0} \frac{1}{n_{e0}} \frac{1}{\lambda_{Dk}^2/\lambda_{Dk}^2 + \lambda_{De}^2} b n_d.$$  \hspace{1cm} (46)

These expressions show the electron fluctuations are 180° out of phase (anti-correlated) with the ions and with the dust and provide agreement with the simple model calculation for the short wavelength case in figure 6(a). Anti-correlation between the electron and ion fluctuations for short fluctuation wavelengths may be understood in terms of ambipolar diffusion (Lie-Svendsen et al 2003). After creation of the electron density depletion by electron charging onto the irregular dust density, ambipolar diffusion pulls electrons and ions into the depletion, reducing the electron depletion somewhat but producing an enhancement in the ion density. This ultimately results in anticorrelation of the fluctuations. Of course, due to the electron charging onto the dust, the electron and dust fluctuations are anticorrelated as well. The majority of in situ space measurements show anticorrelation for the ion and electron fluctuations for the shorter wavelengths. Figure 7 shows in situ

<table>
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<tr>
<th>Table 1. Plasma parameters used in calculations.</th>
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<tr>
<td>Plasma Parameter</td>
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<tr>
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<tr>
<td>Electron density $n_e$</td>
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<tr>
<td>Negative dust radius $r_d$</td>
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<tr>
<td>Negative dust density $n_d$</td>
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<tr>
<td>Positive dust radius $r_q$</td>
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<tr>
<td>Positive dust density $n_q$</td>
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<tr>
<td>Ion neutral collision frequency $v_{in}$</td>
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<td>Recombination rate $L$</td>
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<td>Electron-ion production rate $Q$</td>
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<td>Ion mass $m_i$</td>
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space measurements from rocket payloads launched from the Andoya range in 1993 and 2001 that demonstrate anti-correlation (a) and also correlation (b) of electron and ion fluctuations, respectively. An important result of the work by Lie-Svendsen et al (2003) was that correlation could be explained as due to larger dust particles (which enhance ion charging) or longer wavelength fluctuations (as shown in figure 6(b)), both of which tend to reduce the impact of ambipolar diffusion. Such reasoning would predict the fluctuations of figure 7(b) may possibly exist in a region of larger dust particles near the bottom of the dust layer described in section 2.2. Therefore, the phasing of fluctuations may provide an important diagnostic for particle size and other dust characteristics during in situ measurements. This investigation also led to predictions of an optimal size of 10–30 nm particles for production of electron fluctuations that cause PMSE. However, this analysis was found to have some inconsistencies with observations of the ECOMA experiment (Bratli et al 2009) unless positive dust particles were somehow included in the plasma.

The previous calculations have considered only negatively charged dust. Positive dust particles have been measured at mesospheric altitudes (e.g. Robertson 2009). This has brought into question concepts on the basic charging models of dust particles in the mesosphere. Concentrations of a mixture of positive and negative dust may also impact the electron and ion fluctuations just described. A proposed model (Robertson 2009) considers the growth of small positive particle embryos of nm size, which eventually become large enough to become neutral and then finally negative as they approach several nm in size, as schematically shown in figure 8.

It may be argued that a modified Natanson charging model would be appropriate under circumstances in which there are such small dust particles that only carry a few charges and are in a mixture of positive, neutral and negative charge states (Mahmoudian and Scales 2013). The modified Natanson model includes the induced dipole force, which may increase ion and electron collection rates by a factor of 2 for small dust particles during attractive interaction between dust and
electrons and ions. In this case, equations (13) and (15) are still utilized, however the attractive attachment rate for the modified model, equation (14), is given for the \( j \)th dust particle by (Robertson and Sternovsky 2008)

\[
\nu_{j} = n_0 \pi r_d^2 \nu_{\text{ms}} \left( 1 + C_Z \frac{e^2}{16 \pi \varepsilon_0 \varepsilon_k k_B T_s} + D_Z \frac{|Z| q_s^2}{4 \pi \varepsilon_0 \varepsilon_k k_B T_s} \right). \tag{47}
\]

Here \( C_Z \) and \( D_Z \) depend on charge state \( Z \) and some numerical values are given in table 1 of Robertson and Sternovsky (2008). The terms involving \( C_Z \) and \( D_Z \) correspond to the Coulomb and dipole force contributions, respectively. The subscript \( s \) is either \( e \) or \( i \) for electron or ion attachment respectively. For implementation in a stochastic discrete charging model (e.g. Cui and Goree 1994, Chen and Scales 2007) the electron and ion attachment probability can be defined during the time interval \( dt \) as

\[
P_{j} = 1 - e^{-\nu_{j} dt} \tag{48}
\]

where \( \nu_{j} \) is the appropriate (repulsive, attractive, or neutral interaction) charging rate for the \( j \)th particle of species \( s \) (e.g. Birdsall 1991). The above probability is compared with a uniform random number \( \alpha \) and if \( \alpha < P_{j} \), then the plasma species particle will be collected by the dust grain and the corresponding dust charge number will be adjusted by one charge unit. The plasma species density is also adjusted according to equation (27).

Figure 8 provides the time evolution of the density structures using this charging model in the plasma model of the previous section assuming the dust particle growth where positive particles grow from small molecular ions or cluster ions (Arnold 1980, Turco et al. 1982, Sugiyama 1994, 1995, Gumbel et al. 2003) and become neutral by capturing electrons as they grow (Robertson 2009). It is observed that there is a variation between correlation and anticorrelation of the electron and ion fluctuations depending on whether the dust particles are dominantly positive or negative which may provide another important diagnostic. In general, the qualitative agreement with the experimental observations is better assuming a mixture of neutral, positive and negative dust particles (Mahmoudian and Scales 2013). Therefore, further insight into the charge state and size of dust particles may be obtainable from the relative phasing of the electron and ion fluctuations from \textit{in situ} observations.

4.1.2. Larger-scale structures. Larger-scale localized dust clouds of course also have an important impact on a background space plasma. The most obvious is the possibility of a large-scale depletion in electron and ion density. There may also be important influences in the electric field and plasma flow structures. This influence is particularly clear in the boundary layer between the ambient plasma and the dusty plasma that exists inside the dust cloud. This may ultimately lead to the collective effects that will be discussed shortly. To briefly demonstrate this basic concept, consider an initial model neutral dust density of the form

\[
n_0(x) = n_0 \left( \tanh \left( \frac{x - x_1}{w} \right) - \tanh \left( \frac{x - x_2}{w} \right) \right) \tag{49}
\]

where \( w \) defines the density scale length of the boundary layer and \( x_1 \) and \( x_2 \) describe the width of the cloud. Figure 9 shows an example of the dust, electron and ion density that illustrate the creation of a bite-out, as well as the electrodynamic structure at the edge of the dust cloud. Note that an ambipolar electric field (which can be described by equation (43)) as well as a significant associated electron flow develops in the boundary layer. The ion flow is relatively small (Scales and Ganguli 2004a, 2004b). This field depends on the steepness of the boundary.
It is also influenced by the collision frequencies, particularly the dust–neutral collision frequency. This electron flow is particularly important as it may possibly lead to dusty plasma-associated waves inside the dust cloud as will be described later. Also in a background magnetic field $\mathbf{B}$, a strong $\mathbf{E} \times \mathbf{B}$ drift may result and produce plasma waves (e.g. Fu and Scales 2013). In situ space measurements show rich wave (fluctuation) behavior associated with such configurations.

