



Infrared observations of asteroids from space: The past and future

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Abstract—Infrared observations from space have large sensitivity and total instantaneous field of view advantages over ground-based measurements. The limits to telescope performance from thermal emission from the atmosphere and sky noise are eliminated in space and the instrument can be cooled to temperatures where the photon noise from the zodiacal background provides the fundamental limit to the sensitivity of the system. Furthermore, the entire thermal infrared spectral range is available; the atmosphere is virtually opaque at the wavelengths of molecular absorption bands from water vapor and CO₂ to ground-based observations. Space-based infrared radiometry from the experiments described in this article supplied the basis for the largest, consistent set of derived diameters and albedos of asteroids. Radiometry over a large spectral range and a large span of phase angles provides essential information of the detailed thermal properties of a body. Infrared measurements resolve the ambiguity of whether a visual observation is of a small highly reflective object or a large dark one. Infrared spectroscopy obtained by the previous space-based experiments, and the spectral capability of two infrared missions to be flown within the next several years, is a powerful remote sensing tool to assay the mineralogy of a surface. A description is given of what knowledge has been and will be gained from past and future infrared missions on the physical characteristics of asteroids. Why the database derived from previous satellites remains the major source of new radiometric measurements is explained and the benefits to be had from a space-based infrared spectrometer/photometer dedicated to studying small bodies in the solar system presented.

INTRODUCTION

As many have pointed out (*e.g.*, Cellino *et al.*, 2000; Price and Egan, 2001), the advantages of a space-based platform for thermal infrared observations are considerable compared to those of ground observatories. The vastly increased performance and scientific return justifies the cost of missions such as the space infrared telescope facility (SIRTF; Fanson *et al.*, 1998) and the next generation space telescope (NGST). These advanced instrument concepts build on the legacy of over 30 years of instrument development and space flight demonstrations. The Air Force infrared survey experiments (Walker and Price, 1975; Price and Walker, 1976; Price and Murdock, 1983; Price *et al.*, 1983) were the first to successfully exploit the emerging instrument and detector technology to conduct large-scale space-based mid-infrared surveys from probe rockets. The Air Force Cambridge Research Laboratories (AFCRL) survey experiments initiated the era of mid-infrared solar system observations from space with the first space-based 11 and 20 μm asteroid measurement on 1971 April 3. As discussed by Price (1988), an Air Force infrared sky mapping experiment

later that year made the first satellite-based infrared observations of an asteroid.

I review, in the historical context, what information we have derived about asteroids from space-based radiometry, the current state of affairs, and what future prospects might be.

HISTORICAL REVIEW OF THERMAL INFRARED OBSERVATIONS FROM SPACE

The Air Force Cambridge Research Laboratories/Air Force Geophysics Laboratory Space-Based Observations

Walker and Price (1972, 1974) reported the first space-based mid-infrared observations of asteroids. A total of 19 asteroids were observed during the seven-flight AFCRL survey conducted between April 1971 and December 1972. In an unpublished 1975 report, Murdock and his colleagues listed the measurement parameters for the 23 observations of these 19 asteroids and confirmed that their radiometrically derived diameters were systematically larger than those obtained from filar micrometer measurements, an important finding at the time. This result is

consistent with Murdock's (1973) earlier predictions in which he estimated the number of asteroids that a mid-infrared sky survey could detect as a function of survey sensitivity. He assumed that asteroids had similar thermal and emissive properties as those he measured for Mercury (Murdock, 1974). The temperature profile he derived to predict the infrared brightness of an asteroid at opposition was essentially the same as that used in the standard thermal model (STM) of Lebofsky *et al.* (1986). Murdock then increased the visually derived diameters by 20% to bring the infrared radiometry into agreement with his results on Mercury. LeVan and Price (1984) published the first readily accessible article on the Air Force probe rocket results. They reported the 20, 27 and 85 μm measurements that were obtained on the final two Air Force Geophysics Laboratory (AFGL) probe rocket survey experiments, which were flown in the early 1980s. The major finding from these measurements was that while the infrared diameters derived from the 20 μm measurements using the STM were in good agreement with those in the literature, the far-infrared fluxes from asteroids and, consequently, their emissivities were significantly lower than those predicted by the STM.

