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Final Report for Grant NAGW-2084

Study of the Effects of Photometric Geometry on Spectral Reflectance Measurements

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1.0 INTRODUCTION:

In October 1995, our grant NAGW-2084 (formerly NSG 7606) "Study of the Effects of Photometric Geometry on Spectral Reflectance Measurements" was renewed for another three-year cycle. The objective of this research is to investigate how the spectrophotometric properties of planetary surface materials depend on photometric geometry by refining and applying radiative transfer theory to data obtained from spacecraft and telescope observations of planetary surfaces, studies of laboratory analogs, and computer simulations. The goal is to perfect the physical interpretation of photometric parameters in the context of planetary surface geological properties and processes. The purpose of this report is to document the research achievements which were fully or partially funded by this grant. Detailed yearly reports of progress for this grant are submitted to NASA in May of each year and are on file at NASA Headquarters, Office of Space Sciences, Washington D.C.

2.0 RESEARCH ACHIEVEMENTS:

Our research activities can be broken into two major categories: The first major focus of our effort is in refining and testing radiative transfer models that are used to estimate surface physical properties of planetary surfaces from remotely sensed telescope and spacecraft imaging observations. The second major focus is to apply the radiative transfer models to derive physical information from photometry of real planetary, satellite, and asteroid surfaces.

2.1 General Theory of Radiative Transfer in Planetary Surfaces

We have investigated three different topics in this field. The first involves the effect of macroscopic scale surface relief on reflected light. The second is the origin of the well-known opposition effect, the third is the directional scattering properties of realistic regolith grains.

2.1.1 Photometric Surface Roughness

Over the last year, we constructed the first-ever high-resolution digital elevation maps of undisturbed lunar soil from stereoscopic photographs of the lunar surface returned by Apollo astronauts. We are using these maps to provide "ground truth" for the testing of radar and optical photometry models that claim to be able to measure topographic roughness of planetary surfaces. Our results were recently presented at the 29th Lunar and Planetary Science Conference in Houston, Texas. We are completing a detailed scientific manuscript and will submit

Helfenstein, P. and M.K. Shepard (1998). Submillimeter-scale topography of undisturbed lunar regolith (in preparation).

to the scientific journal *Icarus* in April 1998.

2.1.2 The Opposition Effect

Soil-covered surfaces exhibit a rapid, non-linear surge in brightness as the solar phase angle approaches zero--a phenomenon called the opposition effect. Last summer, we demonstrated that two physical mechanisms, coherent-backscatter and interparticle shadow-hiding, both contribute to the Moon's opposition effect. Our results are published in

Helfenstein, P., J. Veverka, and J. Hillier (1997). The lunar opposition effect: A test of alternative models. *Icarus* **128** (in press).

We have applied our new knowledge of the opposition effect to new measurements of its behavior on Jupiter's icy satellite, Europa. The work is reported in Helfenstein et al. (1998) cited in Section 2.2.1.

2.1.3. Realistic Particle Phase Functions

We have investigated a practical approach to modeling the directional scattering properties of realistic planetary regolith particles. Our approach, which seeks to relate the albedo of regolith particles to their scattering behavior, is detailed in a paper submitted for publication and currently in revision:

Helfenstein, P., J. Hillier, and J. Veverka (1997). The albedo dependence of particle phase functions (submitted to *Icarus*).

2.2 Application of Radiative Transfer Modeling to Planetary Surface Photometry:

Our progress in this area comes not only from directly from research funded by this grant, but also from productive collaboration with other Cornell and outside scientists funded by their own grants. Over the past three years, we have applied photometric modeling to understanding the surface properties of a wide range of planetary, natural satellite, and asteroid surfaces. The results can be found in the following scientific papers and books:

2.2.1 Icy Satellites

Brown, R.H., D.P. Cruikshank, J. Veverka, P. Helfenstein, and J. Eluszkiewicz (1995). Surface composition and photometric properties of Triton. In **Neptune and Triton**, University of Arizona Press, Tucson. pp. 991-1030.

Clark, B., P. Helfenstein, J. Veverka, M. Bell, P. Geissler, C. Phillips, A.S. McEwen, R. Greeley, R. Sullivan, G. Neukum, and T. Denk. 1997. Multispectral terrain analysis of Europa from Galileo images. submitted to *Icarus.*

Denk, T., G. Neukum, P. Helfenstein, M.J.S. Belton, K.C. Bender, P. Geissler, R. Greeley, J.W.Head, R. Jaumann, R.T. Pappalardo, and the Galileo SSI Team. 1997.Disk-resolved spectral characteristics of Ganymede and Callisto. *Lunar Planet. Sci.* 28, 899-900.