The DROPPS experiment (Goldberg et al 2001) has provided simultaneous measurement of the charged dust cloud, electron density reduction and fluctuating electric field structures using both in situ space and ground-based measurements. Results are shown in figure 10. It can be seen that in the region of the electron depletion (bite-out) in figure 10(b), due to dust charging, significant electric field wave activity was observed figure 10(a). Some possible interpretations of this activity will be discussed shortly. Also observed are the subvisible dust particles in the 1 nm to 10 nm range (which produce PMSEs) in figure 10(c), visible particles near 50 nm in figure 10(d) associated with NLC and the resulting radar scatter (PMSE) at 53 MHz, figure 10(e). It was noted the electric field waves/fluctuations associated with electron bite-out region have a frequency of the order of 10 Hz and electric field amplitude of about 10 mV m$^{-1}$. The fluctuations below the PMSE source region have a higher frequency, of the order of 1 kHz, which is associated with the larger dust particles and NLCs.

4.2. Electric field and plasma density fluctuations via neutral turbulence coupling

The previous section considers what are called ‘fossil turbulence’ structures in the plasma (Cho et al 1996, Rapp and...
Lubken 2004). That is, plasma density structures resulting from stationary dust density structures caused by neutral turbulence that has previously decayed away. This section will consider the consequences of the impact of an active driving neutral wind velocity field on the dusty plasma. Neutral air turbulence can couple to mesospheric dusty plasmas to generate electric fields and density fluctuations in the charged particle species, including the electrons, ions and dust. Neutral air turbulence is typically considered the driver for the electron density fluctuations that scatter radar signals at the Bragg scale ($\lambda/2$) ultimately resulting in the PMSEs described in section 2.2. The other critical factor is that the dust particles, which collisionally coupled to the turbulent neutrals, also slow the electron diffusion to allow the electron fluctuations to be long-lived enough to be observed (particularly at very short spatial scales or high radar frequencies). This allows electron structures in the plasma to exist that are of much shorter spatial scales than those in the neutral gas. As discussed in section 2.3.4, the parameter that describes this slowing of the electron (particle) diffusion to neutral (velocity) diffusion is the Schmidt number, $S_c$. It will be shown that an enhanced $S_c$ larger than one implies electron fluctuations exist at smaller spatial scales than the smallest neutral velocity fluctuation scales determined by the Kolmogorov energy dissipation scale $\eta_K = (\nu^2 E)^{1/4}$ where the turbulence energy dissipation rate is defined as $\varepsilon = 8.4\sigma_v^2$ and $\sigma_v^2$ is the velocity variance. The length scale that separates the inertial subrange from the viscous subrange where fluctuations are suppressed by dissipation processes is $\sim 40\eta_K$. $S_c$ increases with reduction in the slow mode diffusion coefficient $D_2$, described in section 2.3.4, which depends on the Havnes number $h = |Z_{AI}n_{AI}/n_e|$. Typical values of $S_c$ must be of the order of 100 for VHF observations and 1000 for UHF observations.  

4.2.1. Linear analysis. Before considering the full coupling to a turbulent neutral field with a statistical analysis, it is instructive to gain some basic insight from a small amplitude linear analysis. The impact of a neutral turbulence driving field on small amplitude plasma fluctuations in such a configuration and some of the important consequences was described in a theoretical model by Robertson (2007). This also has important consequences for electric field and potential measurements on rocket probes as well (Sternovsky et al 2004). The model of section 3 may be utilized to demonstrate some of the important concepts. To model the neutral air turbulence a driving velocity field is considered to be a superposition of sinuosoids, similar to equation (44), and given by

$$\vec{V}_d(x, t) = \sum m N_{n_m} \cos(k_m x - \omega_m t + \phi_m).$$

An acoustic wave is assumed with the dispersion relationship $\omega = ke u$ where the neutral sound speed is $c_m = \sqrt{\gamma / \kappa T_e} |m| \gamma / \kappa T_e$ where $\gamma$ in general corresponds to the ratio of specific heat for the s species. Assuming small amplitudes of the neutral fluctuations, a linearized continuity equation can be used to relate the fluctuating amplitude of the velocity field and the amplitude of the fluctuating neutral density (for a single mode) as

$$\frac{\delta n_e}{n_0} = \frac{\varepsilon \varepsilon_0}{\omega^2 + c_m^2 - \omega \gamma_d} \left( \frac{\delta n_d}{n_0} \right)$$

Equation (55) demonstrates that for $k\lambda_{De} \gg 1$, when electron Debye shielding is ineffective, electric fields are generated by the bare charge of ions and dust. Owing to reduced $\lambda_{De}$ and therefore reduced $k\lambda_{De}$ in an electron bite-out region as shown in figure 10, electric fields and potentials may be expected to be enhanced by neutral turbulence. This may also have other consequences for in situ measurements. Owing to the fact that typically the dust–neutral collision frequency $\nu_{dn}$ is much larger than the frequency associated with the passage of the shock wave created around a measurement rocket payload, equation (54) implies the negative dust fluctuations are much smaller than the neutral fluctuations $\delta n_d/n_{d0} \ll \delta n_e/n_{e0}$. Also from equation (53) $\delta n_i/n_{i0} \ll \delta n_e/n_{e0}$ Therefore, in a bite-out region where there is a shock compression on the ions and not on the dust, a positive charge in the wake of the shock is produced which has been observed (Sternovsky et al 2004) and therefore measurements within the shock may provide useful information about the charged dust density and mobility.

Again, ‘fossil turbulence’ refers to inhomogeneities in the dust density when neutral air turbulence is absent (Cho et al 1996, Rapp and Lubken 2004). The spatial scales of this turbulence of course do not match the dispersive nature of driving neutral air turbulence, i.e. $\omega = ke u$. Fossil turbulence can be described within the Robertson (2007) model to be of spatial–temporal scales such that $\omega \ll ke u$. It was shown in the section 4.1, that the electron and ion density fluctuations are out of phase (i.e. anticorrelated) in this case as they are generated by the ambipolar electric field force for fossil
turbulence rather than the driving velocity field for active turbulence. This is consistent with the case of section 4.1.1 for shorter wavelengths.

The model of section 3 may be used to consider the coupling of a neutral wind field to the dusty plasma region in a mesospheric electron density bite-out region and to consider the impact on electric field structures. A neutral dust cloud density of the form in equation (49) subject to neutral wind forcing is allowed to charge and create an electron bite-out. Figure 11 shows the electron, ion and dust density for an electron bite-out of 50 m in size. The electric field is also shown. A neutral wind of the simple monochromatic form described earlier (equation (50)) is imposed on the dusty plasma. It is observed that the electric field fluctuations are enhanced inside the electron bite-out. This is also reminiscent of the experimental data in figure 10 during the DROPS experiment (Goldberg et al 2001). It was postulated by Robertson (2007) that such enhancement of the electric field is the interpretation of the DROPS fluctuating electric field observations in the bite-out region. The neutral wind field also couples into electron, ion and dust density fluctuations consistent with equations (52)–(55) as seen in figure 11 as well.