The Infrared Astronomy Satellite

Because the Air Force probe rocket surveys rapidly scanned the sky, the dwell time on any one object, such as an asteroid, was only a few milliseconds. Ground-based telescopes were much larger than the instruments used on the Air Force rocket probe experiments and, operating as observatories, could integrate for longer times. Thus, many more asteroids were measured from the ground during the time that the Air Force survey experiments were being conducted (*e.g.*, Morrison, 1977).

The full potential of space-based infrared observations was realized in 1984 with the launch of the infrared astronomical satellite (IRAS). At $>50\times$ the sensitivity of the Air Force experiments, IRAS obtained high quality 12, 25, 60 and 100 μm observations of the asteroid population. IRAS redundantly surveyed 96% the inertial sky $2\frac{1}{2}\times$ during the 10 month mission. As for the asteroids, Tedesco (1994) estimates that the IRAS survey scanned across 94% of the Main Belt asteroids and 98% of the Trojans during that time.

The IRAS observations constitute the largest homogeneous radiometric database on the asteroids. The initial IRAS survey, *IRAS Asteroid and Comet Survey—Preprint Version 1* dated October 1986 (hereafter referred to as the "preprint"), reported associations with 1811 asteroids and derived information such as albedos and diameters on them. Of this total, information on 1790 of the asteroids was deemed of high quality by virtue of being observed more than once; 21 objects had associations with only a single IRAS measurement. The preprint also displayed 47 low-resolution spectrometer (LRS) spectra on 31 asteroids and provided details of 213 radiometric measurements on comets. Subsequently, Walker and Cohen (1999) surveyed

the LRS database and extracted several hundred spectra on ~ 100 asteroids.

The preprint was never formally published although the information was provided to the National Space Science Data Center. Tedesco *et al.* (1992, 2002a) describe how the IRAS asteroid database was rescued from oblivion and then used to create larger, more reliable catalogs. Tedesco *et al.* (1992) reprocessed the IRAS asteroid database against the known asteroid list as of December 1990 with more stringent position association criteria to create the IRAS minor planets survey (IMPS) catalog. At that time, there were 7311 asteroids with "good" orbital elements, more than double the 3458 available for the 1986 comparison. The input list consisted of numbered asteroids and those with preliminary orbits based on observations from two or more oppositions; Tedesco *et al.* (1992) did not include comets in his study. The more stringent positional matching criteria in the IMPS processing rejected 210 of the associations listed in the preprint, resulting in 1580 asteroids being in common to both catalogs. The IMPS catalog contains derived albedos and diameters for 2001 asteroids associated with IRAS observations; of this total 1796 asteroids were observed two or more times. Four near-Earth asteroids are among the IRAS observations: three Apollos, including the discovery of 3200 Phaeton and one Aten (3554 Amun).

Tedesco *et al.* (2002a) recently updated the IRAS asteroid associations and compiled the results into the supplemental infrared minor planet survey (SIMPS). The SIMPS processing found 2228 asteroids associated with two or more IRAS sightings among the 26 791 asteroids numbered by the Minor Planet Center as of July 2001. This is 432 more multiply observed asteroids than in the IMPS catalog, a 24% increase. The SIMPS results include updated albedos for $\sim 15\%$ of the asteroids in common. Tedesco *et al.* found that the SIMPS albedo distribution confirmed the IMPS results: namely $\sim 20\%$ of the small asteroids, defined as having diameters <44 km, have intermediate albedos ($0.09 < p_H < 0.14$). This ratio is $4\times$ greater than for the asteroids larger than 44 km.

Both the IMPS and SIMPS catalogs account for the statistical flux overestimation in all the IRAS bands at low signal-to-noise (Tedesco, 1994). This correction is empirically derived from the mean deviations of the measured IRAS fluxes from those predicted as a function of the signal-to-noise of the IRAS observation. The predicted fluxes were based on higher quality 10 and 20 μm measurements made with the IRTF. Although, the correction factor was found to be negligible above signal-to-noise ratios of 10, it is an important factor for the database. According to Tedesco (1994), a large fraction of the IMPS asteroid fluxes were measured at a signal-to-noise of <10 , 47% at 12 and 60 μm and 39% at 25 μm .