Geissler, P., R. Greenberg, G. Hoppa, A. McEwen, R. Tufts,B. Clark, M. Ockert-Bell, P. Helfenstein, J. Burns, J. Veverka, R. Sullivan, R. Greeley, R. Pappalardo, M.J.S. Belton, and T. Denk 1997. Evolution of Lineaments on Europa: Clues from Galileo multispectral imaging observations. Submitted to *Icarus.*

Hillier, J., P. Helfenstein, and J. Veverka (1996). Latitude variations of the polar caps on Ganymede. *Icarus* **124,** 308-317.

Helfenstein, P., J. Veverka, T. Denk, G. Neukum, J.W. Head, R. Pappalardo, and the Galileo Imaging Team. 1997. Dark-floor craters: Galileo constraints on a Ganymede regolith component. *Lunar and Planetary Science* XXVIII, 547-548.

Helfenstein, P., N. Currier, B. Clark, J. Veverka, M. Bell, R. Sullivan, J. Klemaszewski, R. Greeley, R.T. Pappalardo, J.W. Head III, T. Jones, K. Klaasen, K. Magee, P. Geissler, R. Greenberg, A. McEwen, C. Phillips, T. Colvin, M. Davies, T. Denk, G. Neukum, and M.J.S. Belton (1998). Galileo observations of Europa's Opposition Effect. (submitted to *Icarus*).

Oberst, J., B. Schreiner, B. Giese, G. Neukum, J.W. Head, R.T. Pappalardo, and P. Helfenstein (1998). The distribution of brighrt and dark material on Ganymede in relationship to surface elevation and slopes. (submitted to *Icarus*).

Verbiscer, A. and P. Helfenstein (1998). Reflectance spectroscopy of icy surfaces. In **Solar System Ices**, (B. Schmitt, C. de Bergh and M. Festou eds.), Kluwer Academic Publ., Dordrecht, Astrophys. Space Sci. Lib. (in press).

2.2.2 Asteroids and Small Natural Satellites

Chapman, C.R., J. Veverka, P. Thomas, K. Klaasen, M. Belton, A. McEwen, M. Davies, P. Helfenstein, and D. Davis (1995). Discovery and Physical Properties of Dactyl, a Satellite of the Asteroid Ida. *Nature* **374**, 783-785.

Clark B., J. Veverka , P. Helfenstein , P. Thomas, J. F. Bell III, J. Joseph, A. Harch, B. Carcich, M.S. Robinson, S. Murchie, A. Cheng, N. Izenberg, L. McFadden, C. Chapman , W. Merline, M. Malin(1998). NEAR Photometry of C-type Asteroid 253 Mathilde (submitted to *Icarus*).

Helfenstein, P., J. Veverka, P.C. Thomas, D. Simonelli, K. Klaasen, T.V. Johnson, F. Fanale, Granahan, A.S. McEwen (1996). Galileo photometry of Asteroid 243 Ida. *Icarus* **120**, 48-65.

Simonelli, P. , J. Veverka, P.C. Thomas, P. Helfenstein, and M.J.S. Belton (1996). Ida lightcurves: Consistency with Galileo shape and photometric models. *Icarus* **120**, 38-47.

Simonelli, D.P., M. Wisz, A. Switala, D. Adinolfi, J. Veverka, P.C. Thomas, J. and P. Helfenstein (1996). Photometric properties of Phobos surface materials from Viking Images, *Icarus* **131**, 52-77.

Thomas P.C., D. Adinolfi, P. Helfenstein, D. Simonelli and J. Veverka (1996). The surface of Deimos: Contribution of materials and processes to its unique appearance. *Icarus* **123**, 536-556.

Thomas, P., J. Veverka, and P. Helfenstein (1995). Neptune's small satellites. In **Neptune and Triton,** University of Arizona Press Tucson, pp. 685-699.

Veverka, J., P. Helfenstein, A. McEwen, M. Belton, C. Chapman, T.V. Johnson, and F. Fanale (1996). Ida and Dactyl: Spectral reflectance and color variations. *Icarus* **120**, 66-76.

Veverka, J., P. Helfenstein, P. Lee, A. Harch, S. Calvo, C. Chapman, K. Klaasen, T.V. Johnson, and M. Davies (1996). Dactyl: Galileo observations of Ida's satellite. *Icarus* **120**, 200-211.