4.2.2. Statistical analysis. The linearized model just described can be used to gain some insight into the basic coupling between small amplitude neutral fluctuations and the plasma density, charged dust and electric field fluctuations. However, the neutral background may be more appropriately described to be in a nonlinear turbulent state and accordingly structures the dusty plasma. Another useful approach used in statistical plasma physics is to investigate the behavior of the spectral characteristics of the electron density fluctuations (e.g. Ichimaru 1973), which is another important process and critical for describing radar scattering that will be discussed in section 4.5. The electron fluctuation spectrum behavior results from nonlinearity in the plasma transport equations (e.g. equation (27)) that lead to cascading from low to higher wave-numbers and also dissipation processes at high wavenumbers through viscosity and diffusion. The spectral characteristics of the electron density fluctuations associated with such coupling has been investigated in detail in the past (Hill 1978b, Hill and Mitton 1998, Hill et al 1999) and also more recently (Varney et al 2011). The electron density fluctuation power spectrum is defined as \[ \Phi(k) = \langle \delta n_e(k) \delta n_e(k) \rangle \] where \( k \) is the wavenumber vector, \( \delta n_e(k) \) is the fluctuating electron density wavenumber spectrum, \( * \) denotes complex conjugate, and \( \langle \cdot \rangle \) denotes ensemble average. A 1D power spectrum dependent on the magnitude of the wavenumber vector \( k = |k| \) is often defined for isotropic density fluctuations by integrating over solid angle in wavenumber space and is given by

\[ \Gamma_e(k) = 4\pi k^2 \Phi_e(k). \] (56)

Using spectral transfer function theory for the minor plasma constituents (electrons, ions and charged dust) advected by neutral turbulence (e.g. Hill et al 1999), a simplified analytical expression for the 1D spectrum assuming large wavenumbers (appropriate for VHF and UHF radar observations) is given by (e.g. Varney et al 2011)

\[ \Gamma_e(k) = -\frac{\chi_{dd}}{\gamma} k^{-1} \exp \left( \frac{D_2 k^2}{\gamma} \right) \] (57)

where \( D_2 \) is the slow diffusion coefficient given in equation (24) in section 2.3.4, \( \gamma = -\sqrt{\frac{\varepsilon}{\nu_q}} \) is the effective rate of strain of Kolmogorov eddies (Hill 1978b) with \( \varepsilon \) the energy dissipation rate, \( \nu_q \) is the kinematic viscosity of the neutral air, and Batchelor’s constant \( q \). The effective dissipation of variance, written in terms of the dissipation of dust fluctuation variance \( \chi_{dd} \) is
\[\chi_{\text{dd}} \approx Z_{\text{D}}^2 \left( \frac{n_e}{n_e + Z_{\text{D}}^2 n_i} \right)^2 \chi_{\text{dd}} \] (58)

\[\chi_{\text{dd}} \text{ may be expressed in terms of dust and neutral parameters (e.g. Varney et al 2011)}\]

\[\chi_{\text{dd}} = 2 \frac{R_{\text{e}}}{P_{\text{e}} \omega_{\text{B}}^2} \left( \frac{2 \omega_{\text{B}} n_i}{g} - \frac{dn_{\text{d}}}{dz} - \frac{n_{\text{d}}}{H_n} \right) \] (59)

where \(R_{\text{e}}, P_{\text{e}}, \omega_{\text{B}}, g, \) and \(H_n\) are the Richardson number, turbulent Prandtl number, Brunt–Vaisala frequency, gravitational acceleration and neutral scale height. The variation of dust density with altitude is \(dn_{\text{d}}/dz\). Several important points can be made about the electron fluctuation power spectrum in equation (57). At small wavenumbers it exhibits \(k^{-5/3}\) behavior and then transitions to \(k^{-1}\) indicative of transition from the inertial to viscous subrange in Kolmogorov turbulence. However, at large wavenumbers, the behavior is more complex owing to the multimode diffusion process involving the charged dust. The fact that the power spectrum depends on the slow diffusion coefficient \(D_2\) is an indication of the electron density turbulence extending to smaller spatial scales (larger \(k\)) due to the charged dust. It should be noted that the argument of the exponential in equation (57) can also be written in terms of \(S_\gamma\) since \(D_2 k^2 / \gamma = -q(\eta k)^2 S_\gamma\) which of course shows that an increase in \(S_\gamma\) extends the electron fluctuations to higher wavenumber. The dependence of the power spectrum on the electron density and dust particle radius is also important for explaining radar observations to be described subsequently.

### 4.3. Collective effects involving dust

The previous section considered plasma density structuring in the space plasma environment due to charging on embedded dust structures driven by neutral turbulence. A dusty plasma, however, exhibits wave phenomenon. A diverse spectrum of wave phenomena exists in conventional plasmas as well as in a dusty plasma. However, the concentration here will be primarily on low-frequency waves associated with the dust (and ion) motion. The most fundamental wave is the dust acoustic mode (Rao et al 1990). The model of the previous section may be used to study linear and nonlinear aspects of disturbances associated with this wave mode in the space plasma environment. Using a perturbation analysis of the basic plasma continuity and momentum equations, the linear dispersion relation of this wave mode is given by (e.g. Shukla and Mamun 2002).

\[\omega = k C_{\text{da}} \sqrt{1 + k^2 \lambda_{\text{D}}^2} \] (60)

where \(k = 2\pi / \lambda\) is the wavenumber. The dust acoustic speed \(C_{\text{da}} = \omega_{\text{pd}} / \lambda_{\text{D}}\) where \(\omega_{\text{pd}} = e Z_{\text{D}} \sqrt{\gamma_{\text{D}} / \epsilon_0} m_{\text{D}}\) is the dust plasma frequency and the dusty plasma Debye length \(\lambda_{\text{D}} = \lambda_{\text{D}} \sqrt{\lambda_{\text{D}} / \lambda_{\text{D}} + \lambda_{\text{D}}^2}\) as described in equation (2).

The dust acoustic wave frequency is quite low being much lower than the dust plasma frequency with a phase velocity of the order of the dust acoustic speed. The frequency can be in the 1–10 Hz range for many upper atmosphere applications.
In the ionosphere, as charged dust occurs naturally in the meteor ablation zone (80–120 km) and in particular in polar mesospheric regions such as NLC and PMSE regions (80–95 km altitude), it has been proposed that such dust may lead to a spectrum of possible plasma instabilities involving dust modified wave modes such as the basic dust acoustic wave just described. These have been extensively reviewed in Mann et al (2011). Several important examples will be briefly noted here.

For instance, the charged dust in meteor trails may affect the collective behavior of the meteor trail plasma including the behavior of waves and instabilities. It should be noted that charged dust in a meteor trail may also affect trail diffusion. It has been suggested that the presence of negatively charged dust may slow down the diffusion by reducing electron diffusivity, similarly to the effect of negatively charged dust in preserving small scale plasma fluctuations in PMSE regions (Kelley et al 1998, Zhou and Kelley 1997). Kelley (2004) presented a new explanation for long duration meteor trains involving persistent charged dust trains.

