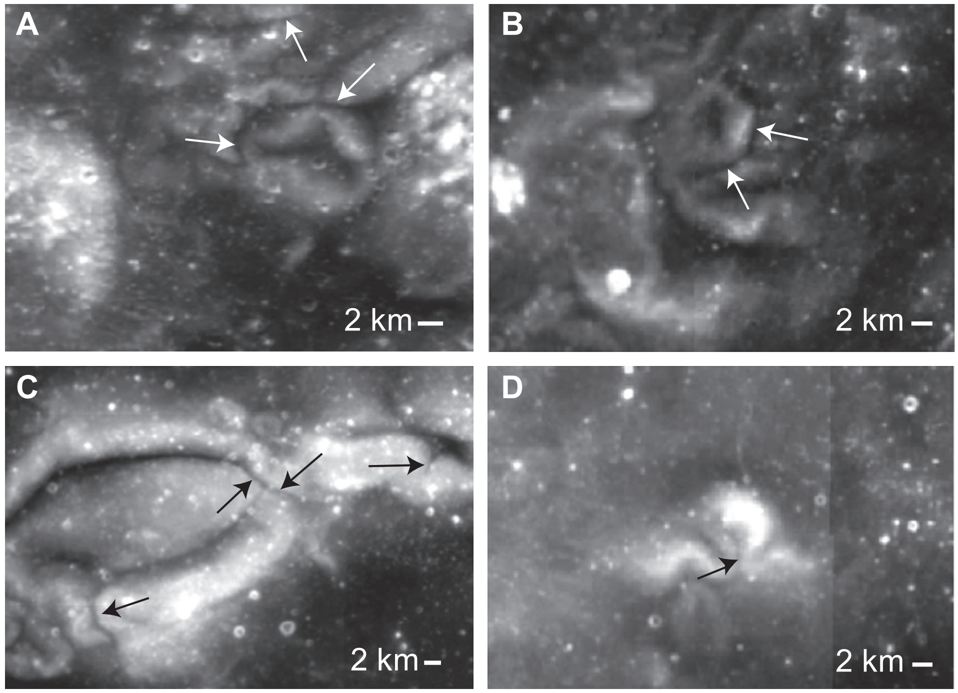

Fig. 1. Dark lanes in lunar swirls (750 nm Clementine reflectance), indicated by arrows. (A) Mare Ingenii (−35.0°S, 163.2°E), (B) Mare Marginis (13.3°N, 84.4°E), (C) Reiner Gamma swirl (7.5°N, 301.5°E), (D) region south of Reiner Gamma swirl (−1.0°S, 298.7°E).

wind weathering may be sufficient to cause surface brightening (Hood and Williams, 1989). Another concern with the stand-off model is that many swirls, such as those at Mare Marginis (Richmond and Hood, 2008), have weak magnetic anomalies compared to the center of Reiner Gamma swirl, yet Reiner Gamma is the only swirl for which deflection of protons has been modeled (Hood and Williams, 1989). In addition, a reduced solar wind flux also does not easily explain possibly anomalous photometric properties of Reiner Gamma (Kreslavsky and Shkuratov, 2003; Pinet et al., 2004; Chevrel et al., 2006; Kaydash et al., 2009), which suggest a unique regolith microstructure. Radar observations also indicate anomalous surface roughness at the 3.8 cm scale, but not at the 70 cm scale, at the putative Descartes swirl (Zisk et al., 1972; Thompson et al., 1974; Blewett et al., 2005a,b). Reiner Gamma may also exhibit anomalous 13-cm-scale roughness (Campbell et al., 2006).

The outline of the paper is as follows. In Section 2 we present an analysis of near-surface magnetic field strengths at swirls, as well as new spectral observations of lunar swirls. In Section 3 we present a model for swirl formation by dust transport. In Section 4 we discuss the implications of the dust transport model, as well as an alternative interpretation of the spectral data. In Section 5 we conclude the paper.

2. Magnetic and spectral properties of swirls

2.1. Magnetic field strength at swirls

Knowledge of the near-surface magnetic field strength at lunar swirls would be useful in determining both the swirl forming process and the origin of the magnetic anomaly. For example, the near-surface field strength can help constrain the volume magnetization and distribution of magnetized material, which in turn relates to how the anomaly formed. Previously, only inversions from orbital spacecraft data collected above ~20 km have been used to constrain the near-surface field strength (Hood et al., 1979; Hood, 1980; Kurata et al., 2005). Below we explain how unique morphologic features of swirls can be related to the near-surface field strength, and with a better model of the plasma interaction with lunar magnetic fields, provide a means of measuring surface field strengths.

Inside the high albedo areas of many swirls are dark lanes where the swirl forming process apparently does not operate. The thickness of these lanes may be related to the magnetic field strength. For example, if the solar wind stand-off hypothesis is correct, dark lanes suggest the solar wind is being focused into an otherwise wind-deflected region (Fig. 1) (Hood and Schubert, 1980). The focusing width is limited by the proton gyrodiameter, which in turn can be related to the near-surface field strength. Hood and Williams (1989) performed simple, Lorentz force-only simulations of protons incident on arrangements of buried magnetic dipoles, and found focusing regions of ~2 km thickness for surface fields of 2800 nT. Swirls, however, often exhibit dark lanes with thicknesses on the order of 600 m, Fig. 1, which would imply surface fields of the order of 9000 nT, if only the Lorentz force was important.

For at least two reasons, however, more detailed models of the solar wind interaction with magnetic fields are required before lanes can be used to measure field strength, if the solar wind hypothesis is correct. Firstly, charge separation electric fields and proton–electron momentum transfer will reduce the proton gyrodiameter to a value intermediate between the electron and proton values (Hood and Schubert, 1980; Hood and Williams, 1989). Secondly, it is possible the precipitation of particles along open magnetic field lines that connect to the interplanetary magnetic field will result in the surface impact of particles with low pitch angles and gyro diameters. A similar process produces aurorae on the Earth (Zhang et al., 2007), Mars (Bertaux et al., 2005; Lundin et al., 2006), and Jupiter (Bhardwaj and Gladston, 2000). Some of the martian aurorae occur at clefts and boundaries between magnetic anomalies, and some even exhibit a sinuous appearance.

Previous inversions for the near-surface field strength at Reiner Gamma found fields of ⩾1000 nT (Hood et al., 1979) and ~1000 nT