DEEP IMPACT PHOTOMETRY OF THE NUCLEUS OF COMET 9P/TEMPEL 1. Jian-Yang Li[1], M. F. A'Hearn[1], L. A. McFadden[1], J. M. Sunshine[2], C. J. Crockett[1], T. L. Farnham[1], C. M. Lisse[1,3], P. C. Thomas[4], and the Deep Impact Science Team, [1]*Dept. of Astronomy, University of Maryland, College Park MD (jyli@astro.umd.edu)*, [2]*Science Applications International Corporation (SAIC), Chantilly VA*, [3]*Applied Physics Laboratory, Johns Hopkins University, Laurel MD*, [4]*Center for Radiophysics and Space Research, Cornell University, Ithaca NY.*

Introduction: Deep Impact (DI) successfully encountered comet 9P/Tempel 1 on July 4th, 2005, and conducted an impact experiment with the nucleus [1]. The high-resolution instrument (HRI) and the medium-resolution instrument (MRI) onboard the flyby spacecraft, and the impactor targeting sensor (ITS) onboard the impactor, acquired disk-resolved images of Tempel 1 at solar phase angle 63° before, during, and after the impact. Images were obtained through wideband and narrowband filters from 309 nm to 950 nm [2]. The photometric properties of the surface of comet Tempel 1 at visible wavelengths will be studied from these images.

Data reduction: To study the disk-resolved limb-darkening and color properties of Tempel 1, we focused on the last color sequences from both HRI and MRI before the impact, as well as the last ITS image that contains the whole nucleus in frame, to avoid any contamination from the impact ejecta. The images are calibrated through DI calibration pipeline [3] to the standard reflectance unit, I/F. Then each color sequence is spatially co-registered to better than 1/10 pixel, and scaled to the highest resolution in that sequence (17.7 m/pix for HRI, 88.8 m/pix for MRI). The ITS image we used provides a slightly different aspect angle from HRI and MRI (3°), with a resolution of 31.2 m/pix). The shape model of Tempel 1 constructed from DI images [4] was used in conjunction with the flyby geometry and Tempel 1's ephemerides to calculate the scattering geometry maps for HRI, MRI, and ITS, respectively. Then the I/F data and the geometry maps are averaged over 4×4-pixel box for HRI, and 2×2-pixel box for MRI and ITS, to compensate for mis-registration between geometry maps and images. Finally, the I/F data were binned into 5° bins for both incidence angle and emission angle.

Whole-disk photometry: By integrating the flux of the nucleus in the above images, a spectrum of the nucleus at visible wavelengths can be constructed. The contamination from the foreground coma is estimated to be less than 5%. The spectrum of Tempel 1 shows a straight line with a red slope of about 12%/μm at the solar phase angle of 63°. At the spectral resolution of these images, no spectral features are present.

Disk-resolved analysis: Disk-resolved I/F data were first fitted with Minnaert's limb darkening model [5] (Fig. 1) The Minnaert's albedo shows the same red slope of 12%/μm as the whole-disk spectrum of Tempel 1. The Minnaert k parameter is independent of wavelength, with an average of about 0.66.

Hapke's model [6,7] is also used in our analysis. Since all disk-resolved images are obtained at a single phase angle, it is not possible to retrieve any information about either the single-particle phase function or the opposition effect. We assumed an opposition amplitude of B_0=1, and a width of h=0.01, which are typical for dark objects. The single-particle phase function was assumed to have an asymmetry factor of g=-0.42,

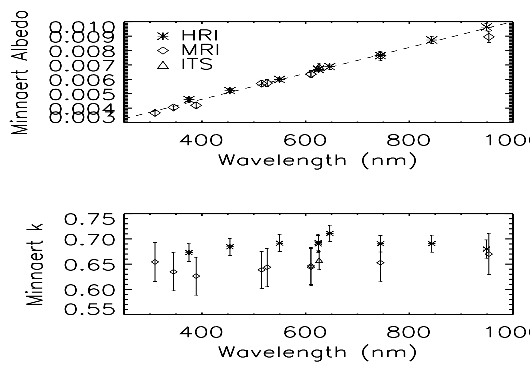

Figure 1: The Minnaert's modeling for Tempel 1. Upper panel shows the modeled Minnaert's albedo, lower panel the modeled k parameter. The error bars shown here only include 1-σ modeling uncertainty, not including absolute radiometry calibration error.

which is close to the value found for comet 19P/Borrelly [8], but slightly adjusted according to the preliminary analysis of the phase function of Tempel 1 from DI approach data. Since the albedo of Tempel 1 is very low (about 4%), the uncertainty introduced by assuming these three parameters will most likely affect the modeled single-scattering albedo (SSA) linearly, but will not likely affect the modeled roughness parameter ($\bar{\theta}$). The modeled Hapke's parameters are shown in Fig. 2, where the SSA spectrum shows the same red slope of about 12%/μm as the disk-integrated spectrum and the Minnaert albedo spectrum (Fig. 1). The modeled $\bar{\theta}$ is independent of wavelengths, with an average at about 21°.

The uncertainty of Hapke's SSA is dominated by both the absolute radiometric calibration error for each filter, and the modeling uncertainty. Calibration uncertainty is about 5% for HRI filters except for 950 nm, which is 10%, and about 10% for MRI filters except for narrowband filters, which is about 15% [3]. The uncertainty from photometric modeling is about 12%. Therefore the error bar will be 13-15% for the modeled SSA from HRI and MRI broadband images, and 20% from MRI narrowband images. The uncertainty for modeled $\bar{\theta}$ is almost completely determined by modeling uncertainty, and was estimated to be about 10°.