In the altitudes of PMSE and the meteor ablation zone (upper D–lower E layers of the ionosphere) where trails form, electron $E \times B$ or crossfield drifts can drive the known electrojet instabilities, such as the Farley–Buneman instability. Plasma simulation studies (Oppenheim et al 2000, Dyrud et al 2001) of the role of gradient drift type ion wave instabilities at the edges of dust-free meteor trails and their relevance to certain meteor echoes have been performed. Studies by Dyrud et al (2001) have shown that the excitation of such ion wave instabilities may affect trail diffusion, as well as the interpretation of radar echoes from meteor trails. Oppenheim et al (2003) and Dyrud et al (2002) showed that Farley–Buneman type instabilities could occur in meteor trails, driven by ambipolar electric fields due to plasma gradients in the trail, and that the instabilities can lead to non-specular meteor trail echoes. Thus, it is of interest to understand how charged dust can affect these and related wave instabilities in the lower ionosphere.

Charged dust may affect the Farley–Buneman instability (Rosenberg and Chow 1998) through modifying the phase speed of ion waves. At altitudes $<95$ km, the phase speed increases as the negative charge density of the dust increases. Therefore, the possibility of dust carrying most of the negative charge density can lower the critical drift for excitation of the Farley–Buneman instability in a plasma with $\psi = \nu_e v_{te} / \Omega_e \Omega_i > 1$. If such an instability can occur in a dusty meteor trail, VHF/UHF radar scattering from the ion-acoustic waves would result. This may be a possible diagnostic for the presence of substantial amounts of negatively charged dust at such meteor trail heights.

The possibility of ion acoustic instability in dusty meteor trail regions in the upper mesosphere (the low E layer) was considered by Rosenberg and Merlino (2007). When $T_e \sim T_i$ (often the case in ionospheric plasmas), the critical electron drift, parallel to $B$, for an ion acoustic instability is roughly $-v_{te}$, the electron thermal speed. It has been shown that if the density of sub-nanometre-sized negatively charged dust (i.e. heavy negative ions) is comparable to the positive ion density, the ion-acoustic instability may occur for electric field values of the order of 10 mV m$^{-1}$. This mechanism may have some relevance to the observations of enhanced ion acoustic echoes in meteor trails reported by Pellinen-Wännberg and Wännberg (1996).

Rosenberg and Shukla (2000, 2002) investigated a very low frequency analog of a gradient drift instability, the dust-acoustic-drift (DAD) instability, which might occur in certain meteor trails containing positively charged dust (due to photoemission by solar UV radiation). These were the first studies of the possibility of a very-low-frequency dust acoustic instability in a dusty meteor trail in the upper mesosphere. A relatively large dust charge is favorable for dust acoustic instability, but even larger dust of tens of nm in size would become charged negatively to only a few electron charges in the cold ionosphere. Therefore, Rosenberg and Shukla (2000) suggested that if the dust has low work function (<4 eV), grains, they could become charged positively to larger charge states by photoemission in daytime conditions (see also Havnes et al 1990). It has been shown that, in trails containing a sufficient density of positively charged dust, this DAD type instability might be driven by electron diamagnetic and $E \times B$ drifts with magnitudes smaller than the ion thermal speed $v_t$ (Rosenberg and Shukla 2000).

The nonlinear evolution of dust waves generated by a low-frequency Hall current instability (Rosenberg and Shukla 2000) in a magnetized collisional dusty plasma was investigated by Scales and Chae (2003) with theory and nonlinear numerical simulations for the applications to the production of fluctuations in regions where dust is present in the earth’s ionosphere such as Noctilucent clouds and meteor trails. The instability is driven by an electron $E \times B$ current and is an analog, in the dust acoustic type wave regime, of the well-known Farley–Buneman instability. The results indicate that the instability nonlinearly saturates with dust heating and the production of secondary waves that propagate in a direction perpendicular to the primary dust acoustic type waves. The nonlinear wave saturation physics are therefore in line with that of the standard ionospheric Farley–Buneman instability as described by Oppenheim et al (1996). It should be noted that further work is needed to scope out the range of dust and meteor trail parameters required for instability.

4.4. Active dust release experiments

Active space experiments provide the possibility of investigating a spectrum of plasma phenomena including dust related processes in space. It has been pointed out that solid rocket motor burns will effectively create dusty (or dirty) plasmas in space (Bernhardt et al 2012) that have the potential to exhibit some properties of natural dusty plasmas at lower mesospheric altitudes, including producing radar scatter due to electron fluctuations at the Bragg scale from dust related plasma instabilities created (e.g. Rosenberg et al 2011, Bordikar and Scales 2012, Fu and Scales 2012, 2013). These processes may include dust acoustic, ion acoustic, dust ion acoustic, lower hybrid and various shear and density gradient driven instabilities depending on geometric orientation of the cloud expansion relative to the geomagnetic field. Also, larger scale reductions in electron density due to the dust charging process are also possible. As discussed in section 2.4, the CARE series of sounding rocket experiments, which use solid rocket motors that produce $\text{Al}_2\text{O}_3$ to effectively create a dusty plasma in space, were conducted to test many of these principles but particularly the impact of charged dust layers on scatter of UHF, L-Band and S-Band
radars (Bernhardt et al 2011). Full analysis of the data from these experiments is still ongoing at this time.

Another artificial source of charged dust to drive dust related plasma turbulence was postulated to be space shuttle exhaust (Bernhardt et al 1995). The exhaust plume may produce a streaming dusty plasma to drive the dust acoustic wave instability (Rosenberg 1993). This instability relies on dust streaming with velocity of \( v_{th} \) with respect to the background plasma. The growth rate is

\[
\gamma \approx Z_d \frac{\pi n_d m_i}{8 n_e m_d} k v_{th}.
\]

(63)

It was noted that for typical space shuttle exhaust conditions, the growth rate is sufficiently large to observe the dust acoustic instability, however, the condition for instability, which is that the dust acoustic wave phase velocity \( v_{ph} \) is larger than the dust thermal velocity \( v_{th} = \sqrt{T_d/m_d} \), was typically not satisfied (Bernhardt et al 1993) where

\[
v_{ph} = \frac{n_d m_i T_d}{n_e m_d T_e} C_{dd} Z_d.
\]

(64)

This may possibly rule out uniform dust streaming as a generation mechanism for plasma turbulence that produces radar scatter under a number of circumstances.

