Survey of the Physical Properties of Cometary Nuclei: Recent Progress[1]

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Abstract. We report progress on our survey to determine physical properties of the cometary nucleus population. Previous studies have been hindered by the exclusive use of optical data and due to contamination by coma; we have attempted to survey nuclei by combining mid-infrared with optical imaging, and using a technique to separate comatic and nuclear flux in an image of a comet. So far we have data on 6 comets, and we present three newly-determined radii and temperatures and two newly-determined albedos here, of comets 55P/Tempel-Tuttle, 81P/Wild

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2, and C/Utsunomiya (C/1997 T1). Previously, the properties of the nuclei of 55P and C/1997 T1 were completely unknown.

1. Introduction

By studying the ensemble of cometary nuclei, the most pristine observable objects remaining from the Solar System's birth, we can understand the dynamics and chemistry of the young System and the characteristics of its planetesimals. However, detailed knowledge on the properties of the nuclei is lacking; usually a nucleus is too small, too far away, and hidden by coma to be observable. We rigorously know the physical properties (e.g., radius, reflectivity, spin state) of only a handful of comets (A'Hearn 1988, Belton 1991), though less constrained estimates have been obtained for about two dozen objects (Meech 1998). Most of these are short-period objects; telescope time allocation methods have assured that the long-period comets (with unpredictable apparitions) are less understood.

To sample the ensemble properties our group has initiated a program to image the thermal radiation as well as the reflected of as many comets as possible. This multiwavelength approach can provide a more accurate characterization of the physical properties of the nuclei, as well as of the thermal behavior. In this report we give a description of the methodology of our survey, and report some recent results on comets of interest. We have already reported our results on comets Hyakutake (C/1996 B2; Fernández *et al.* 1997, Lisse *et al.* 1998), and Hale-Bopp (C/1995 O1; Fernández *et al.* 1998). We are presently working on data obtained on comet 2P/Encke (Fernández 1999). Here we report results from our observations of the Halley-family comet and Leonid meteor stream parent 55P/Tempel-Tuttle, the Jupiter-family comet and target of the *STARDUST* mission 81P/Wild 2, and the recently-discovered long-period comet Utsunomiya (C/1997 T1).

2. Methodology

2.1. Motivation

Let $F_{\rm opt}$ be the optical flux from the nucleus, and $R_{\rm N}$ its radius. We have

$$F_{\rm opt} \propto R_{\rm N}^2 p \phi, \tag{1}$$

so it is proportional to two quantities that are potentially quite unconstrained, the geometric albedo p and the phase effect ϕ, neither of which are known *a priori* for a specific comet. The canonical value of p is 0.04 but there are comets for which it is as low as 0.02 and as high as 0.13 (Meech 1998). The phase effect ϕ is usually approximated by $\phi = 10^{-0.4\beta\alpha}$, where α is the phase angle and β is some coefficient, but this does not account for an opposition surge nor has the effect been well studied at high α. A value of 0.035 or 0.04 mag/deg is frequently assumed for β; the few measured values for nuclei fall near this range (28P/Neujmin 1, 0.031 ± 0.005 mag/deg [Sekanina 1976], and 0.034 ± 0.012

mag/deg [Jewitt and Meech 1988]; 49P/Arend-Rigaux, 0.035 ± 0.006 mag/deg [Sekanina 1976]), though they have only been measured across $5° \leq \alpha \leq 30°$. Clearly, using optical observations alone can leave a significant uncertainty in the determination of as simple a property as the nucleus' width.

Observations of a cometary nucleus' thermal flux, $F_{\rm th}$, can complement optical data. In that case

$$F_{\rm th} \propto \epsilon R_{\rm N}^2 \phi_{\rm th}, \qquad (2)$$

where ϵ is the emissivity (typically between 0.9 to 1.0 [Campbell et al. 1989, Morrison 1973]), and $\phi_{\rm th}$ is the thermal phase effect, so an observation done at "low" phase angle returns a well-constrained estimate of the nuclear size, which can then be used in Eq. 1 to derive p. No assumption for p is needed. In addition to this physical information, thermal measurements over many wavelengths can yield information on the thermal structure and behavior of the nucleus.

Many comets do have significant comae that radiate at thermal wavelengths, and we have developed a technique to separate the relative contributions of the coma and the nucleus in an image of a comet; our "coma-fitting method" is described by Lisse *et al.* (1998). Briefly, it involves fitting the coma's structure as a power law of brightness at many azimuths, and then extrapolating the function back to the central pixels. It is very similar to a technique developed by Lamy and co-workers for use in optical imaging (e.g., Lamy *et al.* 1998, Lamy 1998a).