Tedesco *et al.* (2003) analyzed the size–frequency distribution of Main Belt asteroids using diameters and albedos from the SIMPS and other sources. Analogous with the earlier study of Cellino *et al.* (1993) that used data in the IRAS preprint, they divided the asteroid population into a number of separate

groups. The statistical asteroid model of Tedesco *et al.* (2003) is the sum of individual size distributions for each of 15 Hirayama families and for asteroids in nine zones of the Main Belt that are defined by semi-major axis from Mars crossers to Trojans. The observed size distribution for each component is extrapolated to 1 km diameter and the results summed over all groups. Tedesco *et al.* (2003) found that the total number of asteroids >1 km diameter thus derived is 2×10^6 and that the slope of the cumulative number–size distribution for the smaller asteroids varied as the inverse cube of the diameter. Analysis of observations from the Sloan digital sky survey commissioning data by Ivezić *et al.* (2001) indicate a shallower slope with $D^{-1.3}$ for asteroids smaller than ~5 km. If the Ivezić *et al.* results are correct, the total number of Main Belt asteroids larger than a kilometer would be several hundred thousand, significantly smaller than predicted by Tedesco *et al.* (2003).

The Midcourse Space Experiment

The midcourse space experiment (MSX) surveyed ~15% of the sky in four mid-infrared spectral bands centered at 8, 12, 15 and 21 μm during 10 months beginning in April 1996. The infrared instrument had ~4 \times greater sensitivity and 30 \times better spatial resolution of IRAS. Mill *et al.* (1994) give an overview of the MSX mission, the suite of instruments, and the experimental objectives. Price *et al.* (2001) described the astronomy experiments on this platform, as well as the data processing and some of the results on the inertial background.

MSX specifically targeted eight active comets and four dead comet nuclei, or transition objects. The two major MSX surveys, that of the galactic plane over the latitude range of $|b| < 5^\circ$ and the areas missed by IRAS, were well suited to detect asteroids and short-period comets multiple times, albeit only over a limited range of ecliptic longitudes. The MSX survey geometry limited the coverage to four narrow (~10° wide) strips separated by roughly 90° in ecliptic coordinates. However, a number of asteroids and comets were serendipitously observed on these survey scans.

Walker (pers. comm.) calculated the asteroids and comets in the field of view for each MSX observation using the orbital elements of the objects known at the end of 1999. These predictions were used to flag transient sources in order to remove them from the images of the inertial sky (Price *et al.*, 2001). Walker's predictions indicate that MSX surveys scanned over 10 relatively bright periodic comets (defined to be within ~3 AU of the Sun) 27 times and 18 faint comets (beyond ~3 AU from the Sun) 51 times. Tedesco *et al.* (2002b) used the same database of numbered asteroids as that for SIMPS to find 332 MSX observations on 169 different asteroids. Thirty-one of these asteroids were observed by MSX but not by IRAS, thus adding to the space-based mid-infrared database of observations and derived parameters. These observations comprise a significant database of space-based infrared measurements on

small bodies in the solar system as they were observed with a single well-characterized instrument (Cohen *et al.*, 2001a,b).

MSX demonstrated that, as noted by Tedesco *et al.* (2000), much more of the sky is accessible to a space-based infrared asteroid survey than a ground-based visible survey. The relatively high spatial resolution of MSX resolved much of the confusion in the galactic plane experienced by IRAS. Consequently, MSX was able to detect asteroids within a few degrees of the galactic center. In fact, about half of the MSX asteroid observations were made near ($|b| < 5^\circ$) the galactic plane and about half of these were within 30° longitude of the galactic center. The galactic plane is avoided by ground-based surveys owing to confusion from the high source densities therein. MSX also demonstrated that an appropriately designed space-based experiment can look close to the Sun in regions that is inaccessible from the ground. Indeed, six of the asteroids were observed within 35° of the Sun.