However, an alternate generation mechanism may exist due to the localized nature of artificially created dust clouds. Another proposed mechanism by Mahmoudian and Scales (2012a) involves development of a plasma instability in the dust cloud boundary layer that may generate dust acoustic waves as well as associated spiky electric field structures typically associated with such turbulence. Owing to the ambipolar electric field development in the dust cloud boundary layer, created by the dust charging process, the electron flow in the boundary may be sufficiently large to drive dust acoustic waves. An example of this ambipolar field and electron flow is shown for the localized cloud simulation in figure 9. This quasi-equilibrium state exists on a timescale shorter than the dust plasma period (Scales and Ganguli 2004a, 2004b). If this electron flow exceeds the dust acoustic speed \( C_{dd} = \omega_{pd} \lambda_0 \) then there may be dust acoustic wave generation. Such processes are observed in laboratory plasmas and are described as self-generated dust density waves in dust clouds (e.g. Fortov et al 2003, Arp et al 2007). The initial generation of these waves may be considered with a simplified electrostatic dispersion relation within the localized cloud boundary in which there is a uniform electron flow relative to the background of ions and negatively charged dust. The linear dispersion relation is

\[
1 + \chi_e(\omega, k) + \chi_d(\omega, k) = 0
\]

(65)

where the susceptibility of species \( s \) is given by

\[
\chi_s(\omega, k) = \frac{1}{k^2 \lambda_{Ds}^2} \left\{ 1 + \xi(Z) \right\} \right\} \left\{ 1 + \frac{i \nu_{sn}}{\sqrt{2} k v_{th}} Z(\xi) \right\}^{-1}
\]

(66)

where \( Z(\xi) \) is the plasma dispersion function, \( \xi = (\omega - k v_{th}) + i \nu_{sn} \sqrt{2} k v_{th} \) where \( v_{th} \) is the flow speed in the boundary layer and is only of consequence for the electrons in this case. Numerical solution of equation (65) shows for parameters suitable for dust particles of 10s of nm radius and of relatively high dust density \( n_d/m_e \sim 1 \) (which may be typical of such aerosol release environments), the growth of the dust acoustic waves is in the range \( 10^{-3} < \gamma/\omega_{pd} < 10^{-2} \) and a relatively broad spectrum of wavenumbers are generated \( 0.1 < k \lambda_{Ds} < 2 \) (in the cm to m range) and a threshold excitation electron flow of approximately \( 2 C_{dd} \) in the boundary layer.

Figure 13 shows the growth of the dust acoustic waves in the boundary using the model described in section 3, which shows good agreement with the simple instability analysis just

![Figure 13. Simulation of growth of dust acoustic waves in actively generated dust cloud boundary layer. Electric field fluctuations, dust density and electron density are shown. Waves propagate into the interior of the cloud (to the right) with dust density fluctuations exhibiting nonlinear character as shown in figure 12 (after Mahmoudian and Scales 2012a). Reproduced with permission from John Wiley & Sons, Inc., copyright 2012.](image-url)
provided. The dust density, electron density and electric field are shown after the initially neutral dust cloud has charged. It is observed that when the electron flow exceeds $C_{de}$, then the fluctuations begin to grow. Close examination of the dust density shows a structure similar to the nonlinear structure in figure 12 with flattened troughs and sharp crests described by the second-order dust acoustic wave equation (61). Also, there is the appropriate phasing between the electron density and dust density. Although the waves initially develop in the boundary, there is subsequent propagation of the waves into the interior of the cloud. Spiky electric field structure is also associated with the density fluctuations. These may also have some consequences for space measurements of ac electric fields associated with large-scale dust clouds such as those shown in figure 10 in the mesosphere. As described by Mahmoudian and Scales (2013a), it should be noted that the high collisionality of the dust and neutrals may have a tendency to significantly weaken or quench dust acoustic wave generation by various instability mechanisms. A 2D analysis of this dust acoustic wave generation mechanism including magnetic field effects is provided in Fu and Scales (2013).

4.5. Radar scattering

Radar scatter observations from charged dust layers in the upper atmosphere have been one of the most important drivers for dusty space plasma research. This is particularly true of PMSEs. This field of study has a rich history and is still a vigorous area of research as described earlier. There have been a number of excellent reviews in the past describing the concepts of scattering from dust layers (e.g. Cho and Kelley 1993, Cho and Rottger 1997, Rapp et al 2013, Lubken 2014 and Rapp and Lubken 2004). Newer developments involve approaches to obtaining as much information as possible about the dust layer parameters. It is the objective here not to be exhaustive but to provide several of the important concepts and recent results.

Some early theoretical work on electromagnetic wave scattering from dusty plasmas with application to the Earth’s mesosphere was performed by la Hoz (1992) and Hagfors (1992). Both of these studies used the dressed test particle kinetic theory approach (e.g. Ichimaru 1973) to determine the scattering cross-section for charged heavy dust with multiple charges. The scattering in this case being due to electromagnetic waves with wavelength much longer than the Debye length causing coherent oscillations in the electron screening clouds around the dust particles. An important result of these works was that an enhancement in the backscattering cross-section $\eta(k)$ over the value for Thompson scatter $\eta_T$ in the usual long-wavelength regime ($k\lambda_D \gg 1$), is proportional to the dust charge, that is

$$\eta(k)/\eta_T \sim hZ_d$$

where $\eta_T = r_e^2$ and $r_e$ is the classical electron radius. These works also showed that this behavior was only possible for relatively low dust densities in which the dust inter-particle spacing was larger than the Debye length, i.e. $\lambda_D < a$. This implies the dust-in-plasma regime described in section 2, in which there are no dust collective effects and the dust behaves as isolated charges. Another requirement is relatively low dust densities so the electron screening clouds have substantial density around the dust particles. Calculations show that when $Z_d$ is several hundred, a significant enhancement in scattering may be possible. However, this is inconsistent with the number of charges on dusty ice particles in the mesosphere (la Hoz et al 2006), which are only expected to carry a few charges as described in section 2.3.1. Of course, there are other potential important applications of the results, possibly such as active space experiments described in section 2.4.

The impact of charged dust (specifically mesospheric smoke particles MSP) on the Arecibo incoherent (Thompson) scatter radar ISR spectrum was first systematically investigated with modeling by Cho et al (1998), the scattering being due to thermally excited electron density fluctuations. The Doppler spectrum width is proportional to the ion diffusivity for this measurement and it allows calculation of ion characteristics. Therefore, an extension to the formal three-fluid theory approach of Mathews (1978) for the incoherent scatter spectrum was used to incorporate dust particles. The spectrum is then related to both the ion and dust diffusivity, with the heavy dust diffusivity being much slower. This work was the first to predict the narrowing of the so-called ion line spectral region due to the introduction of heavy negative charged dust (larger than 1 nm in radius) in the background plasma. Further work by Rapp et al (2007) at EISCAT and Strelnikova et al (2007) at Arecibo subsequently showed that the spectrum in this range could be described by two Lorentzians that incorporate both the charged dust and ion contributions in the dusty plasma. The retrieval of dust information was possible from this incoherent radar spectrum. The model of Strelnikova et al (2007), although empirical, shows quite good agreement with the full theory of Cho et al (1998) and allows relatively easy retrieval of the dust density (assuming positive dust) and dust radius from the ISR spectrum. Assuming a double Lorentzian form for the spectrum, the autocorrelation function $R(t)$ (obtained from Fourier transform of the scattering spectrum) is of the approximate form

$$R(t) \approx A_i \exp(t/\tau_i) + A_d \exp(t/\tau_d)$$

(68)

where for each species $\alpha$, $\tau_\alpha = \lambda_R^2 m_{\alpha} v_{\alpha} / (32 \pi^2 k_B T_\alpha)$ with $\lambda_R$ the radar wavelength, and $m_{\alpha}$, $v_{\alpha}$, and $T_\alpha$ the species mass, collision frequency and temperature, respectively. The two terms correspond to the electron–ion and electron–dust interactions, respectively, as described in section 2.3.4. The total received power is the sum $A_i + A_d$ and is proportional to the total electron density. Assuming positive dust (which is a limitation of this method) allows interpretation of $A_i$ and $A_d$ as proportional to the ion and (positive) dust densities, respectively. The dust density can then be retrieved as $n_d m_e = A_d (A_i + A_d)$. The dependence of $\tau_\alpha$ on the dust–neutral collision frequency $v_{\alpha}$, which can be seen from equation (19) to depend on dust radius $a$, allows retrieval of the dust particle radius from the decay time in $R(t)$. This method has proven to give very reasonable results for dust radii in the range of 0.5 nm to 1 nm and densities (assuming positive dust) of $10^8 - 10^9$ cm$^{-3}$ at Arecibo, which are in line with the
predictions of Hunten et al (1980). Some results using this method of determining dust radii and density with altitude at Arecibo are shown in figure 14.