Since Tempel 1 is very dark, the bidirectional reflectance will be almost proportional to its SSA. Therefore we can construct albedo maps by taking the ratio between the original images and the corresponding models. Fig. 3 shows such maps at 750 nm from both HRI and MRI. The reflectance maps at other wavelengths are very similar, consistent with the

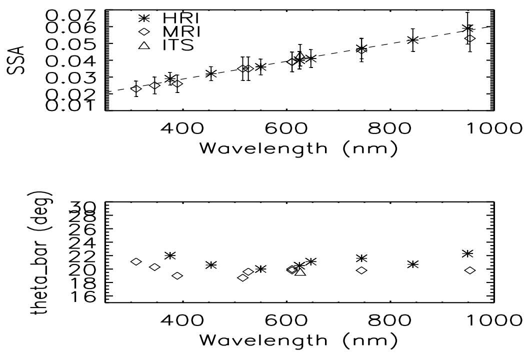

Figure 2: The Hapke's modeling for Tempel 1. Upper panel shows the modeled SSA, lower panel the modeled $\bar{\theta}$. Error bars are 1-σ. The error bar for $\bar{\theta}$ is about 10°. See text for discussions of the uncertainties of modeled SSA.

small color variations of Tempel 1 as shown later. The albedo variations have a FWHM of 20%, much smaller than those of Borrelly (2-2.5×) [8]. The albedo of the small regions that have been confirmed to contain water ice [9] is 1.8 to 2.2× brighter than the rest of the surface.

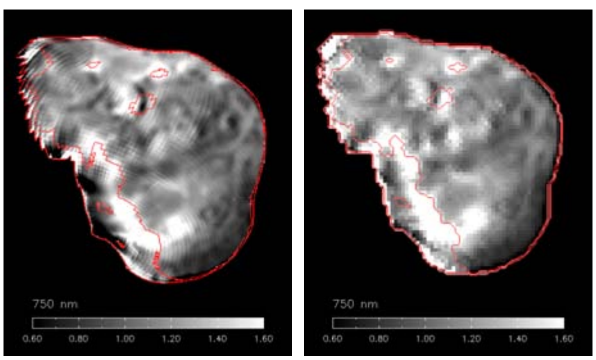

Figure 3: The albedo maps (ratio between the original images and the models) of Tempel 1 at 750 nm from HRI (left) and MRI (right). The contour is the boundary where the data with incidence angle or emission angle greater than 75° are disregarded in photometric modeling. Small scale variations are from topography that is not included in the shape model.

It is easy to notice that, close to the lower-right limb, the reflectance of Tempel 1 is lower than the modeled values (appears darker than average in Fig. 3). Similar cases can be seen at all wavelengths we studied. Later ITS images of this area with higher resolution (a few m/pix) suggest a high roughness explanation rather than low albedo. Hapke's modeling for HRI images excluding this rough area results in an average $\bar{\theta}$ of about 16°, and almost the same SSA as obtained above, but much less modeling error (8% RMS). Same modeling for the rough area from the ITS image shows that the SSA for this area is the same as the rest of the surface, but the modeled $\bar{\theta}$ is about 30°. This confirms that high roughness is responsible for the apparent darkening of this area.

Color variations: The color variations on Tempel 1 are very small, except for the three small areas where water ice was discovered [9] (Fig. 4). For most of the surface the color variations are less than 12%. The FWHM of color distribution is only 3%. The distribution of colors shows some correlation with terrains and the layer structure [10,11]. The reddest color appears in the middle horizontal band, where it is at the top of layer structure. The smooth area in the lower half of the nucleus shows slightly redder colors than the average surface. The bottom of the layer structure at the lower half of the nucleus shows slightly bluer colors than the adjacent higher areas. The bluest color on the surface is evident for the three small areas near the image top where water ice is confirmed to exist [9]. The possible causes of this correlation include the variations in photometric properties, topography, compositions, surface exposure time, etc.

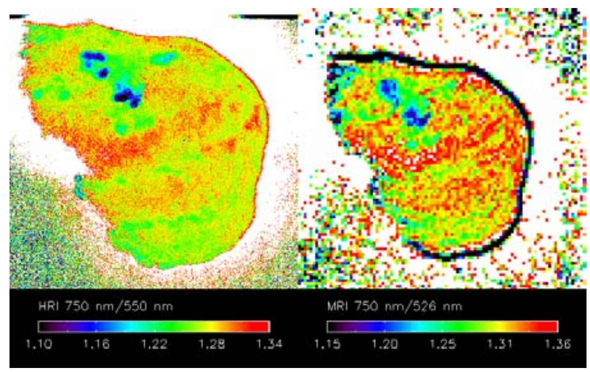

Figure 4: The color ratio maps from HRI (left) and MRI (right). The large apparent color variations on the edge of nucleus and near large topographic boundaries are due to registration. The regions with water ice [9] are much bluer than the rest of the surface.

Conclusions: The disk-resolved photometric properties of the nucleus of Tempel 1 are studied from DI images. The single-scattering albedo at 550 nm is modeled to be 0.036, and is linear with a slope of 12%/μm between 309 nm and 950 nm. The roughness is found to be about 21°. The albedo variations are very small (20%), with small areas containing water ice [9] very bright (1.8 to 2.2×). The color variations are small (3%), and show correlations with terrains.

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