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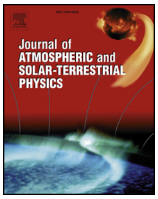

Dust modification of the plasma conductivity in the Earth's mesosphere

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ABSTRACT

Relative transverse drift (with respect to the ambient magnetic field) between the weakly magnetized electrons and the unmagnetized ions at the lower altitude (<80 km) and between the weakly magnetized ions and unmagnetized dust at the higher altitude (<90 km) gives rise to the finite Hall conductivity in the Earthś mesosphere. If, on the other hand, the number of free electrons is sparse in the mesosphere and most of the negative charge resides on the weakly magnetized, fine, nanometre sized dust powder and positive charge on the more massive, micron sized, unmagnetized dust, the sign of the Hall conductivity due to their relative transverse drift will be opposite to the previous case. Thus the sign of the Hall effect not only depends on the direction of the local magnetic field with respect to the Earth's rotational axis but also on the nature of the charge carrier in the partially ionized dusty medium.

As the Hall and the Ohm diffusion are comparable below 80 km, the low frequency ($\sim 10^{-4} - 10^{-5}\,\mathrm{s}^{-1}$) long wavelength ($\sim 10^3 - 10^4$ km) waves will be damped at this altitude with the damping rate typically of the order of few minutes. Therefore, the ultra–low frequency magnetohydrodynamic waves can not originate below 80 km in the mesosphere. However, above 80 km since Hall effect dominates Ohm diffusion the mesosphere can host the ultra–low frequency waves which can propagate across the ionosphere with little or, no damping.

1. Introduction

The Earthś ionosphere consists of horizontally stratified layers of partially ionized gas immersed in its magnetic field. The various altitude range of the ionosphere is divided for convenience as D, E and F layer, with the D region spanning between $60 - 90$ km, the E region between $\sim 90 - 150$ km and the F region between $150 - 400$ km (Kelly, 1989). The temperature from the ground up to ~ 15 km altitude (troposphere) decreases with height. The temperature rises in the stratosphere ($\in [15\,,\,50]$ km) before decreasing again in the mesosphere where it has the lowest value at about $\sim 80 - 90$ km. The temperature in the mesosphere is about ~ 190 K though 160 K or even lower temperature is also possible at occasions. Surprisingly, the mesopause temperature in the polar regions is higher in winter than in summer.

The altitude profiles of the dominant neutrals as well as the ionized components and their variations above about ~ 100 km is quite well known. However, the lower ionosphere ($\sim 60 - 100$ km), owing to the limited experimental data base, to a large extent, is still poorly understood. The $60 - 150$ km altitude region is too high for balloons and too low for satellite observations posing considerable observational challenge, yet understanding of this region is crucial to the behaviour of radio transmission, the initiation of sprites above thunderstorm etc. Owing to the D-regionś impact on the global climate change, this region has started receiving renewed attention (Beig et al., 2003).

While the magnetic field shields Earth from the solar wind, meteoroids and dust freely penetrate the atmosphere. Meteors are observed at all altitude between $70 - 400$ km with small meteors evaporating between $70 - 120$ km (Strober et al., 2013). Meteoric smoke particles ($\sim$ nm in size; $1\,\mathrm{nm} = 10^{-9}$ m) form from the recondensing of the ablated meteoroid material at $80 - 90$ km (Rosinski and Snow, 1961; Hunten, 1981). The polar mesospheric summer echoes (PMSE) and noctilucent clouds (NLCs) also called polar mesospheric clouds (PMCs) are also observed at this altitude. There is a strong correlation between the observations of NLCs and PMSEs suggesting that they might have a common origin. The PMSE refers to the strong radar echoes observed at $50 - 1.3$ GHz due to electron scattering at Bragg scale whereas the NLC which is also observed in the similar range of frequencies refers to the formation of water ice particles (Cho and Kelly, 1993; Cho and Rottger, 1997; Rapp and Lübkin, 2004). Typical density of these ice particles can vary between ~ 10 to $10^3\,\mathrm{cm}^{-3}$ and their radius

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can vary between $\sim 10-100$ nm (Rapp and Lübkin, 2004; Friedrich and Rapp, 2009). It is quite plausible that the size of the dust particles and the condensation of the water vapour in the NLCs are interlinked. For example, the presence of large dust can noticeably reduce the concentration of water vapour in the upper atmosphere and this in turn can decrease the particle sizes (Klumov et al., 2005).