Information on dust particles can also be obtained by coherent radar that scatters from structures at the Bragg scale from index of refraction fluctuations associated with electron density fluctuations. These electron fluctuations are due to electron charging on an irregular dust (ice particle) background density as described in sections 4.1 and 4.2; the dust fluctuations being due to neutral turbulence coupling. This is the mechanism for PMSEs as described in section 2.2. Such radar scattering is proportional to the electron density fluctuation spectrum described in section 4.2.2 and the radar backscattering cross-section is given by (e.g. Varney et al 2011)

\[ \sigma_T(k,n) = 8\pi k^{-1} \Gamma_d(k) \]  

where an approximate expression for \( \Gamma_d(k) \) is given in section 4.2.2. This reflectivity has important dependences on the ratio of the electron and dust density, \( n_e/n_d \). For \( n_e/n_d \gg 1 \) the reflectivity is primarily dependent on \( n_d \) and independent of \( n_e \) and for \( n_e/n_d \ll 1 \) the reflectivity has a strong dependence on \( n_e \) which can be seen primarily through the behavior of \( \chi_{\text{eff}} \). Therefore it can be seen the reflectivity depends on \( n_d, r_d, d_n/dz, \) and \( Z_d \). Although these parameters cannot necessarily be extracted independently, information on the charged dust layer may be inferred. This behavior of the reflectivity has been important in explaining observations of PMSE in circumstances of highly variable ionization such as during auroral precipitation and nighttime conditions. Finally it is important to underscore again, that due to the dependence of this radar cross-section on the electron density fluctuation spectrum described in section 4.2.2, the inertial subrange of the electron density fluctuations is extended to smaller spatial scales allowing radar echoes to exist where they normally should not. This is now generally accepted as the resolution to the PMSE paradox and may also have application to long-duration meteor trail observations as discussed earlier.

4.6. Interaction of high-power radio waves with dusty space plasmas

4.6.1. Modulation of the PMSE source layer. The interaction of high-power HF radio waves with charged dust layers has recently proven to have potential to provide substantial information about the characteristics of the dust particles in the layer. It has therefore become a dynamic area of research over the past decade. One basic concept involves heating the dust layer with a high-power HF ground-based transmitter that ultimately increases the electron temperature, \( T_e \), through collisional interactions (with period of the order of 10 ms) in the region of the dust layer. This in turn modifies the charging and diffusion characteristics described in section 2, impacting the electron fluctuations, and ultimately produces variations in diagnostic radar scatter. The first such experiments (Chilson et al 2000) were performed to modify the dust layer source regions that produce PMSEs with the European Incoherent Scatter Scientific Association (EISCAT) 224 MHz radar facility at Ramfjordmoen, Norway (Rietveld et al 1993). These experiments showed reduction of the radar scatter (PMSE) during heating. This was attributed to suppression of the electron fluctuations due to enhanced diffusion of the electrons with increased electron temperature (Rapp and Lubken 2000). The first advance in theoretical development was due to Havnes (2004) where the dust cloud potential model (Havnes 1984) was applied to interpret the variation of the radar scatter measurements during cycling the radio-wave heating on and off (Havnes et al 2003). The model utilizes the Boltzmann approximation for electrons and ions, \( n_{e(i)} = n_{e(i)} \exp(\phi/k_B T_{e(i)}) \) where \( \phi \) is the electrostatic potential, quasi-neutrality (equation (1)) and the OML charging model (equation (31)). The comparison between observations and the theoretical model were good and resulted in the so-called overshoot characteristic curve to describe the behavior. It is as follows. During turn-on of radiowave heating, there is a reduction of the radar scatter initially, a gradual recovery, overshoot (enhancement) during turn-off of the heating and finally a gradual return to the equilibrium state. Figure 15
shows a typical experimental observation of the variation of radar scatter during cycling the radiowave heating (on at \( t = 0 \) and off at \( t = 20 \) s). It should be noted that Polar Mesospheric Winter Echoes (PMWEs) have also been found to be modulated by radiowave heating, but the physical process is currently less understood (e.g. Belova et al 2008, la Hoz and Havnes 2008).

The behavior during the turn-on and turn-off of the radiowave heating can be understood in terms of two important timescales discussed in sections 2.3.1 and 2.3.4 which are the charging time \( \tau_c \) and the ambipolar diffusion time \( \tau_d \) (Chen and Scales 2005). This is assuming that the charging process is primarily due to electron attachment initially and the dust is motionless during the heating cycle so ambipolar diffusion is of primary importance. It is important to note that the diffusion time depends on the wavelength of the electron fluctuation \( \lambda \) and equivalently the radar frequency for Bragg scattering at half the radar wavelength. Roughly, \( \tau_c \sim 1 \) s. The behavior at turn-on and turn-off in figure 15 can roughly be understood as follows. During turn-on \( \tau_d/\tau_c \ll 1 \) and the electron fluctuations are suppressed due to enhanced diffusion with the electron temperature increase and therefore the radar scatter is reduced. During turn-off of the radio wave heating, again with \( \tau_d/\tau_c \ll 1 \), when electron temperature is reduced, ion diffusion occurs, which drags electrons along causing an overshoot in the electron fluctuations. The behavior in figure 15 typically occurs for radar frequencies above 50 MHz and was observed in initial experiments at 224 MHz. For radar frequencies less than 50 MHz, \( \tau_d/\tau_c \gg 1 \) may be possible for mesospheric parameters due to a reduction in diffusion time for the longer wavelengths. In this case, it can be shown that the turn-off overshoot is weakened (or completely suppressed) and an overshoot at turn-on is predicted. However, the original model of Havnes (2004) is limited to the case \( \tau_d/\tau_c \ll 1 \) due to the Boltzmann electron approximation. The model of Scales (2004) utilized full ion dynamics, which allows finite ambipolar diffusion (as does the model of section 3) and ultimately allowed investigation of a range of radar frequencies for the first time. Figure 16(a) shows the temporal variation of electron density fluctuation amplitude (whose square is proportional to radar scatter strength as described in section 4.6) with varying radar frequency during a heating cycle using the model of section 3 and assuming stationary dust fluctuations as in equation (44).

