1 Scientific Justification

1.1 Motivation

Planetesimal reservoirs – i.e. protoplanetary disks – have been found around a growing number of young, T Tauri stars (see review by Dutrey et al. 2005), and Spitzer is giving new insight into this phenomenon (e.g. Forrest et al. 2004, Megeath et al. 2005). In our own Solar System, the planetesimals that did not accumulate into planets are represented today by asteroids, comets, Centaurs, and transneptunian objects (TNOs). Most asteroids presumably formed inside the ice line, while at least some outer Main Belt objects, Trojans, and comets formed at or beyond the ice line. Thus small bodies of the Solar System can in principle be used to investigate a fundamental question: what was the thermal, chemical, and dynamical environment of the protoplanetary disk in the young Solar System? In particular, comets hold great promise since they have remained relatively unprocessed, having spent much of their history in the Kuiper Belt or the Oort Cloud. They are the most pristine observable remnants from the formation era.

However comets are not perfectly preserved remnants, so the primary goal of using comets as a probe of Solar System formation is intimately tied to a complementary goal of understanding the evolution of comets in the last 4.5 Gyr (see e.g. review by Meech and Svoreň 2005). Our proposal is to investigate two important aspects of this larger problem: the evolution of geometric albedo and radius in the cometary population. Both properties can be strongly affected by surface processes, so these quantities will give us insight into cometary evolution, particularly in their comparison to related planetesimals.

In particular Jupiter-family comets (JFCs) are well-suited to our proposed survey since their nuclear properties are more accessible than those of long-period comets. JFCs are dynamically connected to other Solar System bodies, to wit: Collisions and dynamical chaos send TNO fragments into the giant planet region, where the object is called a Centaur and has a dynamical lifetime of $\sim 10^6$ yr. A Centaur will be ejected from the region, swallowed by a planet, or shattered in a collision. Surviving Centaurs or their fragments can become JFCs (Levison and Duncan 1997, Duncan et al. 2005). Following prolonged solar heating, subsequent volatile loss, and/or rubble-mantling over $\sim 10^5$ yr, some of the JFCs may eventually evolve into extinct, asteroid-like objects (review by Weissman et al. 2002). This progression from TNOs to Centaurs to JFCs to extinct comets makes intercomparisons between the groups appealing: we can study the sizes and surface properties of all these groups to learn how cometary bodies evolve.

While the dynamical connection between Trojans and JFCs is not as strong (Marzari et al. 1997), one can expect similarities based on similar formation location (e.g. note the recent density measurement by Marchis et al. (2006)). This holds true whether they formed *in situ* or whether they were formed as TNOs and were captured into their location (Morbidelli et al. 2005). The Trojan's 4-Gyr evolutionary path at 5.2 AU demands that conclusions about cometary evolution be consistent with the observed similarities of Trojan and cometary surfaces.

These relationships between comets and Trojans, Centaurs, TNOs, and extinct comets candidates motivate our proposal. It is worth noting that among the five groups, only JFC nuclei have as yet not been the subject of a detailed size and/or albedo survey (either by Spitzer or by ground-based observations). Our scientific goals are as follows. • (a) Measure the thermal emission from a significant fraction of the known JFC nuclei to calculate their effective radiometric radii. • (b) Use complementary ground-based visible-wavelength observations (many of which have already been obtained) to derive the nuclei's geometric albedos. • (c) Test for correlations between the albedos and other properties of the nuclei, such as composition and dynamical age. • (d) Compare the cometary albedo distribution with those of Centaurs, TNOs, Trojans, and extinct comet candidates to test the proposed evolutionary processes. • (e) Resolve once and for all the question of just how safe it is to assume an albedo for a cometary nucleus. A cautionary tale is the TNO albedo story, where 4% was long assumed and turned out to be very wrong. • (f) Use the radiometric radii to derive an unbiased and independent estimate of the JFC size distribution. Among other applications, this can resolve the ongoing debate between several groups about the size distribution as derived from visible observations.

1.2 Albedo

Spitzer has greatly expanded the number of small bodies available for study. Mid-infrared work is fruitful for understanding radii, albedos, and thermal properties, since one can at last break the size-albedo degeneracy that plagues visible observations. A comet's original albedo can be altered by evolutionary processes, such as solar-UV and cosmic ray darkening, space weathering, collisions, and resurfacing from active outgassing. The current sample of albedos, described below, gives tantalizing hints about how surfaces evolve.

◦ Stansberry et al. (2005) used Spitzer GT observations to measure geometric albedos of a sample of TNOs and Centaurs. Their albedo range for TNOs is 0.01 to 0.19 and for Centaurs is 0.03 to 0.07. Combined with other measurements, TNO albedos cover 0.01 to almost 0.5 (e.g. Grundy et al. 2005, Cruikshank et al. 2006), and the Centaur albedos cover 0.03 to 0.15 (e.g. Campins and Fernández 2002). As already known with colors, the Kuiper Belt and Centaur region hold a wide variety of albedos too, though at the moment there is no indication of a correlation between the two. In any case, the albedo range is vastly larger than that seen so far among JFC albedos. This glaring dichotomy must be explained, since JFCs derive from these objects. We hypothesize that JFC albedos will show a trend with the time elapsed since the object left the Centaur region.

◦ Fernández et al. (2003) showed that the large Trojans (radii $>$ 30 km) have an extremely narrow range of albedos: standard deviation of 0.007 with a mean of 0.041. While the mean is similar to that of the (much less constrained) JFCs, the small variation is remarkable. Will JFCs have a similarly taut distribution? Does the gentler devolatilization at higher heliocentric distance affect the surface evolution differently? If so, we could hypothesize that JFC albedos will show a trend with dynamical parameters.

