does not exist. Plasma double layers have been studied in the context of laboratory, magnetospheric, and space plasmas (Schamel, 1986; Raadu, 1989; Charles, 2007). The typical thickness of double layers is limited to <100 Debye lengths (Charles, 2007), or <1 km in the solar wind. The generation of charge separation and a positive electric potential in a plasma with increasing magnetic field strength has recently been demonstrated in a laboratory experiment (Takahashi et al., 2008), analogous to the lunar phenomenon. In this experiment, the authors also observed reflection of protons entering the high magnetic field region, due to the positive electric field of the double layer. These experiments may have applications to observations of proton reflections on the Moon (Saito et al., 2009).

The equilibrium near-surface charge excess due to the magnetic field will be a balance between the penetration of protons, and the downwards draw of electrons due to the positive charge, in spite of the magnetic mirror (a requirement for zero net current) (Reiff, 1975). The equilibrium charge separation voltage depends critically on the field geometry and strength, and the ambient plasma conditions (Reiff, 1975). An upper limit is of the order of the proton energy, since higher voltages would reflect nearly all protons. Assuming 1 keV solar wind proton energies, and separation of charge over horizontal scales of ~10 km (e.g. the swirl scale of Mare Ingenii, Fig. 2a), local electric fields would be <100 mV/m. Smaller length scales would produce higher electric fields.

Charge separation has been inferred from solar wind observations at the Apollo 12 and 14 landing sites. At the 38 nT surface field at the Apollo 12 site (Dyal and Sonett, 1970; Clay et al., 1975) nonthermal electrons were accelerated towards the solar wind spectrometer, suggesting that they were accelerated by a local positive electric anomaly of the order 50–120 eV (Goldstein, 1974; Clay et al., 1975). Such electron energy anomalies were not detected at the Apollo 15 site, where the local field was <6 nT (Goldstein, 1974). In addition, solar wind protons were decelerated at the Apollo 12 site by 70–150 eV, a range comparable to the electrons and interpreted to be due to a local positive electric field (Neugebauer et al., 1972; Goldstein, 1974; Clay et al., 1975). Assuming the positive potential exists over length scales similar to the magnetic anomaly, ~5 km (Barnes et al., 1972; Neugebauer et al., 1972; Clay et al., 1975), an estimate of the maximum electric field is ~20 mV/m, in agreement with the estimate in (McCoy, 1976). At the ~75 nT magnetic anomaly at the Apollo 14 site (Reiff and Burke, 1976), downwelling electron fluxes of 50–70 eV were interpreted to be due to charge separation (Burke and Reiff, 1975; Reiff, 1975; Reiff and Burke, 1976). Assuming a length scale of ~1 km at this site (Reiff and Burke, 1976), the maximum electric field would be ~50 mV/m. Eventually, detailed modeling, laboratory experiments, and measurements of magnetic anomalies will be required to constrain the equilibrium charge separation. We note however that the Apollo 12 and 14 surface magnetic fields are relatively weak compared to swirls, and the electric fields may therefore be higher in swirl regions (although perhaps at a high altitude, next section).

3.2. Lofting of lunar dust

In a separate process unrelated to magnetic anomalies, fine lunar dust in sunlit portions of the Moon becomes positively charged, primarily through photoelectron emission. Under certain circumstances, such as in the deeply shadowed terminator region (Criswell, 1972), the charge buildup may be strong enough to loft grains above the surface. The existence of dust lofting is suggested by Surveyor 5–7 (Rennilson and Criswell, 1974), Lunokhod 2 (Severnyi et al., 1975) and Clementine (Zook et al., 1995) observations, Apollo 16 sky brightness measurements (Page and Carruthers, 1978), Apollo 15 and 17 solar corona measurements (McCoy, 1976), astronaut observations (Zook and McCoy, 1991), and theory (Criswell, 1972; Criswell and de, 1977; Pelizzari and Criswell, 1978; Nitter et al., 1998). Perhaps the best evidence is the surface measurement of increased fluxes of slow moving charged particles during terminator crossings at the Apollo 17 site, with the Lunar Ejecta and Meteorites Experiment package (Berg et al., 1976). A number of laboratory simulations have been performed that support various aspects of dust lofting (Sickafoose et al., 2002; Robertson et al., 2003; Colwell et al., 2009; Wang and Robertson, 2009), but none have completely simulated all aspects of the problem.

The lack of significant dust on Surveyor 3 footpad markings and on the surface of the now functioning laser retroreflectors is not necessarily evidence against dust transport or lofting (Colwell et al., 2007, 2009). Dust transport may be relatively inefficient over 2–40 years, but over geologic timescales it may become important enough for our model. Additionally, in the absence of magnetic or electric fields, a steady-state equilibrium may exist such that over short terms, no net accumulation takes place. Also, some interpretations of lunar laser ranging data do in fact suggest performance degradation due to dust accumulation (Murphy et al., 2010). Note that dust transport processes are also believed to create ponding of spectrally distinct deposits on asteroids (Hughes et al., 2008; Riner et al., 2008; Robinson et al., 2001), and horizontal electrostatic dust transport has recently been simulated in the laboratory (Wang and Robertson, 2009).

While lofted dust can explain a number of spacecraft observations, and electrostatic forces are likely at work, the details of the process or processes are not well known (Colwell et al., 2007, 2009). For example, Criswell (1972) suggests dust is stably levitated, but Colwell et al. (2009) and Stubbs et al. (2006) suggest a form of ballistic transport is also possible. Perhaps the most significant unresolved issue is how dust lifts off from the surface. Most studies imply lift-off occurs mainly in the terminator region. However, observations (Severnyi et al., 1975; Page and Carruthers, 1978) and theory (Singer and Walker, 1962a,b; Walker, 1973; Stubbs et al., 2006) also suggest it may operate globally to some extent. The estimated diameter of the lofted grains is also unclear, varying between submicron (Zook and McCoy, 1991; Colwell et al., 2009), ~10 μm (Rennilson and Criswell, 1974), and >10 μm (Severnyi et al., 1973). Stubbs et al. (2006) estimated that dust with a radius of 0.1–1 μm could be lofted between tens of meters to several kilometers.

Herein we assume that dust is lofted twice a lunar day at each terminator crossing. To allow for the unknown details of the lofting processes in our model for dust transport, we explore different grain sizes and lofting times. Note that if the lofting process only operates in the terminator region, charge separation is still likely to develop if a crustal magnetic anomaly exists (Russell and Lichtenstein, 1975), and thereby produce an electrostatic potential. Furthermore, lunar dust movement has been observed ~60 h (3° at the equator) after sunrise and before sunset (Berg et al., 1976), such that dust lofted at the terminator may arrive at a more fully sunlit magnetic anomaly, where the solar wind is active and able to generate an electric field.

The altitude and detailed geometry of the charge separation region at lunar swirls is not known. For the largest swirls, if they develop full magnetospheres, the altitude may be on the order of 10 km above the surface. However, the altitude of dust lofting is also similarly unknown, ranging from centimeters (Rennilson and Criswell, 1974) to kilometers (Zook and McCoy, 1991; Stubbs et al., 2006). Therefore, it is plausible that the charge separation region interacts with charged lofted dust even at the strongest magnetic anomalies.

A final concern is the sign of the charge of lofted dust. Grains in sunlight and surrounded by minimal electron charging currents, such as at high solar illumination angles under mean solar wind