The variation in behavior of the radar scatter with frequency has been proposed to allow possibilities for diagnosing the dust layer as far as calculating the dust density, radius, charge, etc (e.g. Havnes et al 2003, Chen and Scales 2005, Mahmoudian et al 2011, 2012b). Possible observables may be defined after turn-on and turn-off of the radiowave heating as shown in figures 16(b) and (c). Basic observables during turn-on of the radiowave heating are the maximum (minimum) electron fluctuation amplitude \( \delta n_e(\text{max}) \) and the time to reach that maximum (minimum) \( \tau_{\text{max}} \) when \( \tau_d/\tau_c > 1 \) (\( \tau_d/\tau_c < 1 \)). Another turn-on observable is the timescale for decay of the maximum fluctuation amplitude (determined by the diffusion time \( \tau_d \)). Simplified expressions are given by (Mahmoudian and Scales 2012b)

\[
\tau_{\text{min}} = \frac{\tau_d}{\delta n_{\text{d,01}}} \log \left( \frac{\Delta n_{\text{e,0}}}{\Delta n_{\text{e,0}} + \Delta n_{\text{e}}} \right) \tag{70}
\]

\[
\delta n_{\text{e,0}}^{\text{min}} = \Delta \delta n_{\text{e}} \left( 1 + \frac{\Delta \delta n_{\text{e}}}{\Delta n_{\text{e,0}}} \right) \frac{1}{\delta n_{\text{d,01}}} + \delta n_{\text{e,0}} \tag{71}
\]

\[
\tau_{\text{max}} = \frac{\tau_d}{\delta n_{\text{d,02}}} \log \left[ \frac{\Delta n_{\text{e,0}}}{\Delta n_{\text{e,0}} + \Delta n_{\text{e}}} \left( \frac{1}{1 - \delta n_{\text{d,02}}} \right) \right] \tag{72}
\]

\[
\delta n_{\text{e,0}}^{\text{max}} = \Delta \delta n_{\text{e}} \left( 1 - \delta n_{\text{d,02}} \right) \left( 1 + \frac{\Delta \delta n_{\text{e}}}{\Delta n_{\text{e,0}}} \right) \frac{1}{\delta n_{\text{d,02}}} + \delta n_{\text{e,0}} \tag{73}
\]

Note here that another important timescale, the electron density reduction time, has been defined as \( \tau_r = \tau_d/n_{\text{d}} \). Also, \( \delta n_{\text{e,0}} \) is the initial electron fluctuation amplitude, \( \Delta n_{\text{d,0}} \) and \( \Delta n_{\text{e}} \) are the change in the mean and electron fluctuation amplitudes from their initial to final equilibrium values during the turn-on as shown in figure 16(b). The second quantity is an unknown to be solved for. The unknown normalized dust density fluctuation is \( \delta n_{\text{d,0}} = \delta n_{\text{d,0}}/n_{\text{d,0}} \). During turn-off, the observables are the maximum amplitude \( \Delta \delta n_{\text{e,0}}^{\text{max}} \) (i.e. turn-off overshoot) and time for it to be reached \( \tau_{\text{max}} \) and also the relaxation time back to the equilibrium state (determined by the ion discharging timescale) (Scales and Chen 2008).

\[
\tau_{\text{max}}(\text{OFF}) = \frac{\tau_d}{\delta n_{\text{d,0}}} \log \left[ \left( 1 + \frac{\tau_{\text{r,0}}}{\tau_{\text{r}}(\text{OFF})} \right) \left( \frac{1}{1 - \delta n_{\text{d,02}}} \right) \left( \frac{\Delta \delta n_{\text{e,0}}}{\Delta Z_{\text{d,02}} n_{\text{d,0}}} \right) \right] \tag{74}
\]

\[
\delta n_{\text{e,0}}^{\text{max}}(\text{OFF}) = \frac{\tau_{\text{r,0}}}{\tau_{\text{r}}} \log \left[ \left( \frac{r_{\text{h}} + 1 - 2 \delta n_{\text{d,0}}}{1 - \delta n_{\text{d,0}}(1 + \tau_{\text{r,0}}/\tau_{\text{r}})} \right) \left( \frac{1 + \tau_{\text{r,0}}}{\tau_{\text{r}}(\text{OFF})} \right) \left( \tau_{\text{r,0}}/\tau_{\text{r}} \right) \right] \tag{75}
\]
Here, \( r_h = T_h / T_e \) is the electron temperature enhancement during heating, \( \Delta Z_{d0} \) is the change in electron charges on the dust particles during the heating process, \( \tau_d \) and \( \tau_{ri} \) are the diffusion and density reduction timescales during the turn-off process. Finally, \( \delta n_{e0}^{\text{eq}} = \delta n_{e0}^{\text{obs}} / n_{e0} \) is the normalized equilibrium electron density fluctuation before turn-off. It is proposed that using these analytical expressions for the observables for multi-frequency measurements may allow estimation of the dust density profile and other parameters in the source region (Mahmoudian and Scales 2012b).

The first multi-frequency experiments have been performed recently (e.g. Senior et al 2014, Havnes et al 2015). Figure 17 shows results from the first multi-frequency experiment using 224 MHz (VHF) and 8 MHz (HF) radar (PMSE) observations (Senior et al 2014). The heating transmit frequency used was 8 MHz, transmit power of 38 MW effective radiated power (ERP) and over a 50s period. It is observed that the higher frequency (larger fluctuation wavenumber \( k = 9.39 \, \text{m}^{-1} \)) produces more of the classic behavior of immediate suppression during turn-on and a well-defined overshoot at turn-off. The lower frequency (smaller fluctuation wavenumber \( k = 0.33 \, \text{m}^{-1} \)) shows enhancement at turn-on and much weakened turn-off overshoot. (Note that an adjustment for the D-layer absorption has been incorporated in the calculations.) This behavior is consistent with the basic predictions of the model. Havnes et al (2015) have also performed multi-frequency experiments using 56 MHz and 224 MHz. The basic behavior of the observations is in qualitative agreement with model predictions showing turn-on overshoot behavior at 56 MHz. Fine details of the similarities and differences in temporal behavior between the three frequencies are currently under investigation.

Finally, it is important to underscore here that there may be opportunity for investigation of fundamental dust charging processes in the near-earth space environment by utilizing HF PMSE heating measurements (e.g. 8 MHz as shown above) as charging timescales become shorter and charging physics is dominant over diffusion physics at such long spatial scales.

Figure 16. (a) Simulated variation of electron fluctuations during radiowave heating of a mesospheric dust layer. For high frequencies the behavior is as shown in figure 15. For lower frequencies, weakened turn-off overshoot is predicted as well as a turn-on overshoot. (b), (c), Diagnostics that may be obtained during turn-on (b), and diagnostics that may be obtained during turn-off (c) (adapted from Chen and Scales 2005 with permission from John Wiley & Sons, Inc., copyright 2005, Scales and Chen 2008, Mahmoudian and Scales 2012b with permission from John Wiley & Sons, Inc., copyright 2012).
It can be shown with modeling that the temporal variation of the electron fluctuation amplitude $\delta n_e$ (again related to radar cross-section) and the average dust charge $Z_d$ are very similar at HF frequencies (e.g. 8 MHz in figure 16(a)) and much about the fundamental dust charging processes can be learned from the HF PMSE radar observation.