PI Fernández was awarded Cycle 2 time to measure the albedo distribution of the small (radii $<$ 8 km) Trojans. These Spitzer data are reduced and complementary ground-based data are undergoing reduction. We will soon know if there is a trend of albedo with Trojan size, which would be strong evidence that collisions strongly influence the albedo. We could then hypothesize a similar phenomenon in the JFCs. Note also that the small Trojan project will allow us to make comparisons between Trojans and JFCs of equal sizes.

◦ Fernández et al. (2005) investigated the albedos of low-Tisserand asteroids on comet-like orbits. We found a strong correlation between Tisserand value and albedo, and that many low-Tisserand objects have comet-like albedos. However we were limited by the fact that the range of cometary albedos is not well defined. This is crucial because some low-Tisserand asteroids will not come from cometary sources. Refining this range would strengthen statistical arguments on how many asteroids are extinct comet candidates.

The science questions raised above cannot be adequately addressed with the currently known JFC albedos. As summarized by Lamy et al. (2005), there are only nine JFCs with established albedos. *This situation is strong evidence that ground-based surveys are insufficient for achieving our science goals.* The nine objects include: three large, low-activity objects observed in the 1980s, three objects visited by spacecraft, one object observed by ISO, one dormant comet, and one object observed very close to Earth. Even with the advent of modern mid-IR cameras at ground-based telescopes, we have added essentially *nothing* to the known JFC albedo distribution outside of special situations.

A comparison of the albedo distributions mentioned above is given in Fig. 1. The JFC plot suffers from too few objects, so we are still uncertain about the full range of cometary albedos. Any tightness to the JFC histogram may be spurious: First, the 1σ error bar on most of the plotted albedo measurements is about 25% to 50%. Second, as-yet-unpublished and preliminary results by CoI Reach on several JFC nuclei show a wider range in albedos than this. Third, and more generally, given the remarkable surface variety among spacecraft targets P/Borrelly, P/Wild 2, and P/Tempel 1, there is good reason to suspect that we have not yet seen all the variety that JFC nuclei have to offer.

These points are demonstrated in Fig. 2, where we have created hypothetical cometary albedo distributions and compared them to the observed nine-comet distribution. We used the Kolmogorov-Smirnov test to calculate the probability that the known distribution is inconsistent with the hypothetical distribution. We tried both uniform and Gaussian distributions, and they both fit. There is a wide variety of distributions that cannot be rejected at 3σ confidence. Furthermore this analysis does not incorporate any of the measurement error bars, so the true variety of possible distributions is wider still. We are ignorant of even fundamental characteristics of the distribution.

Figure 1 also shows that there are not enough cometary albedos to search for multiple groupings or trends. For example, our proposed survey would let us search for a correlation with carbon-chain depletion (A'Hearn et al. 1995) or with broad dynamical age. This analysis would indicate if the albedo retains any of its primordial signature.

1.3 Radius

Evolutionary Processes. Although it is likely that many JFCs are collisional fragments, the size distribution may not mimic this. While a collisionally relaxed population of self-similar objects will have a power-law cumulative size distribution (CSD) with index -2.5 (Dohnanyi 1969), the index will be different if the objects have strengths that vary with size (e.g. Benz and Asphaug 1999, O'Brien and Greenberg 2003). For small objects, the global strength of the body increases with *decreasing* size, while for large objects that have gravity the strength increases with *increasing* size. The balance between the two effects is often taken to be at roughly 1-km (diameter) for asteroids, though for lower density comets the critical size could be larger and so diagnostic of collisional evolution processes. This motivates our desire to sample the CSD as close to 1 km as possible, so that we can study the transition regime.

Another possible influence on the CSD is the fact that comets may not be uniformly strong. There is observational circumstantial evidence for this: First, comet D/Shoemaker-Levy 9 was tidally disrupted into broadly similarly-sized primary fragments (Chodas and Yeomans 1996), not a smooth power-law distribution. This may be due to sub-kilometer-scale coherence within the original nucleus. Second, the surfaces of the JFCs imaged by spacecraft have soaring topographic features (e.g. P/Wild 2; Brownlee et al. 2004), suggesting significant strength on the dekametric or hectometric scale. Third, Toth and Lisse (2006) analyzed rotation periods to show that there may be a discrepancy in the densities and strengths of Centaurs versus JFCs. They found that several known Centaurs have "damaged" internal structures, which suggests that the JFCs that are fragments of Centaurs have sizes related to the strength scale of the original Centaur.

In addition to the collisional histories and mechanical properties, the sizes of individual nuclei will be affected by erosion of material (as normal cometary activity) and by fragmentation (Chen and Jewitt 1994, Boehnhardt 2005). In particular, Jewitt et al. (2003) argue that there could have been profound changes in radii since the JFCs became active, as evinced by the large fraction of a comet's mass that is in its meteor stream. The conclusion from all the aforementioned results is that the JFC's CSD will reflect a combination of effects, so the better we determine the CSD, the more we can say about the mechanical and erosional properties of the nuclei.

<u>Previous Work.</u> Recently several groups have given tantalizing peeks into the JFC CSD. While we are starting to understand this basic ensemble property, we caution that this work is based almost totally on visible-wavelength measurements. *In other words, a fundamental assumption of our current supposed understanding of the CSD is that all cometary nuclei have geometric albedos near 0.04.* In §1.2 we showed that this may not be valid, but to avoid this assumption one needs radiometrically-determined radii, of which only nine are known.

The CSDs from several groups are summarized by Lamy et al. (2005) and Meech et al. (2004), and there are discrepancies in the CSDs reported so far. Meech et al. (2004) are the only ones to have corrected for discovery bias, and since this bias means that smaller comets tend to be missed, their CSD is steeper than that of Lamy et al. (2005) or of Weissman and Lowry (2003). Again, we emphasize that this is based on an albedo assumption.