The Infrared Space Observatory

The infrared space observatory (ISO) was a European Space Agency mission that obtained 2.4 to 200 μm observatory style observations from November 1995 to May 1998. According to Müller (2001), ISO made various types of observations on ~40 different asteroids over the entire wavelength range of the two spectrometers and the photometer. Dotto *et al.* (2002) give an overview of the results from some of these observations and the detailed observing parameters for all of the targeted measurements.

ISO asteroid measurements can be loosely divided into three categories of observations. One class of experiment obtained infrared spectra to study the surface composition of the objects (Heras *et al.*, 2000; Dotto *et al.*, 2000). The ISO archive lists PHOT-S observations of 21 asteroids over the spectral range from 2.4 to 11.6 μm at a resolution ($R = \lambda/\Delta\lambda$) of 85 to 95. Dotto *et al.* (2000) compared the PHOT-S spectra of five bright Main Belt asteroids with those of meteorites and mineral obtained on laboratory samples. They concluded that the broad, low-resolution, mid-infrared spectral characteristics of the asteroids are indicative of silicate minerals being present on the surfaces of all five asteroids. The observed features are of moderate contrast with shapes that are somewhat dependent on the model for the underlying thermal emission. So, a more definitive identification of the mineralogy based on these observations is difficult. In contrast, the high-resolution ($R \approx 1100$) spectra taken by the short wavelength spectrometer (SWS) of 4 Vesta examined by Heras *et al.* (2000) resolved rotational lines of various silicates on the surface. Correlating line positions to identify surface mineralogy is more certain than model-dependent morphology of broad emission/absorption bands. Heras *et al.* (2000) suggested that the SWS spectra indicate the presence of olivine and pyroxene on 4 Vesta but that these minerals are segregated on its surface.

A second class of ISO experiments obtained infrared spectra and photometry to derive the global thermal properties of the regoliths through physical modeling of the bulk thermal emission characteristics of the asteroids. Müller *et al.* (1999) used the full spectral range ISO spectroscopy and photometry, plus prior information from ground-based measurements (Müller and Lagerros, 1998) to derive the thermal inertial, wavelength-dependent infrared emissivity, surface roughness and fraction of surface covered by craters for 1 Ceres. Müller and Lagerros (1998) used less complete ancillary observations to derive these physical parameters for four other asteroids: 2 Pallas, 3 Juno, 4 Vesta and 532 Herculina. Harris and Davies (1999) obtained ISO multicolor photometry for the near-Earth asteroids 1980 Tezcatlipoca and 3671 Dionysius. The albedos and radiometric diameters they derived for these objects were significantly different than previous published values.

A third type of ISO asteroid experiment surveyed the asteroid population. Tedesco and Désert (2002) obtained six deep $12\ \mu\text{m}$ exposures in the ecliptic plane with the ISO camera over a ~ 12 square minute of arc minute field. A number of objects with motions commensurate with Main Belt asteroids were detected but only two of the objects were bright enough to be associated with the numbered population. Tedesco *et al.* (2003) found that the observed areal density of 160 asteroidal objects/square degree was consistent with that predicted with their statistical asteroid model. Müller (2001) examined the ISO observing program for the likelihood of serendipitous observations of asteroids. He suggested that images taken by the ISO camera, both when it operated as the primary instrument and in the secondary parallel mode, are potential resources for asteroid radiometry. An initial analysis by Müller (2001) of images from the ISO camera parallel mode produced serendipitous $6.7\ \mu\text{m}$ measurements on 10 Main Belt asteroids and perhaps 10 more on yet to be numbered objects. Among the asteroids observed in the camera parallel mode were 3671 Dionysius, an Amor near-Earth asteroid, and three comets with a perihelion distance of ~ 1 AU. Initial results of the ISO observations in the frames when the camera was operated as the primary instrument and the $170\ \mu\text{m}$ serendipity photometry survey are inconclusive.

CURRENT STATE OF AFFAIRS

Mining the Existing Databases

Because there are no currently active infrared space-based experiments, we have to extract what we can from the existing infrared database established by the missions described above. Since none of these missions had the ability to discover and track an object with sufficient accuracy to establish a good preliminary orbit, further associations in the infrared database requires cross referencing with newly numbered asteroids.