4.6.2 Stimulated electromagnetic emissions. A second potential diagnostic of dust related phenomena during high-power HF radiowave heating is the stimulated electromagnetic emission (SEE) spectrum. SEE is secondary electromagnetic radiation produced by the interaction of the high-power radiowave with the background ionospheric plasma (Leyser 2001). SEE is a relatively mature field of study having been first reported by Thide et al (1982) and has been used to investigate characteristics of the ionospheric plasma environment as well as space plasma turbulence. SEE is produced by a plethora of plasma parametric decay instabilities (PDIs), many of which are related to those well known in laser-plasma interaction physics (e.g. Krue 1988). Sideband spectral lines are produced at frequencies other than the pump (transmit) frequency. The frequency shift from the pump frequency contains substantial diagnostic information. Three-wave PDIs believed to produce many of the SEE spectral lines are described by frequency (energy conservation) and wavenumber (momentum conservation) matching conditions $\omega_0 = \omega_S + \omega_L$ and $k_0 = k_S + k_L$ where $\omega$ and $k$ are the wave frequency and wavenumber vector and subscripts ‘0’, ‘S’ and ‘L’ denote the pump, scattered, and low-frequency decay waves respectively. For PDIs directly involving the electromagnetic pump field, the scattered field is observed on the ground shifted by the low-frequency decay mode frequency $\omega_L$.

Recently, due in part to increases in power available at ionospheric heating facilities, particularly at the High Frequency Active Auroral Research Program HAARP facility in Gakone, Alaska, a host of new spectral lines have been observed produced by stimulated Brillouin scatter (SBS) (Norin et al 2009, Bernhardt et al 2010). Such spectral lines have also been recently observed at the EISCAT facility as well (Fu et al 2015). The proximity of the pump frequency to harmonics of the electron gyrofrequency has long been known to have critical effects on the SEE spectrum (e.g. Leyser 2001) and also has recently been shown to have important impacts on SEE spectral lines produced by SBS (Fu et al 2015, Mahmoudian et al 2014). It was originally postulated that the physics of the environment due to meteoric dust may be sensed with SBS SEE lines by Bernhardt et al (2010). It was first verified by Mahmoudian et al (2014) that such a diagnostic is possible. The fundamental concept is the fact that the SBS spectral-line shift from the pump frequency incorporating magnetic field effects may be near the ion gyrofrequency $\Omega_e = qB/m_e$ due to the low-frequency decay mode in the PDI being an electrostatic ion cyclotron (EIC) wave propagating nearly perpendicular to the geomagnetic field (Chen 1984) with dispersion relation

$$\omega^2 = \Omega_e^2 + k^2 c_s^2 \tag{76}$$

where $c_s$ is the ion sound speed. Of course, for sufficiently long wavelengths $\omega \approx \Omega_e$ therefore assessment of mass composition and perhaps temperature of the constituents can be obtained with such a measurement. A rough approximation for the growth rate, neglecting important gyro-harmonic effects, is $\gamma \approx ku_0\omega_p \sqrt{4\omega_0\omega}$ where the heavy ion plasma EIC (from equation (76)) and pump heating frequencies are denoted by $\omega_p$, $\omega$ and $\omega_0$. The electron quiver velocity $u_0 = eE_0/m_0\omega_0$ where the pump electric field strength is $E_0$ (Shukla and Stenflo 2010). This rate indicates the rapid growth of the sideband as observed since for typical parameters $\gamma/\Omega_e \gg 1$.

As described in section 1, meteoric dust ablation is responsible for the creation of sporadic layers composed of Fe, Mg, Na and Ca ions in the Earth’s E layer. The EIC lines
Figure 18. Stimulated radiation (right) due to SBS observed during frequency stepping near $3f_{ce}$ during ionospheric heating at the HAARP facility. The lower layer observed near 120 km altitude in the ionogram (left) is proposed to be a sporadic layer produced by meteoric dust ablation containing Na$^+$ and is observed in the SEE spectrum (right) as the spectral line shifted by the Na$^+$ gyrofrequency at 37 Hz (adapted from Mahmoudian et al. 2014). Reproduced with permission from John Wiley & Sons, Inc., copyright 2014.

associated with these minor ion species may be resolved in the SEE spectrum. This could be particularly valuable for the identification of metallic ions of meteoric origin in the E layer dusty plasma region, because the composition of the lower ionosphere can be altered by meteorite ablation (Kopp 1997, Mathews 1998). The strength, growth and damping time of these emission lines may possibly be employed to study the role of ion molecular chemistry in the generation of sporadic layers. The right panel in figure 18 shows an SEE measurement at the HAARP facility during frequency stepping the pump frequency from 4.15 MHz to 4.34 MHz, where the 4.21 MHz is the third electron gyroharmonic frequency $3f_{ce}$. Each frequency step is held for 30 s. It is observed that as the pump frequency approaches $3f_{ce}$, a spectral line shift near 37 Hz from the pump frequency is observed along with a spectral line shift near 48 Hz. These correspond to the ion gyrofrequencies of Na$^+$ and O$^+$ respectively. The left panel shows an ionogram of the electron density with altitude. The F-layer peak electron density is observed near 350 km, however, a sporadic layer is observed near 120 km. It is assumed the O$^+$ spectral line is associated with the layer near 300 km where O$^+$ the dominant species is. The layer at 120 km is assumed to be associated with the Na$^+$ line. The sporadic layer is linked to meteoric dust ablation. The variation (quenching) of the strength of the EIC spectral lines, which actually clarifies the Na$^+$ line, with proximity of the pump frequency to $3f_{ce}$ as observed in figure 18, is dependent on the details of the theoretical PDI growth rate very near $3f_{ce}$ and requires further investigation to refine the diagnostic.

5. Conclusions

Some basic characteristics associated with dust immersed in the Earth’s atmospheric plasma have been discussed. Fundamental principles from the relatively mature subject of basic dusty (complex) plasma physics have been applied to interpret these characteristics and it is expected that to further understand unresolved issues, this cross-fertilization must continue into the future. The complexity of the plasma region containing dust of meteoric origin in the upper and middle atmosphere will continue to pose challenges to understanding the creation, evolution and dynamics and the overall impact on ionospheric dynamics. Clearly dust particulates have critical impact on a spectrum of electrodynamics and plasma physics processes including diverse phenomena such as electric field generation, conductivities and therefore potentially large-scale currents, waves and turbulence and lightning-related phenomena. Several critical outstanding issues still exist, including even the most fundamental process of dust charging in such a complex medium and this has been brought into question recently by both ground- and space-based experimental observations. Detailed assessment of this process may not be as easy as in a more controlled laboratory environment. The growth and evolution of these dust particles as well as their composition are expected to impact the charging physics. Clearly more experimental observations are warranted. This includes both ground- and space-based observations as well as more collaboration with laboratory dust experiments. Space-based experiments often may have limited availability relative to ground-based experiments and several new possibilities have been presented here for promising ground-based remote sensing of such dust layers. These may utilize active perturbation and/or creation of dust layers in which initial conditions are somewhat better controlled. Active ground-based heating experiments have great potential for carefully studying the charging physics. Currently these strategies are in their infancy, however they show substantial long-term potential for higher-resolution interrogation of these layers, which continue to be a fascinating and important field of atmospheric phenomena.

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