Mixing Models, Colors, and Thermal Emissions

W.M. Grundy
Lowell Observatory

J.A. Stansberry
University of Arizona, Steward Observatory

2003 May 27

Abstract. Color and spectral observations are important for understanding the taxonomy, composition, formation conditions, and evolutionary history of Trans-Neptunian Objects (TNOs). Colors or spectra do not, however, uniquely constrain the compositions of these objects, as we demonstrate using simple spectral mixing models. We show that thermal flux observations at 70 μm (or any wavelength near or beyond the peak of the object's emission) are much less sensitive to details of how the materials are combined. Coupling reflectance and thermal observations of TNOS will help remove much of the ambiguity intrinsic to color and spectral data.

Keywords: spectroscopy, photometry, colors, radiative transfer, mixing models.

1. Introduction

Trans-Neptunian Objects (TNOs) are thought to be composed of relatively pristine material from the outer reaches of the proto-solar nebula and to be the source population for Jupiter family comets and Centaur objects (*e.g.,* Levison & Duncan 1997). Nearly 1000 have been discovered since 1992 and more are discovered each year, revealing the distribution of TNO orbits (*e.g.,* Jewitt *et al.* 1998; Millis *et al.* 2002; Buie *et al.* these proceedings). Despite their importance for understanding solar system formation, we still know relatively little about TNO physical and chemical characteristics. To advance our understanding, data are needed which constrain their compositions, sizes, shapes, and albedos.

A few of the brightest TNOs have been observed spectroscopically, giving some compositional information (*e.g.,* Jewitt & Luu 2001; Cruikshank & Dalle Ore these proceedings). Even fewer have been observed in the thermal infrared (*e.g.,* Thomas *et al.* 2000; Jewitt *et al.* 2001), yielding estimates of sizes, albedos, and surface temperatures. Observations of broad-band colors are more abundant, and point to a remarkably diverse population (*e.g.,* Tegler & Romanishin 1998, 2000, 2003; Delsanti *et al.* 2001; Doressoundiram *et al.* 2001; Gil-Hutton & Licandro 2001; numerous papers in these proceedings) but these colors do not provide unambiguous information about compositions.

The Space Infrared Telescope Facility (SIRTF) will be capable of observing many TNOs in the thermal infrared, in particular at 70 μm. The simple models we present here indicate that the SIRTF data will not only be important for determining albedos and diameters of significant numbers of TNOs for the first time, but also in interpreting current and future broad-band colors and near-infrared spectral data.

2. Models

Spectral absorbers (species having strongly wavelength-dependent absorption characteristics, such as ices and tholins) are thought to be constituents of TNOs (*e.g.,* Jewitt & Luu 2001). They may be accompanied by continuum absorbers (or scatterers) which can darken (or brighten) a surface, and can reduce (or sometimes enhance) the spectral contrast of spectral absorbers. Devolatilized carbonaceous materials are possible darkening continuum absorbers, while ices can act as bright continuum scatterers at wavelengths lacking absorption bands. Remarkably small weight percents of dark continuum absorbers can efficiently mask the spectral signatures of brighter materials, if they are intimately mixed (*e.g.,* Clark 1981; Clark & Lucey 1984), while small quantities of bright, scattering materials can wash out spectral signatures of darker absorbers, if the bright scatterers are geographically isolated. A bright species, such as an ice, could conceivably dominate an object's reflectance spectrum while only covering a minute fraction of its surface.

We used Hapke theory (*e.g.,* Hapke 1981, 1993) to calculate albedos and spectral contrasts for various mixtures between spectral absorbers (water ice, tholin), a continuum absorber (charcoal), and a continuum scatterer (water ice). We define spectral contrast as the color difference in magnitudes between two wavelengths, relative to solar colors. Fig. 1 illustrates the dependence of spectral contrast on composition for intimate and patchwork mixtures of water ice/charcoal (Fig. 1a), tholin/charcoal (Fig. 1b), and tholin/ice (Fig. 1c). In these models "charcoal" is a proxy for any dark continuum absorber on TNOs, such as devolatilized carbonaceous material, and is simulated with isotropically scattering 10 μm grains having 9% single scattering albedo (the geometric albedo is much lower than the single-scattering albedo due to multiple scattering). Ice and tholin grains are also assumed to have 10 μm mean diameters, with optical constants for H_2O ice I_h taken from Grundy & Schmitt (1998), and tholin optical constants taken from Khare *et al.* (1994). The exact shapes of these curves depend on our assumptions about grain size and shape, as well as numerous additional