One interesting aspect is that the analyses of Lamy et al. (2005), Weissman and Lowry (2003), and J. Fernández et al. (1999) are based on similar datasets, yet they disagree. The difficulty lies in deciding which so-called "nuclear" magnitudes are really indicative of a nucleus's cross section. These are disparate datasets reported by many observers with many different telescope+detector systems. Some observations must be rejected and others kept, and this decision is based on incomplete and subjective information. Our proposed survey would provide a completely different approach that would (a) remove any assumptions about albedo, (b) remove any problem with heterogeneous datasets, (c) remove any problem with coma-confusion (as explained in §2). In other words, Spitzer can address the CSD question without suffering the problems that have plagued all earlier analysis attempts. We emphasize that our goal is *not* to add sizes to these workers' "radii" databases, but rather to tackle the problem afresh.

The number of targets in our survey (100) is driven by the need to determine the size distribution down to a radius of 1 km. This is necessary to test recent observational and theoretical indications (Samarasinha 2001, Meech et al. 2004) that the size distribution may be truncated at sizes smaller than 2 km. Since most of our targets have smaller sizes, our ability to properly constrain the low end of the size distribution is strongly dependent on the sample size (e.g., multiple studies based on optical surveys, which include about 65 objects, are insufficient to constrain the small end). If the size distribution is indeed truncated at radii smaller than 2 km, our study will be the definitive one.

2 Technical Plan

2.1 Targets and Observations

Above all, we want this experiment to be simple and statistically robust. There are about 300 JFCs known (see URL `http://www.physics.ucf.edu/~yfernandez/cometlist.html`). We excluded those that are lost and unlikely to be recovered, and those that are never beyond 4 AU from the Sun during Cycle 3. Of the remainder (about 220), we calculated the thermal emission as a function of time in each comet's observability windows. This procedure requires an estimate of the radius, for which we used the compilation of Lamy et al. (2005) or the following assumption when no estimate at all exists. If a comet's perihelion $q < 2.0$ AU, the assumed radius R is 1.0 km; if $2 < q < 2.5$ AU, then $R = 1.5$ km; if $q > 2.5$ AU, then $R = 2.0$ km. This assumption accounts for the fact that it is harder to discover more distant JFCs so the ones we do find tend to be larger.

We calculated the thermal emission at 16, 22, and 24 μm for all possible targets using the "NEA" Thermal Model (Harris 1998). We declared a target signal-to-noise ratio S/N of 30 and used the senstivities reported on the SENS-PET webpage to calculate the exposure time and AOR time needed to achieve this. We use only 2 AOTs, IRS PU imaging and MIPS pointed imaging.

The next step is to check the ephemeris uncertainty for each target using JPL's Horizons on-line service. Objects with a 3σ uncertainty under 30 arcsec would be observed with IRS PU imaging at 16 and 22 μm. Objects with uncertainty between 30 and 200 arcsec would be observed with MIPS at 24 μm owing to the larger field-of-view. Objects with even larger uncertainty were rejected. To keep things simple, we use only one instrument per target.

Lastly, to cutoff the list, objects predicted to be fainter than 24.0 mag in V-band were rejected (based on the feasibility of ground-based support observations). Of the remainder, we moved a few good-ephemeris comets from IRS to MIPS due to the fact that the required time for 16μm photometry was prohibitive. This yields our final target list in §7 of 100 JFCs, 64 with IRS, 36 with MIPS.

We have two generic but loose timing constraints. First, we want each target to be observed during the window in which it is brightest. Second, we want shadow observations of our MIPS targets to assure indentification. No such shadow data are needed for IRS because the 16-to-22 μm color of our targets will be much redder than virtually all other (λ^{-2}-emitting) objects in the field.

We discuss in §2.4 the need for multiple IRS wavelengths.

2.2 Duplicate Observations

A search of the ROC reveals 24 JFCs in our target list that have been observed by Spitzer already. The relevant PIDs are 131, 210, 668, 2316, 3119, 1095, and 20021. However note that *all* of these programs aim to study cometary dust, not cometary nuclei. In all but one case, the comets were observed within a few months of perihelion and definitely too close to the Sun, so the signal from the dust coma swamps the signal from the nucleus. So there is no real duplication here. This is also the reason we cannot use archival data to achieve our science goals.

The only other potential duplication involves comet 107P/Wilson-Harrington, observed in PID 210 with AOR #6045440. This comet is virtually always bare so there is no worry from coma. However that observation was only at one wavelength, 24 μm. We propose to observe it at two wavelengths (§7) in order to use a more valid thermal model. So there is no real duplication here.

2.3 Coma and Trail

Each of our targets will be more than 4 AU from the Sun and away from perihelion. Coma will be minimized and a majority of our targets will show just the nucleus (cf. Lisse et al. 2005). That said, we recognize that in a few cases a comet will show a coma and/or a dust trail. Observations by CoI Reach of comets near 3 AU show some cases of apparent activity. However, these data also show that the point-source nucleus has high contrast above the diffuse emission from dust. This is important because it will allow us to use image processing to photometrically extract the nucleus from the image with a coma or trail and thereby have photometry uncontaminated by dust. Our team has much experience in exactly this sort of image processing (e.g. Lisse et al. 1999, Fernández 1999, Lamy et al. 2002, Stansberry et al. 2004). This is a well-established and robust analysis method and we have the necessary expertise and computational tools to perform the task. The Spitzer imaging data is precisely the kind of image – high contrast for the nucleus above a detectable coma – from which it is easy to extract a nucleus.

2.4 Modeling

While having only one wavelength restricts our analysis options somewhat, there will be enough two-wavelength IRS targets for an excellent constraint on the parameterization of the thermal model.

