in (Kurata et al., 2005) (using their 11 km depth buried dipole). This value would be in agreement with the Lorentz force estimate from dark lanes and proton gyrodiameters, if the combination of the two plasma effects described above resulted in about an order of magnitude gyrodiameter reduction.

If 1000 nT fields exist at the surface, what volume magnetization is required? If the Reiner Gamma anomaly is modeled as a horizontal disk of diameter 10 km, with a thickness of 1 or 10 km, an axial field of 1000 nT is produced by magnetizations of 10 or 1 A/m, respectively, using equations from Collinson (1983). Larger diameter disks require higher magnetizations. These magnetizations are in reasonable agreement with minimum magnetizations of 1 and 0.1 A/m for layer thicknesses of 1 and 10 km, respectively, derived from an ideal bodies approach (Nicholas et al., 2007). Magnetizations of 0.1–1 A/m would be among the most magnetic samples measured. For example, Apollo breccias 62235 and 15498 have magnetizations of 0.3 and 0.2 A/m, respectively, and are the two most magnetic samples reported by the review in (Fuller and Cisowski, 1987), aside from possibly contaminated samples.

In Section 3 we will develop a new theory for swirl formation, motivated in part by the spectral data below. This new theory, if correct, may give further insight into magnetic field strengths at swirls, and therefore the nature of lunar magnetic anomalies in general.

2.2. Spectral properties of lunar swirls

Several characteristic spectral properties of swirls can be discerned from detailed analysis of Clementine five band UV–VIS data. The first is that swirls show an apparent space weathering trend different from the normal background trend of local maturity. With Clementine data, lunar space weathering trends can be evaluated by plotting 950/750 nm reflectance (low values of which are a proxy for strong ferrous band strength at ~1000 nm) vs. 750 nm reflectance (albedo) (Lucey et al., 2000). A large compositionally homogeneous area of the lunar surface will nominally display a linear trend in this plot. For mare regions, higher maturity pixels are found in upper left, and immature pixels are found in the lower right, herein called the "maturity trend." This trend is illustrated as Trend 2 in Fig. 3a, for the region in Fig. 2a enclosed by the blue labeled rectangle. Trend 2 is as expected for well-developed soils (low albedo, upper left) and small, fresh craters in the area (high albedo, lower right). However, for both highland and mare swirls, brighter, immature portions of swirls do not simply follow such a maturity trend, but form new linear trends that are displaced to higher 750 nm values and slightly lower 950/750 ratios (Fig. 3). This trend is illustrated as Trend 1 in Fig. 3a.

In some ways, Trend 1 is similar to what is observed after a small highlands component of soil is added to a mare soil. For example, Staid and Pieters (2000) found that when mare locations were contaminated with highlands ejecta, their maturity trend was broadened and displaced in the same direction in 750 nm reflectance as described above. Bell and Hawke (Bell and Hawke, 1987) found that Reiner Gamma was best modeled as a mixture of immature mare material and a small component of highlands material. Although there is some evidence that Reiner Gamma may have received ejecta from craters in the highlands (Hood et al., 1979), there is no reason to believe that this same apparent highlands component could be explained by similar processes at all of the other mare swirls (Figs. 2 and 3), or that the ejecta's influence should be so systematic across regions within Reiner Gamma.

Our interpretation of this apparent highlands component is that it may be an enrichment in fine-grained material, which may also be slightly enriched in feldspar. Unusually abundant fine-grained material could create such a feldspathic enrichment because the finest fraction of both mare and highland soils are naturally slightly feldspar rich (Taylor et al., 2001; Pieters and Taylor, 2003).

Another characteristic spectral property of swirls is that transects through prominent mare swirls often show a strong increase in continuum slope or "redness" (herein defined as 750/415 nm) around the periphery of the swirl, previously referred to as a "red halo" at Reiner Gamma (Bell and Hawke, 1987; Pinet et al., 2000). This abnormally high redness compared to background values is most obvious at Reiner Gamma, the swirl north of Reiner Gamma, and swirls at Mare Ingenii (red arrows in Fig. 4e, c, and a, respectively). In contrast, the central bright parts of swirls exhibit a decrease in redness (Fig. 4a–f), and here redness is anti-correlated with albedo and correlated with high band strength. Note that the central part of Reiner Gamma (Fig. 4e, black arrow) has only moderate redness and band strength at its center, suggesting the swirl forming process may be less effective there. Central regions of highland swirls show only a decrease in redness relative to background values (Fig. 4d), and do not appear to have a red halo as do most mare swirls.

The interior "dark lanes" and the periphery of some strong swirls, such as the central part of Reiner Gamma, do not show an appreciable increase in band strength or albedo, at least relative to the local background. For example, the light blue and black *L*-labeled rectangles in Figs. 2e and 3e represent dark lanes with pixels that fall within the background mare trend (blue labeled rectangle in Fig. 2e). Several exceptions to this can be found in smaller swirls south of the main Reiner Gamma feature, where magnetic fields are weaker. One example is shown in Figs. 2e and 3e, as the red colored trend labeled *L*, which is slightly darker than the background soil, but not darker than some other soils south of Reiner Gamma. Generally, however, the dark lanes appear similar to background material in the region.

2.3. Application to Descartes albedo anomaly

The above spectral characteristics of lunar swirls are useful for distinguishing swirls from other albedo anomalies. For example, we can examine in some detail the Descartes region albedo anomaly (Fig. 2f). The Descartes albedo anomaly is a bright, immature feature between two fresh craters (Dolland D and Descartes E) in lunar highlands terrain, with nearly overlapping ejecta deposits, and its status as a swirl is uncertain (Blewett et al., 2005a,b). The region exhibits anomalous 3.5 cm radar reflectance (Zisk et al., 1972).

A transect through the center of the bright patch reveals broad changes in albedo, band strength, and redness (Fig. 4f, transect 2) that are similar to Airy swirl, also located in the highlands (Fig. 4d). A transect an equal distance away from Dolland D, but in the opposite direction of the bright patch, reveals a much smaller change in spectral characteristics (transect 1). A transect an equal distance from Descartes E, but again in the opposite direction of the bright patch, reveals almost no change in spectral properties compared to the background (transect 3). A transect through Dolland D, the center of the bright region, and Descartes E reveals a region of nearly constant but anomalous band strength, redness, and albedo, bounded by a slope break indicated with $*$ in Figs. 4f and 2f. If the bright patch were due entirely to overlapping ejecta deposits, one might expect a decay of the spectral anomalies near the two craters' midpoint, but this is not observed. The reason that the two craters appear fresh may partially be a result of an underlying magnetic anomaly and swirl forming mechanism, and not just a coincidence of two nearby fresh craters. Further measurements of spectral and other physical properties of the Descartes region may resolve the issue (Section 4).

3. Dust transport model for swirl formation

To explain the immaturity and brightness patterns of swirls, without requiring stand-off of the solar wind, we propose an