2.2. Interpretation

The main limitation to our survey is that a comet must be sufficiently close and have a sufficiently large nucleus to be detectable at thermal wavelengths. We most commonly observe in the mid-infrared (5 to 25 μm), but we can also observe at microwave (cm) wavelengths if the nucleus is very large (e.g., Hale-Bopp) or very close (e.g., C/1996 B2 Hyakutake). This long wavelength is especially useful since it does not suffer from much coma contamination. Though it is not a rigid rule, generally we can just detect a cometary nucleus at 10 μm if the comet itself has $m_1 \sim 11$. This requirement means we may have to observe a comet at a very large α, which makes our biggest source of uncertainty the lack of knowledge of the the thermal phase effect.

Presently the canonical solution is to use a similar formalism as in the optical case, with $\beta \approx 0.01$ mag/degree. This value was derived from radiometry of asteroids and the intrinsic scatter covers 0.005 to 0.017 mag/degree (Matson 1972, Lebofsky *et al.* 1986) over $\alpha \leq 30°$. It has not been measured for any cometary nucleus. Fortunately, the effect is less important than for the optical case (since β is smaller) and, since $R_{\rm N} \propto 10^{0.2\beta\alpha}$ (via Eq. 2), the calculation of a nuclear radius is not as uncertain as for the assumption of p required for optical data alone. Microwave observations are even less susceptible to the unknown phase effect since they sample several decimeters inside the nucleus where the diurnal thermal wave is less important.

For this paper we will interpret thermal data using the Standard Thermal Model (STM; Lebofsky and Spencer 1989). This is a model strictly applicable to slowly-rotating asteroids, and does not account for sublimation of ice from the nucleus' surface. However it can be argued that it is applicable to (e.g.) low-activity nuclei (Campins *et al.* 1987). Most previous analyses of thermal data from cometary nuclei have used it, so it does place our results in context. We will assume that $0.9 \leq \epsilon \leq 1.0$, and that the beaming parameter – a parameter of the STM that attempts to account for a thermal opposition surge – is between 0.7 to 0.9. These are standard assumptions of the STM. Presently we are working on an improvement to this model to better interpret our thermal imaging.

3. Specific Comets

3.1. 55P/Tempel-Tuttle

We observed this comet on 21 Jan 1998 at NASA/IRTF with the MIRLIN mid-infrared imager and on 22 Jan 1998 with a CCD on the UH 2.2-m telescope on Mauna Kea, HI. The comet was 1.15 AU from the Sun (r), 0.39 to 0.40 AU from Earth (Δ), and $55.0° \leq \alpha \leq 56.7°$. A typical optical image and its analysis products are shown in Fig. 1 (in logarithmic intensity scale). The left panel is an original (cleaned) image, the middle panel is the model of the coma that was created using the "coma-fitting method" described by Lisse *et al.* (1998), and the right panel is the residual from the subtraction of the two. Clearly we have achieved a good removal of the coma, as can be seen in the plot in Fig. 1, which shows a comparison of the point spread function profile (PSF), the residual profile, and the original image's profile. The residual is a point-source; we ascribe its flux as reflected light from the nucleus. We performed photometry on the optical residuals and found a magnitude of $R_C = 16.7 \pm 0.1$.

We now characterize the optical phase effect, ϕ, of the nucleus by combining our data with the magnitudes reported by Lamy (1998b) and Hainaut *et al.* (1998) (Fig. 2). A straight line gives a satisfactory fit with $\beta = 0.041$ mag/deg, which agrees with the value derived by Lamy (1998a). We have also fit the data according to the pan-asteroidal phase law of Lumme and Bowell (1981). Though the two models yield equally good fits, we prefer the latter since it has a physical basis. The parameter Q, which attempts to account for multiple scattering of light on the surface, is around -0.037, and the zero-phase absolute magnitude is 15.6 ± 0.1. Note the large, 0.4-mag difference in absolute magnitudes between the two models.[1]

Our mid-IR dataset is shown in Fig. 3 (in logarithmic intensity scale); each frame shows a separate filter, and the wavelength and bandpass are written in white (in μm). There are two images of the comet (and two negatives) in each frame because our chop and nod throws were smaller than the field of view of the instrument. An M band (4.7 μm) observation is not shown since only upper limits could be had from that wavelength. There is some coma visible in the images, and we performed the extraction of the nuclear signal as was done for the optical images. About 50 to 60% of the flux is due to coma. We performed photometry on the residuals and the result is shown as a broad-band spectrum in Fig. 4. The S/N is low but we find a consistent flux of about 1 Jy in the 10-micron range.