The long-used method to derive an object's radius and albedo requires the measurement of the thermal flux and the reflected flux. It also requires knowing the temperature map of the object's surface, and in standard practice for most objects one assumes that the thermal inertia is very low, which makes the temperature map easy. For small bodies one must account also for infrared beaming, i.e. an anisotropy of the thermal emission. For example an object that has significant night-side thermal emission will have less infrared beaming, while an object with many deep craters will have more infrared beaming. This is represented by the parameter η. This parameter is not yet well constrained across a class of objects, and so it is best to let it be a third parameter to be solved. Otherwise one must assume a value and this introduces inherent extra error into the radius and albedo results. Deriving η requires thermal measurements at two wavelengths instead of one. This is our primary motivation for obtaining 16 and 22 μm photometry.

We demonstrate our ability to derive η in Fig. 3, where we have plotted the 22-to-16 μm flux ratio for various heliocentric distances r and values of beaming parameter η. Playing it conservatively, if we achieve photometry with only $S/N = 25$ at both wavelengths, we will constrain the flux ratio to about $\pm 6\%$. As Fig. 3 shows, this immediately yields only a ± 15 to 20% uncertainty in η. E.g., for an object at 4 AU, if we measure a flux ratio of 1.47 ± 0.08, then the beaming parameter must be $\eta = 1.00 \pm 0.20$. This corresponds to just a 10% uncertainty in the radius. Given recent results on a few nuclei (Lamy et al. 2002, Fernández et al. 2004, Groussin et al. 2005), we expect that the JFCs will have very low thermal inertia and that the mean value of η will be near unity. This will immediately give us the correct thermal model to use to interpret our program's MIPS 24μm photometry.

Note that our observational and modeling approach is not new or unusual. The exact same goals have been achieved on individual targets, for example Comet 9P/Tempel 1. This comet was observed in March 2004, well in advance of the Deep Impact encounter, while the comet was at $r = 4$ AU. Lisse et al. (2005) report that the comet was completely bare, with neither coma nor trail in IRS PU imaging. While IRS spectra were the primary data products, imaging photometry was an independent check, and constrained the size of the nucleus. Our results were spectacularly confirmed by the spacecraft flyby imaging. We have a proven track record of extracting nuclear properties from Spitzer comet data.

2.5 Ground-based Observations

The thermal emission from an object depends on $1 - A$ (A being the Bond albedo), so for expected low values of cometary albedos, the thermal emission will be very weakly dependent on the albedo. This is important because obtaining simultaneous thermal and reflected flux data is impossible with Spitzer. We can derive robust radii without the visible-wavelength measurements; e.g., two otherwise identical objects at $r = 4$ AU with albedos of 0.02 and 0.10 will only differ in their thermal emission at 16, 22, and 24 μm by 2 to 3%.

Ground-based observations are required to obtain the albedos, but the two sets of data need not be simultaneous. We can correct for the different heliocentric and geocentric distances, and the phase angle. (At $\sim$4 AU phase angle will not change much.) Since cometary nuclei are generally elongated, strictly speaking one must know the rotational context of the observations as well. However it has been shown by Weissman and Lowry (2003) and Lamy et al. (2005) that snapshot observations without knowledge of the rotational phase will still provide a good estimate of the cross section. Over all possible obliquities and rotation phases, the average effective radius of a snapshot will be within just 6% of the true value for a nucleus with axial ratio of 2. The uncertainty will be even less for smaller axial ratios. Though we will not be deriving the most exact albedos for individual targets, our large sample size will still allow us to achieve our science goals since on average we will be sampling very close to the true value of the cross section.

2.6 Management Plan

PI Fernández will lead the project and oversee all aspects of data aquistion, reduction, and analysis. He will also be the lead for the publication to be derived from this work, describing the nucleus and albedo distributions.

CoIs Lisse and Reach have extensive experience with Spitzer data and IR observations of comets. They will provide oversight for the data reduction effort by independently calibrating the data products. They will be part of the analysis team writing the resulting publication.

CoIs Groussin and Toth will provide their expertise in image processing and coma removal. Groussin will apply his thermophysical surface models to the photometry.

CoIs A'Hearn, Campins, Weaver, Toth, and Lamy will provide significant input into the interpretation of results, comparing measurements to their databases of cometary properties. Their expertise is required to ensure a robust data analysis by avoiding systematic errors in the reduction effort.

CoIs Bauer, Licandro, Meech, A'Hearn, Lowry, and Fernández will obtain ground-based visible wavelength photometry of our targets. They all have access to telescopes of sufficient diameter through their home institutions and/or countries. Our team is large so that the telescope burden may be distributed widely.

