may reduce the equilibrium charge from the theoretical free-space value for an individual grain, but this effect is likely small at the column densities of $\sim$5 grains/cm^2 inferred by Criswell (1972).

A lower limit on the timescale (or N) for efficient swirl production may be calculated assuming that (i) the albedo markings are related to a lack of soil maturity (Section 3.4), and (ii) a grain must be transported the length scale of the swirl before it becomes greatly weathered. We therefore seek a lower bound on the space weathering timescale. Based on ion implantation experiments, solar wind maturation is estimated to take place within 10^5–10^6 years of surface exposure on the Moon (Hapke, 2001; Brunetto and Strazzulla, 2005; Strazzulla et al., 2005). For a lower bound we therefore assume $t_y = 10^5$ years. Note that t_y derived from ion implantation experiments is not equal to the total elapsed time on the Moon because a grain will spend variable amounts of time at the surface as the regolith is churned (Gault et al., 1974). For example, the upper 1000 μm of regolith is churned $\sim10^3$ times in 10^7 years (Gault et al., 1974). If we ignore depth-dependent mixing rates, in this layer a 10-μm-diameter grain would have been exposed at the surface $(10\ \mu m/1000\ \mu m) \times 10^3 = 10$ times, or a total of $(10/10^3) \times 10^7 = 10^5$ years out of 10^7 elapsed years. An estimate for the total elapsed time for solar wind weathering is $<10^6$ years in the asteroid belt (Vernazza et al., 2009). If we convert this weathering rate to the value expected at 1 AU (dividing by 2.5^2, Lazarus et al., 1995), we obtain 1.6×10^5 years. However, differences in the regolith churn rate and surface chemistry between asteroids and the Moon make such a comparison difficult, and the elapsed time for solar wind weathering on the Moon may be $>1.6 \times 10^5$ years.

An added complication is that a grain has only a finite chance of being lofted. After each flight, a grain may not land in a position amenable to lofting during the next terminator crossing. Only a crude estimate of the likelihood of lofting is possible using Surveyor data. Using Surveyor optical measurements of dust clouds, Criswell (1972) inferred a lofted mass flux rate equivalent to a soil churn rate of $\sim$6 μm/year. Therefore, since there are 25 terminator crossing per year, a 6 μm diameter grain has roughly a 1/25 chance of being lofted each crossing. Until more information is available about dust lofting, for simplicity we calculate transport times assuming a lofting probability of 0.1 (two loftings every 295 days).

Two significant unknowns, E and t, are explored in Fig. 6 with a range of values. The range of plausible E values was estimated in Section 3.1 to be 10–100 mV/m. The most conservative estimate of t is to assume that all lunar dust lofting is not actually stable levitation, but rather ballistic transport up to the height observed by the Surveyor spacecraft (Colwell et al., 2009). Assuming a cloud height of $\sim$25 cm (Rennilson and Criswell, 1974) gives a total up and down flight time of $\sim$1 s, assuming only the gravity force is a work. However, Pelizzari and Criswell (1978) suggest levitation times of up to hours, and Nitter et al. (1998) and Colwell et al. (2009) report stable levitation modes lasting minutes to hours. Stubbs et al. (2006) suggest high-altitude ballistic flights that may last several minutes. We explore lofting times from 1 s to 10 min.

Fig. 6a and b shows the distance d for grains of diameter 2 and 10 μm for a range of lofting times. It is clear that dust can travel greater than the required 2–10 km length scale of most swirls, with values of E and t that are within the range of plausible values. Because the distance traveled depends linearly on E and on the square of t, t has a stronger effect on d. As an intermediate example between the cases plotted, a 6 μm diameter grain at 10 V (charge of 2.8×10^{-15} C) will travel about 1 cm horizontally after a 20 s lofting, in a 10 mV/m field.

3.4. Swirl color production

Because the <10 μm fraction of soil is significant in determining a soil's spectral properties (Noble et al., 2001), horizontal transport of this fraction has the potential to change a region's band strength and albedo. The most fundamental spectral observations we have to constrain the swirl forming process are: (1) swirl material is higher in albedo, (2) swirl material appears slightly enriched in a component that mimics highlands material, possibly, but not necessarily, with a weak feldspathic enrichment, (3) swirl material apparently has higher band strength than the surrounding material.

The most cohesive hypothesis to explain the above data is that positively (negatively) charged fine dust is being repelled (attracted) into bright areas. Because fine dust is brighter and slightly feldspar rich (Taylor et al., 2001; Pieters and Taylor, 2003), this would explain the first of the two spectral constraints. However, the finest dust (by itself) is also expected to have weak band strength (Taylor et al., 2001), which is in conflict with the third spectral observation. A possible resolution is if the transport process is rapid enough to ensure that newly created dust is deposited and accumulates fast enough to bury material before it weathers, altering the local steady-state equilibrium (McKay et al., 1974). Because we demonstrated that dust can be transported on the timescales of space weathering, this resolution is plausible. A second possible resolution is that the dilution of local materials with finer, more transparent materials increases the optical path length to enhance local absorption bands.

Despite difficulties with the poorly constrained Clementine spectral data, the dust transport model deflects several of the difficulties of the solar wind hypothesis, and is the first to provide a plausible explanation for the apparent highlands component in swirls. It is important to note that a variety of other spectral effects may take place when dust is removed from or emplaced into a region. Many of these effects will be difficult to predict given the complex weathering and mixing processes in the finest fraction of the lunar regolith.

An alternative interpretation that allows for the solar wind stand-off model is given in the Discussion (Section 4.1).

3.5. Dark lanes

Electrostatic dust transport also offers a new explanation for the morphology of dark lanes. If there is a small region inside a swirl where there is zero horizontal electric field, dust transport may be close to nonexistent and result in normal soil and weathering. Since the dust transport model above allows for solar wind weathering, the width of the lanes is not limited by the proton gyrodiameter, and can explain the very fine scale of some lanes.

There are two means by which electrostatic anomalies can produce regions of zero horizontal electric field. The first mechanism is that closely adjacent regions of positive electric field may have regions between them where the horizontal component of the field cancels. For example, the horizontal component of the electric field between two positive point charges on a plane is zero, while around this region there are areas of positive electric field. This mechanism may explain the dark lanes between labels B in Fig. 2a, assuming that labels C and Z represent positive charge distributions.

The second mechanism that can produce lanes is if the charge distribution is sufficiently symmetric to yield zero net field in the central regions of the anomaly. For example, the horizontal component of the electric field produced by a cylinder of positive charge, with decreasing radial (x) charge density like $1/x$, will be exactly zero along its axis, and increase with radius when $x < R$, where R is the cylinder radius. The same holds true for a cylinder cut in half along its central axis. This may explain the narrow dark lanes in Fig. 2a, labels C and D, which are imbedded in bright swirls, assuming an approximately half-cylindrical charge distribution intersects the lunar surface at the rectangles near labels C and D.