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[1] Note that we have updated and improved our results from those presented in the actual conference presentation.

Figure 1. Optical image of comet P/Tempel-Tuttle (left), the coma model (middle), and the residual from the subtraction (right), which is a point source and shows the reflected light from the nucleus. Intensity scale is logarithmic. The plot compares the profiles of the point spread function (PSF), the residual, and the original comet image.

Figure 2. Fit of the phase law for the nucleus of comet P/Tempel-Tuttle. Symbols (and references): asterisk (this work), triangle (Lamy 1998b), rhombus (Hainaut *et al.* 1998, photometric points), cross (Hainaut *et al.* 1998, possibly photometric points). Dashed line represents the common β-formalism for ϕ, with $\beta = 0.041$ mag/deg, and the absolute magnitude (m_0) is 16.03. Solid line represents the best fit to the Lumme-Bowell phase law, with $Q = -0.037$ and $m_0 = 15.64$.

Overplotted on the spectrum are various fits based on the STM. Plausible input parameters yield a radius of 1.75 ± 0.4 km, a subsolar temperature (T_{SS}) of 380 to 410 K, and a brightness temperature (T_B) of about 280 to 350 K. (The rotation period of the nucleus is thought to be about 15 hr [Jorda *et al.* 1998], which is long enough to qualify the nucleus as a slow rotator at this distance from the Sun.) Our derived radius implies that $p = 0.06 \pm 0.015$, higher than the canonical value but not out of the range. (Assuming the β-formalism for ϕ would have yielded $p = 0.04 \pm 0.01$.) The main source of error in the results is the wide range of possible β for ϕ_{th}.

3.2. Utsunomiya C/1997 T1

On 23.9 Nov 1997 we imaged this long-period comet at NASA/IRTF with the MIRAC infrared camera (Hoffmann *et al.* 1998). At the time, $r = 1.38$ AU, $\Delta = 1.65$ AU, and $\alpha = 36.6°$. The comet was a point source (Fig. 5a) with flux 0.6 Jy at 10.6 μm, but, since the image is the coaddition of several low-S/N frames with poorly defined centroids, we are not absolutely certain of zero coma contamination. Assuming all of the flux is nuclear, the STM with the standard range of parameters gives $R_{\mathrm{N}} = 5.8 \pm 0.5$ km, $T_{SS} = 350$ to 370 K, and $T_B = 275$ to 315 K. To our knowledge this is the only infrared data on this comet and the only estimate of its nuclear size. Unfortunately we have access to neither nuclear magnitudes of this comet nor deep images, so we cannot yet estimate p.

3.3. 81P/Wild 2

On 29.3 Jan 1997 we imaged this short-period comet (the target of the *STARDUST* spacecraft mission) at NASA/IRTF with the MIRAC infrared camera.

Figure 3. Mid-infrared imaging of comet P/Tempel-Tuttle, with logarithmic intensity scale. Each image has 2 positive and 2 negative components since our chop and nod throws were smaller than the instrument's field of view. The effective wavelength and bandpass of each image is shown, in microns.

A the time, $r = 1.85$ AU, $\Delta = 0.87$ AU, and $\alpha = 5.9°$. The comet was a point source (Fig. 5b) with flux 0.5 Jy at 11.7 μm, but, again, since the image is the coaddition of several low-S/N frames with poorly defined centroids, we are not absolutely certain of zero coma contamination. Assuming all of the flux is nuclear, the STM with the standard range of parameters gives $R_{\rm N} = 3.0 \pm 0.3$ km, $T_{SS} = 300$ to 320 K, and $T_B = 265$ to 285 K.

We have estimated the nucleus' value of $pR_{\rm N}^2$ by using reports of the nuclear magnitude by Meech (1989) ("the comet was stellar in appearance") and Fitzsimmons and Cartwright (1995) ("...report this comet as of near-stellar appearance"). Using the β-formalism for ϕ (the data were taken at low α), we derive $pR_{\rm N}^2 = 0.17 \pm 0.1$ km^2; with our derived $R_{\rm N}$ this yields $p = 0.02 \pm 0.01$. This is lower than the canonical value but again within the range. We may be overestimating the nuclear IR flux from unseen coma contamination, which would drive up p, but the optical flux may have the same problem, countering this. Assuming $p = 0.04$ would have yielded $R_{\rm N} = 2 \pm 1$ km; here we clearly see the usefulness of the combination of optical and thermal observations.