3 Legacy Data Products Plan

4 Figures and Tables

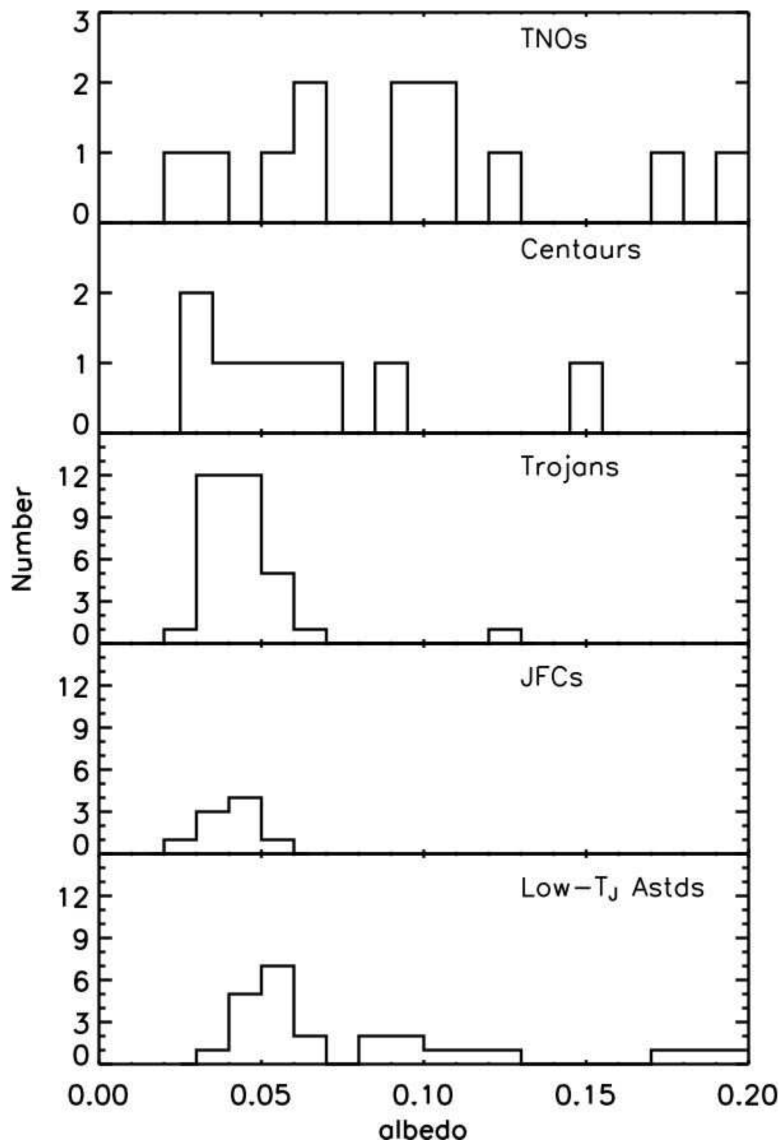

Figure 1: Comparison of geometric albedos across multiple groups. Note the differing vertical scales. JFCs are the only group of the five that has not been the subject of a detailed Spitzer or ground-based survey. Data come from Cruikshank et al. (2006), Grundy et al. (2005), Stansberry et al. (2005), Lamy et al. (2005), Fernández et al. (2005), Fernández et al. (2003), and Campins and Fernández (2002).

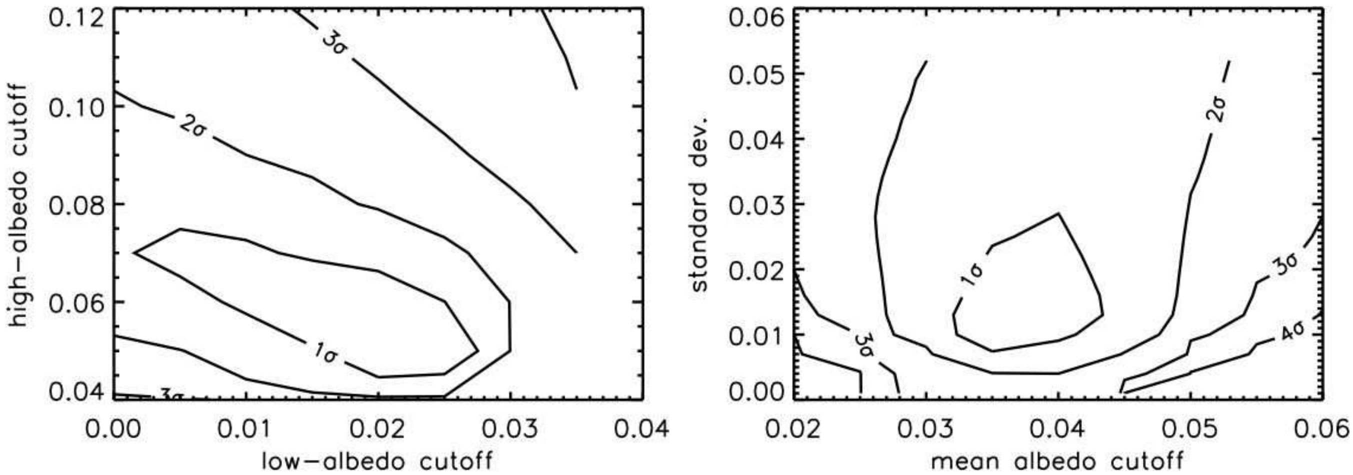

Figure 2: Contour plots of probabilities that the observed nine-comet albedo distribution is consistent with a hypothetical distribution. Left panel: hypothetical distribution is a uniform distribution between low-albedo and high-albedo cutoffs. Right panel: hypothetical distribution is a normal distribution with given mean and standard deviation. Contours indicate $n\sigma$ levels of probability. From these plots we conclude that neither the shape nor extent of the albedo distribution is constrained.