The measurements during PMSE conditions shows a pronounced depletion of the electron number density. In fact electron density can decrease by an order of magnitude where strong PMSE are observed. The depletion of electron density, usually called electron *bite–outs*, is a generic feature of the PMSE (Pedersen et al., 1969; Ulwick et al., 1988). It would appear that the electron deficit at this altitude occurs only during PMSEs. However, the electron depletion is much more generic in the D-—region owing to the availability of meteoric smoke particles. In fact, there is a distinct deficit of electrons between 80 and 90 km. This deficit can be explained by the presence of negatively charged meteoric smoke particles (Baumann et al., 2013).

Clearly, the plasma composition in the altitude region between $60-100$ km is chemically complex. Whereas toward the E—-region, the dominant ions are molecular (NO^+ and O_2^+), below a marked transition height cluster ions ($H^+(H_2O)_n$ and $NO^+(H_2O)_n$) constitute the bulk of the population (Kopp et al., 1985; Friedrich and Torkar, 1988). The presence of charged and neutral dust (mesospheric smoke particles, ice particles) are also important constituent of the partially ionized gas. After forming at higher altitude (~ 90 km), the largest of dust particles settles to the lower altitude where they are visible as NLC whereas smaller dust is *visible* through strong radar echoes (Rapp and Lübkin, 2004; Friedrich and Rapp, 2009; Havnes et al., 1996a, 1996b). Estimates for the number density of small dust particles in the ionosphere ($\sim$ a few tens of nm to sub-visual in size) appears generally to be larger than about $10^2\ \mathrm{cm}^{-3}$ under PMSE conditions (Havnes et al., 2001).

As noted above the dust in the D-region is either neutral or carry electronic charge. The ratio of charged to neutral dust particles is about 5–10 percent of the total dust number density (Gelinas et al., 2005; Lynch et al., 2005) implying that the small dust particles are predominantly neutral. However, large (>20 nm) ice crystals are often negatively charged in the NLC. The presence of large dust can significantly augment the electron recombination rate causing the electron biteouts. The average charge on the dust is negative owing to the large mobility of electrons. The typical charge Z on the dust will be $-1\,e$ for particles with radius $a \in [1,10]$ nm, $-2\,e$ for 30 nm particles and $-3\,e$ for 50 nm particles (Friedrich and Rapp, 2009). Here e is the electron charge. We note that on the one hand, charged and neutral grains couple to the electromagnetic field via collisions with the electrons and ions and on the other hand, charge fluctuation modifies this field (Vladimirov, 1994; Bhatt and Pandey, 1994; Vladimirov and Ishihara, 2017). Thus, dust–-plasma coupling is responsible for some of the novel collective features in a dusty medium (Pandey and Vranjes, 2006; Pandey and Vladimirov, 2009; Pandey et al., 1999; Dwivedi and Pandey, 1995). The collision between the plasma, neutrals and dust grains not only causes the dissipation of the high frequency waves but can also help the dissipationless propagation of the low frequency fluctuations. For example, if various collision frequencies are higher than the dynamical frequency of interest then collision will move the bulk medium (which is a sum of the plasma, dust and neutral particles) together. In such a scenario collision facilitates undamped propagation of the wave (Pandey and Vladimirov, 2007a, 2007b; Pandey et al., 2012, 2013). However, in the opposite limit, when the collision frequencies are smaller than the dynamical frequency of interest, collision causes damping of the waves.