The singularly significant resource for discovery and recovery of small bodies in the solar system is the on-going

near-Earth asteroid searches (Stokes *et al.*, 2000; Pravdo *et al.*, 1999; Perry *et al.*, 1998). A by product of these searches is the current rapid discovery of a large number of Main Belt asteroids. The most productive of these surveys, the Lincoln near-Earth asteroid research (LINEAR; Stokes *et al.*, 2000, 2002), has "discovered" over 100 000 Main Belt and Trojan asteroids since it began operations in 1998 (Stokes *et al.*, 2002). By "discovery", the LINEAR team means that the object in question has been given a preliminary designation by the Minor Planet Center. About half of the total (~ 52 000) were detected in 2000 alone; the 2001 discovery rate is comparable to that for 2000 according to J. Evans (pers. comm.), the LINEAR principle investigator. A significant fraction of these preliminary designations are newly undiscovered asteroids. Indeed, as of 2002 October 23, the Minor Planets Center credits LINEAR with discovering nearly 40% of the 48 380 asteroids numbered at the time.

Zappalà and Cellino (1996) and Jedicke and Metcalfe (1998) estimated that, by the mid-1990s, the inventory of Main Belt asteroids was complete down to an apparent opposition magnitude of ~ 15.5 . LINEAR has a limiting magnitude of ~ 2.5 magnitudes fainter than this. Since the LINEAR survey covers as much of the sky as weather permits during each lunation (Stokes *et al.*, 2002), and the program is averaging 50 000 plus preliminary designations each year, it is estimated that the LINEAR discoveries of new asteroids in the Main Belt and beyond should reach saturation at ~ 150 000 by the end of the survey in 2008. Other near-Earth object searches, such as the near-Earth asteroid tracking (NEAT) program (Pravdo *et al.*, 1999; Talent *et al.*, 2000), use telescopes similar in size to LINEAR. Consequently, these programs have a similar limiting magnitude and contribute to the pace of discovery at this limit. Spacewatch (Perry *et al.*, 1998) and Lowell near-Earth object survey (LONEOS) are about a magnitude more sensitive (see Harris, 1998) but cover a correspondingly smaller area. These surveys, and their anticipated upgrades, should add about a quarter of a million asteroids to the numbered inventory.

Muinoon, Bowell and Lumme (1995) have shown that it is possible to derive reasonable cumulative number-size distributions from such observations. However, the sizes of individual asteroids derived from the visual magnitudes have errors proportional to the uncertainties in the estimated albedos, which are large for most objects. Furthermore, the typical measurement uncertainties in the magnitudes provided by the near-Earth object surveys are ~ 0.5 magnitudes. On the other hand, the visual survey results are a resource for deriving radiometric diameters. Once numbered, the visual survey discoveries can be associated with the IRAS, MSX and ISO databases. Not surprisingly, most of the SIMPS associations are with small bodies and dark objects, precisely the type of objects being discovered by the current optical surveys. For example there are 390 SIMPS objects with derived $D < \sim 40$ km and 220 with $D < 20$ km. As for the very dark asteroids, SIMPS lists infrared radiometry on 30 Trojans, a 77% increase over

the number in the IMPS catalog. Eventually, the IRAS database will be completely mined of asteroids, that is all asteroids that IRAS could have detected will have been discovered. However, there are still observations of yet to be numbered asteroids lurking in the IRAS database. Based on the association rate of the asteroids numbered in the first 6 months of 2001, Tedesco *et al.* (2002a) estimated that of the next ~25 000 asteroids to be numbered, 150 should be bright enough in the infrared to be associated with objects that the IRAS potential asteroid observation list. Given the current rate at which asteroids are being numbered, asteroid 55 000 should be designated by the end of 2002. Tedesco *et al.* commented that 150 new associations with IRAS infrared measurements over the next year "...is between one and two orders of magnitude greater than the rate at which asteroid radiometric observations are being currently made". Thus, over the next few years the IRAS and, to a lesser extent, MSX and ISO databases are projected to remain a valuable resource for infrared radiometry on asteroids.