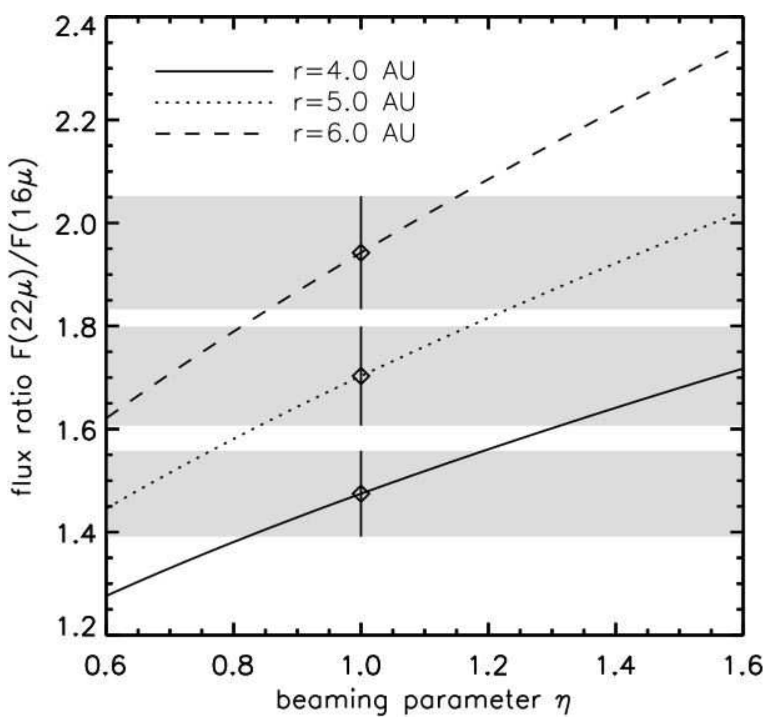

Figure 3: Correlation between flux ratio (at 16 and 22 μm) and beaming parameter η for three choices of heliocentric distance r. The diamonds and their error bars represent potential measurements of the flux ratio; the error bar is derived from having $S/N = 25$ photometry at both wavelengths. With such photometry (which is slightly worse than our observational goal) we can constrain the flux ratio to $\pm 6\%$. Just by reading off the graph that immediately implies we can constrain η to better than $\pm 20\%$. That in turn means that we can constrain the radius to better than $\pm 10\%$.

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6 Brief Resume/Bibliography

• PI: Y. R. Fernández, Assistant Professor at University of Central Florida. He has studied cometary nuclei in visible, infrared, and radio wavelengths for ten years. He is a former Spitzer Fellow and has extensive experience with Spitzer data. He is an expert in determining physical properties of small bodies in the Solar System.
• Co-I: M. A'Hearn, University of Maryland, College Park. He is the PI for NASA's Deep Impact mission, and has published dozens of papers on comets in 40 years in the field.
• Co-I: J. M. Bauer, NASA/Jet Propulsion Laboratory. He is an expert on outer Solar System small bodies and has extensive experience in ground-based observations of faint and distant comets.
• Co-I: H. Campins, University of Central Florida. He has been studying comets and related bodies for over 20 years, primarily in the infrared.
• Co-I: O. Groussin, University of Maryland, College Park. He is an expert in cometary nuclei and in image processing and analysis, having worked extensively with ISO datasets.
• Co-I: J. Licandro, Instituto de Astrofísica de Canarias. He is an expert in cometary behavior and has extensive experience in ground-based observations of faint and distant comets.
• Co-I: S. C. Lowry, Queen's University Belfast. He is an expert on cometary behavior and cometary sizes, and has extensive experience in ground-based observations of faint and distant comets.
• Co-I: P. Lamy, Laboratoire d'Astrophysique de Marseille. He is an expert in cometary nuclei and in image processing and analysis.
• Co-I: C. M. Lisse, JHU Applied Physics Laboratory. A member of the Deep Impact science team, he is an expert on cometary dust and cometary nuclei as studied in the visible and infrared.
• Co-I: K. J. Meech, Professor at University of Hawai'i. She is an expert in cometary behavior and cometary dust and has extensive experience in ground-based observations of faint and distant comets.
• Co-I: W. T. Reach, SSC. He is an expert in cometary and zodiacal dust and has extensive experience with Spitzer observations.
• Co-I: I. Toth, Konkoly Observatory. He is an expert in cometary nuclei and in image processing and analysis.
• Co-I: H. Weaver, JHU Applied Physics Laboratory. He has been studying cometary nuclei and comae for more than 20 years. He is Project Scientist for New Horizons.
• Selected Relevant Publications (aside from those in §5):

- ○ Bauer, J., et al., 2003, Icarus, 166, 195
- ○ Campins, H., et al., 2005, BAAS 37, 1602
- ○ Fernández, Y. R., et al., 2003, Icarus, 164, 481
- ○ Lisse, C. M., et al. 2004, Icarus, 171, 444
- ○ Meech, K. J., et al., 2005, Science, 310, 265
- ○ Reach, W., et al., 2005, ApJ, 635, L161

7 Observation Summary Table

We request 72.1 hours of IRS PU imaging time in 64 AORs to observe 64 targets. We request 33.4 hours of MIPS imaging time in 72 AORs to observe 36 targets. We request a total of 105.4 hours for this project.

IRS PU Imaging targets. The total integration time assumes a safe exposure time of 14 s. We aim to achieve $S/N = 30$ in both wavelengths. Fluxes are given for optimal window of observation.

Comet	16μm Flux (mJy)	16μm Cycles	16μm Int. (sec)	22μm Flux (mJy)	22μm Cycles	22μm Int. (sec)	AOR duration (hours)	estim. nuclear V mag
143P/Kowal-Mrkos	7.05	1	73	12.10	1	73	0.16	20.8
47P/Ashbrook-Jackson	4.59	1	73	6.98	1	73	0.16	21.4
48P/Johnson	3.63	1	73	5.75	1	73	0.16	21.6
7P/Pons-Winnecke	3.13	2	146	4.91	1	73	0.19	21.8
P/2004 F3 (NEAT)	2.95	2	146	4.36	1	73	0.19	22.0
129P/Shoemaker-Levy 3	2.82	2	146	4.19	1	73	0.19	22.0
P/2005 GF8 (LONEOS)	2.72	2	146	4.06	1	73	0.19	22.0
31P/Schwassmann-W. 3	2.56	2	146	4.26	1	73	0.19	22.0
14P/Wolf	2.52	3	220	3.94	1	73	0.22	22.0
119P/Parker-Hartley	2.31	3	220	3.53	1	73	0.22	22.2
74P/Smirnova-Chernykh	2.21	3	220	3.48	1	73	0.22	22.2
107P/Wilson-Harrington	1.97	4	293	2.94	2	146	0.29	22.1
118P/Shoemaker-Levy 4	1.79	5	367	2.96	2	146	0.32	22.3
P/2005 L4 (Christensen)	1.66	6	440	2.45	3	220	0.38	22.6
P/2005 R2 (Van Ness)	1.50	7	513	2.24	3	220	0.41	22.7
137P/Shoemaker-Levy 2	1.37	8	587	2.47	3	220	0.44	22.5
172P/Yeung	1.37	8	587	2.07	4	293	0.47	22.8
121P/Shoemaker-Holt 2	1.36	8	587	2.09	4	293	0.47	22.7
P/2005 R1 (NEAT)	1.34	9	660	2.04	4	293	0.50	22.8
68P/Klemola	1.32	9	660	2.23	3	220	0.47	22.6
P/2001 YX127 (LINEAR)	1.28	10	734	2.11	4	293	0.53	22.7
6P/d'Arrest	1.24	10	734	1.93	4	293	0.53	22.8
173P/Mueller 5	1.24	10	734	2.05	4	293	0.53	22.7
101P/Chernykh	1.15	12	880	1.78	5	367	0.62	22.9
78P/Gehrels 2	1.09	13	954	1.65	6	440	0.68	23.0
127P/Holt-Olmstead	1.07	14	1027	1.68	6	440	0.71	23.0
79P/du Toit-Hartley	1.03	15	1101	1.60	6	440	0.74	23.0
131P/Mueller 2	1.02	15	1101	1.60	6	440	0.74	23.0
33P/Daniel	0.99	16	1174	1.56	6	440	0.78	23.0
P/2004 V5 (LINEAR-Hill)	0.96	17	1247	1.65	6	440	0.81	22.9