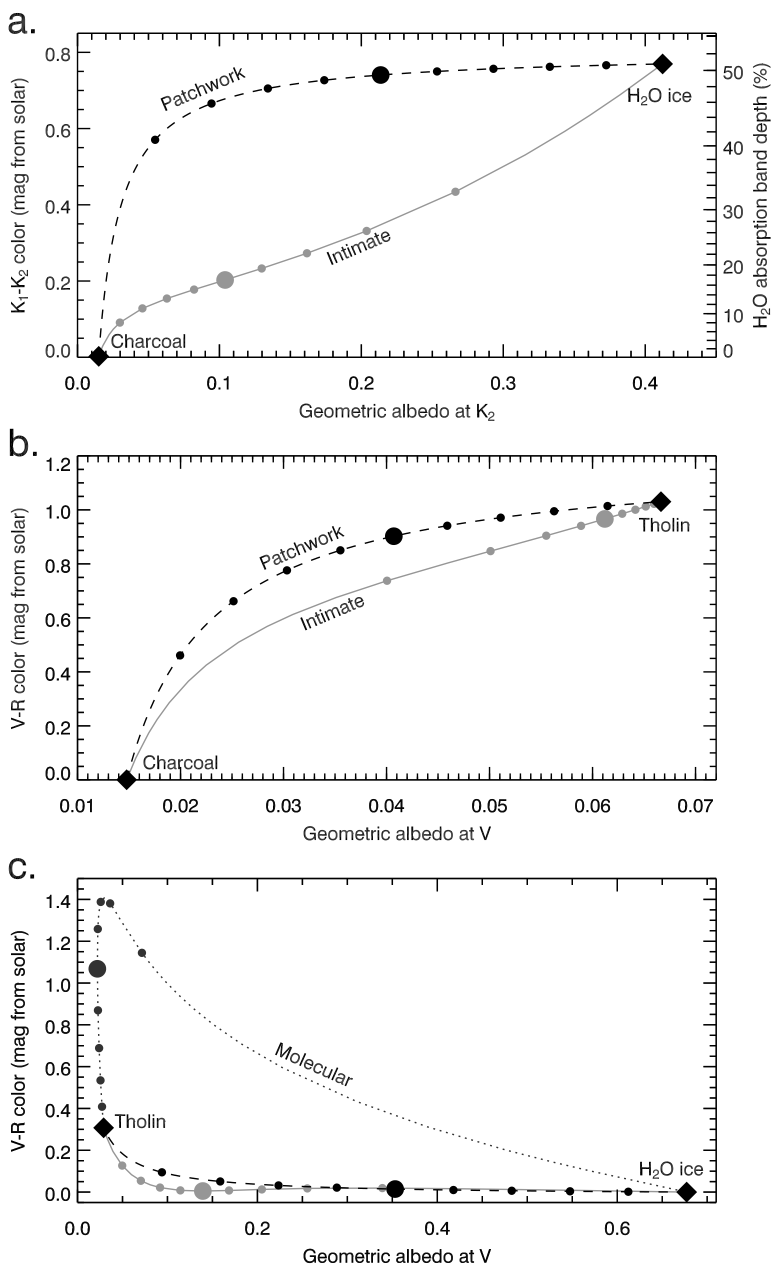

Figure 1. Mixing curves between possible TNO surface components. End-members are marked with black diamonds and intermediate compositions are indicated by a large dot at 50% composition and smaller dots at 10% intervals. In panel **a.**, K_1 and K_2 are custom filters: K_1 is centered on the 2 μm water ice absorption band and K_2 on the continuum region around 2.25 μm. In **c.**, intimate and patchwork models are not labeled, but are represented as in other panels, while the dotted curve represents a molecular mixture.

assumptions inherent in the Hapke theory. There is nothing particularly unique about the curves in Fig. 1, but they are useful for exploring typical optical behavior of mixtures of possible TNO constituents.