Thermal Modeling and Asteroids

Harris and Lagerros (2002) give an excellent review of thermal modeling of asteroids. Only a few explicit statements need to be made. The passive thermal emission from Main Belt asteroids peaks in the mid-infrared as a natural consequence of their being in thermal equilibrium with the incident sunlight. Most asteroids are dark, reflecting <20% of the incident sunlight. Consequently, they absorb most of the incident sunlight and efficiently re-radiate this energy in the mid-infrared with an average emissivity of 0.9. Necessarily, the predicted flux from an asteroid is model dependent, being a function of the temperature profile across the projected surface area at the time of observation. The projected area depends on the size, shape, pole of rotation and the Earth–Sun–asteroid geometry. The temperature profile depends on the distance from the Sun, emissivity, total fraction of sunlight absorbed, the thermal inertia, rotation rate, orientation of the rotation pole, surface roughness and degree of cratering. A complex model, such as the one developed by Lagerros (1996, 1997, 1998), is required to account for all the variables. An extensive set of measurements that can sufficiently separate the effects of the various parameters is needed in order to apply the model. In lieu of sufficient observations, simpler models are used.

The STM of Lebofsky *et al.* (1986) works well for Main Belt asteroids (see Table 1 of Harris and Lagerros, 2002). This simplified model assumes that the asteroid does not rotate and is in instantaneous thermal equilibrium between absorbed sunlight and emitted radiation. Empirical factors for flux enhancement (beaming) and phase function are adopted and a value of 0.9 is assumed for the infrared emissivity. An iterative solution for the geometric albedo and diameter of an asteroid is required as these quantities are coupled in the thermal model through expressions that relate these parameters to the observed

visible magnitude and infrared flux. Tedesco used the STM to derive the diameters in the IMPS and SIMPS catalogs to develop the largest, consistent database of derived asteroid diameters and albedos. However, the STM does not produce acceptable results for certain definable types objects, most notably the near-Earth asteroids, and modifications, such as the one by Harris (DLR) (1998), have been developed in which one or more of default parameters are constrained with additional information.

The additional constraint for the Harris STM variant for near-Earth asteroids is a fit of the infrared spectral energy distribution to flux measurements at two or more wavelengths. This permits the beaming factor that modifies the temperature profile to be included in the solution. Harris devised this variant of the STM to address the discrepancies noted by Veeder *et al.* (1989) between the geometric albedos derived using the STM on several near-Earth asteroids and those typical of the taxonomic class to which they were assigned. (There were too few direct measurements of near-Earth asteroid sizes at the time to compare with radiometric diameters.) If only a single infrared flux is available, Harris (1998) suggested using a default beaming factor of 1.2, the average for the near-Earth asteroids he measured, in deriving the geometric albedo and diameter of a near-Earth asteroid. This default value leads to somewhat larger radiometric diameters and smaller albedos than derived from the STM, which assumes a beaming factor of 0.756.

The default parameter values for the Lagerros model are the representative values ascribed by Müller and Lagerros (1998) based on analysis of five well-measured asteroids. Müller *et al.* (1999) claim that the model with the proposed default parameters can very accurately account for the thermal emission from all Main Belt asteroids for which the shape, absolute magnitude and slope parameter (used to derive the fraction of total sunlight absorbed) are known. It needs to be shown that this model produces effective projected surface areas and albedos that are consistently superior to the simpler models. This is because, as Spencer (1990) noted, the effects of shape, rotation pole and rate, thermal inertia and surface roughness can be expressed in a single parameter, the beaming parameter.