IRS PU Imaging targets (cont'd).

Comet	16μm Flux (mJy)	16μm Cycles	16μm Int. (sec)	22μm Flux (mJy)	22μm Cycles	22μm Int. (sec)	AOR duration (hours)	estim. nuclear V mag
P/2003 S1 (NEAT)	0.95	17	1247	1.64	6	440	0.81	22.9
130P/McNaught-Hughes	0.95	17	1247	1.51	7	513	0.84	23.1
77P/Longmore	0.85	22	1614	1.37	8	587	1.02	23.2
22P/Kopff	0.82	23	1688	1.38	8	587	1.05	23.1
P/2004 VR8 (LONEOS)	0.80	24	1761	1.30	9	660	1.11	23.2
43P/Wolf-Harrington	0.75	28	2055	1.30	9	660	1.23	23.2
94P/Russell 4	0.74	28	2055	1.22	11	807	1.29	23.3
89P/Russell 2	0.72	30	2202	1.19	11	807	1.36	23.3
32P/Comas Sola	0.70	32	2348	1.05	14	1027	1.51	23.5
163P/NEAT	0.70	32	2348	1.03	15	1101	1.54	23.6
P/2004 V3 (Siding Spring)	0.69	32	2348	1.25	10	734	1.39	23.2
120P/Mueller 1	0.69	33	2422	1.15	12	880	1.48	23.3
P/2002 X2 (NEAT)	0.68	34	2495	1.22	11	807	1.48	23.2
P/2004 DO29 (Sp.-L.)	0.63	39	2862	1.15	12	880	1.66	23.3
P/2005 JQ5 (Catalina)	0.63	39	2862	0.95	17	1247	1.81	23.6
113P/Spitaler	0.63	39	2862	0.97	17	1247	1.81	23.6
50P/Arend	0.63	40	2936	0.95	17	1247	1.84	23.6
54P/de Vico-Swift-NEAT	0.62	41	3009	1.04	14	1027	1.78	23.4
124P/Mrkos	0.60	44	3229	0.91	19	1394	2.03	23.6
37P/Forbes	0.59	45	3303	0.90	19	1394	2.06	23.6
159P/LONEOS	0.59	45	3303	1.07	14	1027	1.91	23.4
57P/du Toit-Neujmin-D.	0.58	46	3376	0.89	20	1468	2.12	23.7
132P/Helin-Roman-Alu 2	0.58	46	3376	0.86	21	1541	2.15	23.8
149P/Mueller 4	0.58	47	3449	1.06	14	1027	1.97	23.4
146P/Shoemaker-LINEAR	0.57	47	3449	0.85	22	1614	2.21	23.8
162P/Siding Spring	0.57	49	3596	0.87	21	1541	2.24	23.7
69P/Taylor	0.56	49	3596	0.86	21	1541	2.24	23.7
141P/Machholz 2	0.56	50	3670	0.85	21	1541	2.27	23.7
P/2003 S2 (NEAT)	0.54	50	3670	0.91	19	1394	2.21	23.6
171P/Spahr	0.54	50	3670	0.83	23	1688	2.33	23.7
160P/LINEAR	0.53	50	3670	0.92	19	1394	2.21	23.6
56P/Slaughter-Burnham	0.53	50	3670	0.93	18	1321	2.18	23.5
152P/Helin-Lawrence	0.51	50	3670	0.96	17	1247	2.15	23.5
123P/West-Hartley	0.49	50	3670	0.86	21	1541	2.27	23.6

MIPS Imaging targets. The total integration time assumes a safe exposure time of 10 s. We aim to achieve $S/N = 30$ in each AOR. Fluxes are given for optimal window of observation.