4. Summary and Conclusions

We have presented a progress report on our survey of the physical properties of cometary nuclei. Our primary method is the combination of mid-infrared and optical imaging since that can provide good constraints on the nucleus size, albedo, and thermal behavior; the exclusive use of optical data introduces too much ambiguity. We note that the problem of the infrared phase effect for cometary nuclei has been not studied very much and that our best estimates of this effect are based on asteroid data taken 25-30 years ago. With the huge

Figure 4. Broadband spectrum of the nucleus of comet P/Tempel-Tuttle. The point at 4.7 μm is an upper limit. Variously styled lines show predicted spectra from the STM (beaming parameter is 0.8, $\epsilon = 0.9$): dash-dot, $R_{\rm N} = 1.75$ km, $\beta = 0.005$ mag/deg; short dash, $R_{\rm N} = 1.75$ km, $\beta = 0.01$ mag/deg; dash-3 dot, $R_{\rm N} = 1.75$ km, $\beta = 0.015$ mag/deg; long dash, $R_{\rm N} = 2.15$ km, $\beta = 0.015$ mag/deg; dot, $R_{\rm N} = 1.35$ km, $\beta = 0.005$ mag/deg. The largest source of error is the fairly unconstrained phase effect.

Figure 5. Mid-infrared images of comet Utsunomiya at 10.6 μm (a) and P/Wild 2 at 11.7μm (b). The images are the coaddition of 13 and 53 frames, respectively, and the intensity is logarithmically scaled. There is no obvious coma, but the individual images were of sufficiently low S/N to make accurate coaddition problematical. This may have introduced spurious coma-like extension to the images.

advance in infrared detector technology this problem should be addressed for cometary nuclei.

With these caveats, and the assumption that we have no contamination by coma in our reduced images, our results for three comets are as follows: For 55P/Tempel-Tuttle, we find $p = 6 \pm 1.5\%$, $R_{\rm N} = 1.75 \pm 0.4$ km, $\beta = 0.041$ mag/deg in the optical, and $T_{SS} = 380$ to 410 K when $r = 1.15$ AU. For 81P/Wild 2, we find $p = 2 \pm 1\%$, $R_{\rm N} = 3.0 \pm 0.3$ km, and $T_{SS} = 300$ to 320 K when $r = 1.85$ AU. For C/1997 T1 Utsunomiya, we find $R_{\rm N} = 5.8 \pm 0.5$ km, and $T_{SS} = 350$ to 370 K when $r = 1.38$ AU.

It is useful to put p into context, since there are so few known. The well-constrained values are listed in Table 1 (there are few comets such as Hale-Bopp [Fernández *et al.* 1998] and *IRAS*-Araki-Alcock [Sekanina 1988] for which p is in the vicinity of the other values but not as well-constrained). It is clear that the oft-used $p = 0.04$ assumption, while appropriate if no other information exists, is not necessarily a good representation of reality. One glaring property of Table 2 is the absence of long-period comets. With continued access to telescope time we hope to build up a significant database of cometary nuclear sizes and albedos within a few years, which will allow us to start to interpret the ensemble properties of nuclei vis-à-vis solar system formation. We are also working to improve thermal modeling of the nucleus, to better interpret the thermal data in terms of temperature and thermal lag.

Table 1. Known visual geometric albedos

Comet	p (%)	$R_{\rm N}$ (km)	Reference
55P/Tempel-Tuttle	6 ± 1.5	1.75 ± 0.4	This work
81P/Wild 2	2 ± 1	3.0 ± 0.3	This work
28P/Neujmin 1	2.5 ± 0.8	10.0 ± 0.5	Campins *et al.* 1987
49P/Arend-Rigaux	2.8 ± 0.5^a	5.1 ± 0.25	Millis *et al.* 1988
10P/Tempel 2	$2.2^{+0.4}_{-0.6}$	$5.9^{+0.25}_{-0.68}$	A'Hearn *et al.* 1989
29P/Schwassmann-Wachmann 1	13 ± 4	20 ± 2.5	Cruikshank and Brown 1983
95P/(2060) Chiron	14^{+6}_{-3}	88 ± 5^b	Campins *et al.* 1994
1P/Halley	4 ± 1	5 ± 0.5	Several works[c]

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[a] Tokunaga and Hanner (1985) found $p = 5.4 \pm 1\%$ at a wavelength of 1.25μm, but a similar radius

[b] This is the mean of the values given in the reference.

[c] Sagdeev *et al.* (1986) used *in situ* measurements plus the work of Jewitt and Danielson (1984); Keller *et al.* (1986) used *in situ* measurements and the work of Hughes (1985).

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