Since simultaneous visual and infrared observations are rare, the absolute visible magnitude of the asteroid is used (Tedesco *et al.*, 1992). This quantity is well determined for the largest asteroids but is derived from the discovery and astrometric follow-up measurements for the remainder of the population, which have typical uncertainties of 0.5 magnitudes. This uncertainty is compounded by the unknown light curves for most of the fainter objects. Almost all the slope parameters, which couple the geometric visible albedo to the total amount of reflected sunlight (Bond albedo), are default values. Any information that can improve the accuracy of the absolute magnitudes or constrain the geometric albedo is valuable. There are several multicolor surveys that observed asteroids with a sufficient wavelength baseline and photometric accuracy to assign crude taxonomic classes to the asteroids they observe as a by product of their primary experiment. Sykes *et al.* (2000)

examined J, H and K_s colors of the thousand plus asteroids observed in the 6% of the sky contained in the preliminary release of the two-micron all-sky survey. Sykes *et al.* estimate that ~20 000 more asteroid observations are in the final database. Sykes *et al.* sorted the asteroids into distinct, overlapping groupings in the color-color plane. These groupings correspond to established asteroid taxonomic classes than have characteristic albedos. Baudrand *et al.* (2001) associated nearly 1400 observations of asteroids with sources extracted from about half the database generated by the deep near-infrared survey of the southern sky. The resulting I, J and/or K_s photometry on these asteroids has relatively large errors and, as such, is useful as an adjunct to the two-micron all-sky survey data. The Sloan digital sky survey is performing a deep ($m \approx 22$) survey at high galactic latitudes in five spectral bands from the ultraviolet to the far-red. Ivezić *et al.* (2001) examined the asteroid detections in the commissioning data from this survey and were able to clearly separate asteroid types into what they designate as S (rocky) and C (carbonaceous) in four color space. Thus, these surveys can improve upon the absolute visual magnitude for the fainter asteroids, provide reasonably accurate empirical values of the slope parameter and constrain the visible albedo in the thermal modeling.

Asteroids as Calibration Sources

The largest and brightest Main Belt asteroids are a readily accessible resource for mid- and far-infrared calibration. Since their emission peaks in the mid-infrared, their spectral energy distributions fall off much less steeply than those of stellar calibration standards. As a consequence, the fluxes from large asteroids generally exceed that of the stellar standards for wavelengths of $20 \mu\text{m}$ and longer. However, unlike calibration stars, the asteroid fluxes vary with time. As described above this variation is a complex function of a rather large number of variables and a model is required that can accurately predict the flux at a given time.

Cohen and his colleagues attempted to calibrate the mid-infrared flux from 1 Ceres, in part to support the calibration of the mid-infrared spectrometer on the infrared telescope in space satellite (Tanabé *et al.*, 1997). Cohen *et al.* (1998) obtained 5–14 μm spectra of asteroids 1 Ceres, 2 Pallas and 4 Vesta on a number of Kuiper airborne observatory flights over a 3 year period between 1992 and 1995; 4 Vesta had high-quality ground-based observations. The spectra were put on an absolute scale by direct ratios with the absolutely calibrated composite spectra of α Tau and α Boo. The procedure is the same as that used by Cohen *et al.* (1992) to establish the network of secondary calibration standard stars from composite measured spectra. Subsequently, Witteborn *et al.* (1999) obtained a direct calibration by scaling 4.5 to $30 \mu\text{m}$ spectral measurements of α Boo and 1 Ceres to a laboratory standard blackbody. Both the star and the asteroid were compared to the laboratory standard on the same two flights of the Kuiper airborne observatory.

Müller and Lagerros (1998) modeled the absolute spectral energy distribution of several (at least five) of the brightest asteroids to an accuracy of 10%. The number of asteroids that can be modeled to the same accuracy could be increased with a campaign of visible and infrared observations of the large asteroids over large phase angle variations and several light curve periods. Müller and Lagerros (2001) describe the role asteroids played in calibrating the ISO instruments and as a calibration resource for all infrared space observatories (Müller and Lagerros, 2002).

PROSPECTS FOR THE FUTURE

Cellino *et al.* (2000) and Price and Egan (2001) describe the advantages of an infrared space-based instrument to discover near-Earth objects and to derive physical properties by spectral and radiometric remote sensing. Of historical note, as early as 1980, Dennis (1980) considered the performance and mission parameters required of an infrared system designed specifically to search for 100 m and larger Earth-approaching asteroids. However, no system in development that will be dedicated to infrared solar system observations, specifically to characterize the physical properties of asteroids, so prospects for the near future must rely on obtaining observing time or serendipitous measurements on missions to be flown over the next several years.