The mixing models show that color and albedo tend to be highly nonlinear functions of composition, and that different styles of mixing lead to very different dependence on composition. Intimate mixtures of a bright ice and a dark continuum absorber exhibit low spectral contrast until the ice is nearly pure, while patchwork mixtures show strong spectral contrast unless there is almost no ice at all (Fig. 1a). Mixtures of two dark materials (Fig. 1b) tend to be strongly colored if there is any significant fraction of the spectral absorber, for both intimate and patchwork mixtures. Even more remarkable behavior is seen when materials are combined within individual grains, such as when tholin molecules are introduced into the interior of water ice grains, as in Fig. 1c. A very small quantity of tholin dramatically reddens the ice. Paradoxically, adding ice to tholin also reddens the mixture, because it reduces the opacity of individual particles, increasing their single scattering albedos, most notably in the red. This trend continues until so much ice has been added that the opacity declines at the more strongly-absorbing wavelength, as well.

For all of these mixtures the surface composition inferred from observed spectral contrast can be strongly influenced by the details of how the materials are mixed. This sensitivity illustrates the uncertainties inherent in interpreting colors and/or spectra without further information. Knowledge of the albedo of a surface can remove much of this uncertainty as exemplified by Fig. 1a, where simultaneously knowing the K_2 albedo and K_1-K_2 spectral contrast would likely place an object on one or the other of the two mixing lines and constrain the composition nicely. Figure 2 shows predicted thermal fluxes at 24 and 70 μm from a 100 km radius TNO covered by mixtures of charcoal and H_2O ice, located 40 AU from the Sun. The curves for patchwork and intimate mixtures are nearly coincident, especially at 70 μm. Results for both the Standard Thermal Model (STM) and the Isothermal Latitude Model (ILM) are shown, with the STM giving higher fluxes. The flux uncertainty associated with the pole position is about 30% at 70 μm with a corresponding albedo uncertainty of about 20%. For objects where the pole position can be constrained (binaries, TNOs with strong lightcurves), it should be possible to measure albedos accurate to better than 10%. If we assume SIRTF produces a catalog of large-TNO albedos accurate to 20% including all uncertainties, then Fig. 1a indicates that compositional uncertainties can be determined to a similar accuracy, along with distinguishing intimate from patchwork mixtures.

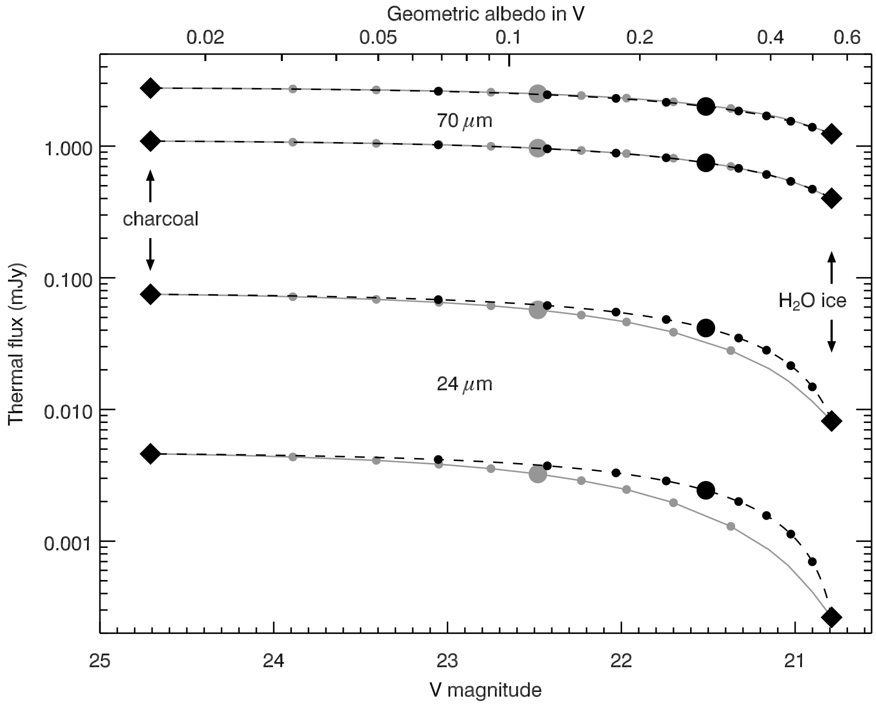

Figure 2. Thermal emission from a hypothetical 100 km TNO at 40 AU for models with intimate (gray curves) and patchwork (dashed curves) mixtures of charcoal and H_2O ice, as in Fig. 1. Curves are shown for the Standard Thermal Model (STM, pole-on orientation) and Isothermal Latitude Model (ILM, equator-on orientation). The STM produces higher fluxes than the ILM. The SIRTF sensitivities at 24 and 70 μm are about 0.15 and 1 mJy, 3σ in 500 seconds.