The $80-120$ km region of Earthś ionosphere is weakly ionized and weakly magnetized with the neutral number density ($>n_n = 10^{14}\ \mathrm{cm}^{-3}$ at 80 km) far exceeding the ion number density ($n_i = 10^3\ \mathrm{cm}^{-3}$). The sub–visible small dust ($\sim$ nm) number density could be similar to the ion number density. Adding to this complexity is the role of the ambient magnetic field. The dynamical processes in the ionosphere are strongly controlled by the coupling of the largely neutral D and lower E region to the magnetic field. This coupling is facilitated by the frequent collisions between the neutrals and the dusty plasma particles which transmits the Lorentz force to the neutrals. It is pertinent to recall here that in the past the D—-layer was considered either a purely neutral layer (Baumjohann and Treumann, 1996) or, the role of dust in the mesospheric plasma dynamics was completely ignored (Alperovich and Fedorov, 2007). But as is clear from the above description, the abundance of tiny charged grains may well exceed the electron abundance in the D-—region and thus the plasma transport properties which neglects the presence of grains at this altitude is incomplete.

The role of dust in modifying the plasma conductivity is well known in the space (Simon et al., 2011; Yaroshenko and Lühr, 2016) and astrophysical environment (Pandey and Vladimirov, 2007b; Wardle and Ng, 1999). The presence of dust not only affects the ionization structure of the plasma but also the gas phase abundances (Wardle and Ng, 1999; Wardle, 2007). Further, owing to the large mass and size distribution, the grains can couple directly as well as indirectly to the magnetic field. Thus the charged grains not only modifies the ambipolar time–-scale, but may also give rise to the Hall diffusion (Wardle and Ng, 1999). By ambipolar diffusion here we mean the diffusion of the magnetic field against the sea of neutrals due to the relative slippage of the frozen–in ions against the neutrals (Spitzer, 1978). This is different from the ambipolar diffusion of the plasma particles against the electric field (Hill, 1978). As we shall see, the mesosphere can be described in the framework of magnetohydrodynamics (with Ohm, ambipolar and Hall diffusion operating at various scale heights). This approach is different from the usual electrodynamics approach in which the magnetic field is assumed static. As has been noted by Parker (2007), in the magnetohydrodynamic approach, the bulk velocity of the plasma fluid and the magnetic field is the primary variable whereas in the electrodynamic approach, electric field and current is the primary variable. Both paradigm may sometimes arrive at the same conclusion (Leake et al., 2014). In the present work, we shall adopt the magnetohydrodynamic approach and first explore relative importance of the various diffusivities before investigating the wave propagation in the dusty mesospheric layer.

We shall provide an expression for the generalized Ohmś law in the next section where the relative importance of Ohm, Hall and ambipolar diffusion is also discussed. In section 3 we describe the effect of Hall and Ohm diffusion on the propagation of low frequency waves. It is shown that the long wavelength waves may suffer significant damping if most of the electrons have been moped by the dust. In section 4 discussion of the result along with a brief summary is presented.

2. Formulation

We shall assume a weakly ionized medium consisting of electrons, ions, charged grains and neutral particles. In order to better elucidate the role of the charged dust, we shall assume that the grains have same size and ignore their size distribution. Likewise, for simplicity the difference between the molecular and cluster ions will be neglected. Since the D-—region is weakly ionized the inertia and the thermal pressure terms in the plasma momentum equations can be neglected.

The most accurate way of calculating the transport properties of a gas is to employ Chapman—-Enskog method which was applied to the ionosphere by Cowling (1945). This method is analytically involved and thus we shall adopt a much simpler *free–path* method similar to the one employed by Baker and Martyn (1953) for the ionosphere. Free—-path theory assumes that the gas is not accelerating, i.e. it makes no distinction between the values of the mean velocity at the beginning of the free path and at the instant considered. Thus the charged particles drift through the sea of neutrals due to instant Lorentz force, i.e.

$$0 = -q_j\, n_j \left(\mathbf{E}' + \frac{\mathbf{v}_j \times \mathbf{B}}{c}\right) - \rho_j\, \nu_{jn}\, \mathbf{v}_j. \tag{1}$$