The Space Infrared Telescope Facility

The SIRTf, NASA's next great space observatory, is scheduled to fly at the end of 2002. Fanson *et al.* (1998) described the spectral and photometric capabilities of the instruments. Collectively, the infrared camera, spectrometer and photometers span the wavelength range from 3.6 to $170 \mu\text{m}$. SIRTf is an observatory facility designed for deep, high-sensitivity measurements. Consequently, the SIRTf instruments saturate at modest flux levels. However, the infrared spectrometer and photometers could provide invaluable spectral and radiometric information on Main Belt asteroids and the Trojan, Centaur and Kuiper belt asteroids, if observing time is given to such observations.

Like ISO, the SIRTf camera has a parallel observing mode in which a $5' \times 5'$ field is imaged near the primary experiment target in two wavelength bands centered at 4.5 and $8 \mu\text{m}$. The pointed and parallel camera images could provide a database for serendipitous observations of asteroids analogous to the ISO database discussed by Müller (2001). However, since both the ISO and SIRTf cameras cover a small total field of view, the probability of serendipitously observing a large number of asteroids is small.

ASTRO-F The Infrared Imaging Surveying

This Japanese sky survey mission, currently scheduled for a 2004 launch, has the greatest potential for obtaining a

significant number of infrared observations of asteroids. Murakami (1998) and Yamamura *et al.* (2001) described the mission, instrumentation and experimental goals. The principal experiment on this mission is to conduct an all-sky survey at wavelengths between 50 and 200 μm . This will be done during the first 6 months after the instrument is commissioned. This survey is anticipated to be about a factor of 10 more sensitive than IRAS and the serendipitous survey of ISO at the corresponding wavelengths. As good as this is, the sensitivity of the far-infrared survey is such that few Main Belt asteroids will be observed during the sky survey that are not in the IRAS database. Although the ASTRO-F far-infrared survey will measure many more asteroids at these wavelengths than IRAS, IRAS will have measured almost all these in the mid-infrared where their fluxes peak.

The infrared camera has considerable potential for asteroid radiometry. The camera has filters that cover the spectral range from 1.8 to 26 μm over a $10' \times 10'$ instantaneous field. This is a secondary instrument during the initial survey but dominates the observing time afterward. The camera spans a larger field than either that on ISO or SIRTf, which increase the probability of serendipitously detecting Main Belt asteroids. The multi-spectral capabilities and sensitivity of the camera meet, or exceed, the performance parameters described by Cellino *et al.* (2000) and Price and Egan (2001) required to characterize the physical properties of Main Belt asteroids as small as a kilometer in diameter.

CONCLUSIONS

Infrared radiometry is a valuable means to derive accurate physical parameters of asteroids, such as diameters and albedos. The mineralogy of the surface can be deduced from infrared spectroscopy and fundamental properties of the surface layers derived from multi-color infrared photometry. Infrared observations over a large range of phase angles from which a light curve can be derived, or when the light curve is known, lead to information on the thermal inertial of the regolith. All these remote sensing techniques are a prerequisite to interpreting the detailed information returned by direct measurements and encounter missions in terms of how the direct measurement can be applied to the population as a whole of small bodies in the solar system.

The tremendous advantages in sensitivity and the ability to use large format arrays by an infrared space-based observatory that were exploited by the IRAS and ISO satellites for measuring inertial sources apply equally to observing small solar system bodies. The rate at which asteroids are being discovered far outstrips that at which even basic parameters, such as size, is being determined (Tedesco *et al.*, 2000). An infrared space observatory that emphasizes solar system studies is essential. The large asteroids are well characterized by optical and infrared observations. However, the smaller asteroids are distinctly different from the larger asteroids. Veeder *et al.* (1989)

suggested that the small near-Earth asteroids have a rocky surface rather than a regolith as an explanation of the failure of the STM for these objects. Tedesco *et al.* (1992, 2001) noted that the albedo–diameter distribution for small asteroids is markedly different than large ones. Large asteroids have almost a bimodal distribution while intermediate albedos are much more common among smaller asteroids. Until such a dedicated system is flown, a strong advocacy needs to be mounted for asteroid and comet measurements with SIRTf and ASTRO-F.

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