3. Conclusions

The diverse and nonlinear effects of various different mixtures of materials present a daunting challenge for interpreting color and spectral observations of TNOs in terms of their compositions. However, with an albedo constraint, the ambiguities can be significantly reduced. For this reason, SIRTF will play an extremely valuable role in advancing understanding of TNO compositions and physical characteristics, when combined with data from ongoing visible and near-infrared observing campaigns.

4. Acknowledgments

This work was made possible by grant NAG5-10159 from NASA's Planetary Geology and Geophysics program, and the Multiband Imaging

Photometer for SIRTF (MIPS) project, supported by NASA through Jet Propulsion Laboratory subcontract 960785.

References

Clark, R.N. 1981. The spectral reflectance of water-mineral mixtures at low temperatures. *J. Geophys. Res.* **86,** 3074–3086.

Clark, R.N., & P.G. Lucey 1984. Spectral properties of ice-particulate mixtures and implications for remote sensing: 1. Intimate mixtures. *J. Geophys. Res.* **89,** 6341–6348.

Delsanti, A.C., H. Boehnhardt, L. Barrera, K.J. Meech, T. Sekiguchi, & O.R. Hainaut 2001. BVRI photometry of 27 Kuiper belt objects with ESO/Very Large Telescope. *Astron. & Astrophys.* **380,** 347–358.

Doressoundiram, A., M.A. Barucci, J. Romon, & C. Veillet 2001. Multicolor photometry of trans-Neptunian objects. *Icarus* **154,** 277–286.

Gil-Hutton, R., & J. Licandro 2001. VR photometry of sixteen Kuiper belt objects. *Icarus* **152,** 246–250.

Grundy, W.M., & B. Schmitt 1998. The temperature-dependent near-infrared absorption spectrum of hexagonal H_2O ice. *J. Geophys. Res.* **103,** 25809–25822.

Hapke, B. 1981. Bidirectional reflectance spectroscopy I: Theory. *J. Geophys. Res.* **86,** 3039–3054.

Hapke, B. 1993. Combined theory of reflectance and emittance spectroscopy. In *Remote Geochemical Analysis: Elemental and Mineralogical Composition*, Cambridge University Press, New York.

Jewitt, D.C., & J.X. Luu 2001. Colors and spectra of Kuiper belt objects. *Astron. J.* **122,** 2099–2114.

Jewitt, D., J. Luu, & C. Trujillo 1998. Large Kuiper belt objects: The Mauna Kea 8k CCD survey. *Astron. J.* **115,** 2125–2135.

Jewitt, D., H. Aussel, & A. Evans 2001. The size and albedo of the Kuiper-belt object (20000) Varuna. *Nature* **411,** 446–447.

Khare, B.N., C. Sagan, E.T. Arakawa, F. Suits, T.A. Callcott, & M.W. Williams 1984. Optical constants of organic tholins produced in a simulated Titanian atmosphere: From soft X-ray to microwave frequencies. *Icarus* **60,** 127–137.

Levison, H.F., & M.J. Duncan 1997. From the Kuiper Belt to Jupiter-family comets: The spatial distribution of ecliptic comets. *Icarus* **127,** 13–32.

Millis, R.L., M.W. Buie, L.H. Wasserman, J.L. Elliot, S.D. Kern, & R.M. Wagner 2002. The deep ecliptic survey: A search for Kuiper belt objects and Centaurs. I. Description of methods and initial results. *Astron. J.* **123,** 2083–2109.

Tegler, S.C., & W. Romanishin 1998. Two distinct populations of Kuiper-belt objects. *Nature* **392,** 49–51.

Tegler, S.C., & W. Romanishin 2000. Extremely red Kuiper-belt objects in near-circular orbits beyond 40 AU. *Nature* **407,** 979–981.

Tegler, S.C., & W. Romanishin 2003. Resolution of the Kuiper belt object color controversy: Two distinct color populations. *Icarus* **161,** 181–191.

Thomas, N., S. Eggers, W.H. Ip, G. Lichtenberg, A. Fitzsimmons, L. Jorda, H.U. Keller, I.P. Williams, G. Hahn, & H. Rauer 2000. Observations of the trans-Neptunian objects 1993SC and 1996TL$_{66}$ with the Infrared Space Observatory. *Astrophys. J.* **534,** 446–455.