Comet	24μm Flux (mJy)	24μm Cycles	24μm Int. (sec)	AOR duration (hours)	No. of AORs per comet	estim. nuclear V mag
P/2005 S3 (Read)	4.46	1	165	0.13	2	22.0
P/2005 T5 (Broughton)	4.27	1	165	0.13	2	22.0
139P/Vaisala-Otererma	4.17	1	165	0.13	2	22.0
C/2005 W2 (Christensen)	3.91	1	165	0.13	2	22.1
P/1998 VS24 (LINEAR)	3.80	1	165	0.13	2	22.1
P/2005 W3 (Kowalski)	2.78	1	165	0.13	2	22.5
P/2002 O8 (NEAT)	2.43	1	165	0.13	2	22.6
P/2005 JD108 (Catalina-N.)	2.30	1	165	0.13	2	22.7
P/2005 Y2 (McNaught)	1.94	2	312	0.17	2	22.9
P/2001 CV8 (LINEAR)	1.74	3	459	0.21	2	23.0
P/1999 WJ7 (Korlevic)	1.69	3	459	0.21	2	23.0
P/2004 H2 (Larsen)	1.69	3	459	0.21	2	23.0
P/2002 LZ11 (LINEAR)	1.25	5	752	0.30	2	23.3
93P/Lovas 1	1.10	6	899	0.34	2	23.5
P/2003 KV2 (LINEAR)	1.02	7	1046	0.38	2	23.6
P/2005 K3 (McNaught)	0.86	10	1505	0.53	2	23.8
P/2004 T1 (LINEAR-NEAT)	0.84	10	1505	0.53	2	23.8
148P/Anderson-LINEAR	0.83	12	1799	0.61	2	23.8
169P/NEAT	0.82	12	1799	0.61	2	23.8
138P/Shoemaker-Levy 7	0.81	12	1799	0.61	2	23.8
P/2003 O3 (LINEAR)	0.80	12	1799	0.61	2	23.8
15P/Finlay	0.79	12	1799	0.61	2	23.8
P/2002 JN16 (LINEAR)	0.78	12	1799	0.61	2	23.9
168P/Hergenrother	0.76	14	2093	0.70	2	23.9
P/2005 XA54 (LONEOS-Hill)	0.76	14	2093	0.70	2	23.9
P/2005 Q4 (LINEAR)	0.75	14	2093	0.70	2	23.9
P/2000 Y3 (Scotti)	0.95	8	1212	0.44	2	23.6
11P/Tempel-Swift-LINEAR	0.74	14	2093	0.70	2	23.9
16P/Brooks 2	0.69	16	2424	0.82	2	24.0
144P/Kushida	0.69	16	2424	0.82	2	24.0
P/2002 S1 (Skiff)	0.77	12	1799	0.61	2	23.8
P/2003 HT15 (LINEAR)	0.84	10	1505	0.53	2	23.7
P/2004 A1 (LONEOS)	0.84	12	1799	0.61	2	23.7
P/2001 R6 (LINEAR-Skiff)	0.72	15	2258	0.76	2	23.9
51P/Harrington	0.68	16	2424	0.82	2	24.0
62P/Tsuchinshan	0.66	18	2699	0.89	2	24.0

8 Status of Existing Observing Programs

• PI - Y. Fernández: PI on Fellowship program 1095, GO-1 program 3698, and GO-2 program 20697. Some of the data from program 1095 have been published in a paper by Lisse et al. (2005, *Ap. J.* **625**, L139). Other data in this project – on dust comae around distant comets – are still being analyzed. Data from program 3698 – on the thermal emission from small Trojan asteroids – are all analyzed; complementary ground-based data are being reduced now. Data from program 20697 – on the rotational behavior of comet 2P/Encke near its aphelion – are undergoing analysis now.
• CoI - C. Lisse: PI on GO-1 programs 3658 and 3660. These data – regarding the dust environment of comet 9P/Tempel 1 before and after the Deep Impact encounter – have been analyzed and are discussed in a paper that has recently been submitted to *Science*.
• CoI - W. Reach: TC on GTO programs 210 and 218; PI on DDT program 256, GO-1 programs 3119 and 3137, and GO-2 program 20039. Results from program 218 on Elephant Trunk Nebula are published by Reach et al. (2004, *Ap. J. Supp.* **154**, 385), and results for the Trifid Nebula are published by Rho et al. (2006 *Ap. J.*, in press). Data from program 3137 (spectroscopy of Spitzer-discovered protostars in IC 1396A) were received in November 2005 and are under analysis. The other four programs are all part of the same project on cometary trails, split among cycles to observe comets when they come to perihelion (and are bright). Observations are mostly complete. First paper has been submitted, on comet 67P (by Kelley et al.). Two more papers are in preparation for submission Spring-Summer 2006. Two main comets (73P, 9P) await final data and will get their own papers in late 2006-early 2007.
• CoI - J. Bauer: PI on DDT program 265. The data for this program have not yet been obtained.
• CoI - M. A'Hearn: PI on DDT program 223. The data - regarding thermal emission from comet 9P/Tempel 1 when it was far from the Sun - are all analyzed and appear in a publication by Lisse et al. (2005, *Ap. J.* **625**, L139).
• CoI - P. Lamy: PI on DDT program 222. Data on the rotationally-resolved thermal emission from the Rosetta mission target, Comet 67P, have been obtained and are reduced. Paper is in preparation.
• CoI - H. Campins, S. Lowry, J. Licandro, K. Meech, H. Weaver, O. Groussin, I. Toth: Not PI on any program.

9 Proprietary Period Modification

There are no modifications to the proprietary period.

10 Justification of Duplicate Observations

The only potential duplication in terms of science goals involves comet 107P/Wilson-Harrington, observed by PID 210 with AOR #6045440. Section 2 describes why this is not a real duplication.

11 Justification of Targets of Opportunity

There are no ToO observations.

12 Justification of Scheduling Constraints

All our targets have low ecliptic latitude and so will generally have two observability windows each of about 40 days duration. In most cases, the Sun-comet-Spitzer geometry is such that the target is significantly brighter in one window compared to the other. For such targets we will request that the AOR (or AORs) be scheduled only during that better window.

13 Data Analysis Funding Distribution

PI- Y. Fernández 45%, CoI- C. Lisse 35%, CoI- H. Campins 14%, CoI- W. Reach 2%, CoI- J. Bauer 2%, CoI- K. Meech 2%

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