Comets, Asteroids and Zodiacal Light as seen by ISO *

Thomas G. Müller
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany; (`tmueller@mpe.mpg.de`)

Péter Ábrahám
Konkoly Observatory, H-1525 P.O. Box 67, Budapest, Hungary; (`abraham@konkoly.hu`)

Jacques Crovisier
LESIA, Observatoire de Paris, 5 place Jules Janssen, F-92195 Meudon, France; (`jacques.crovisier@obspm.fr`)

Abstract. ISO performed a large variety of observing programmes on comets, asteroids and zodiacal light –covering about 1% of the archived observations– with a surprisingly rewarding scientific return. Outstanding results were related to the exceptionally bright comet Hale-Bopp and to ISO's capability to study in detail the water spectrum in a direct way. But many other results were broadly recognised: Investigation of cometary molecules, the studies of crystalline silicates, the work on asteroid surface mineralogy, results from thermophysical studies of asteroids, a new determination of the asteroid number density in the main-belt and last but not least, the investigations on the spatial and spectral features of the zodiacal light.

Keywords: ISO – asteroids – comets – SSO: solar system objects – zodiacal light – dust

Received: 13 July 2004

1. Introduction

The comet, asteroid and zodiacal light programme of ISO –without the planets– covered approximately 325 hours, less than 1 % of all ISO observations. Thus, the solar system community did not expect much from this small number of observations with a 60-cm telescope circulating just outside the Earth' atmosphere. Yet, the ISO results made a big impact on our knowledge of objects on our celestial "doorstep".

11 Guaranteed Time projects and 31 Open Time projects were either dedicated to comets, asteroids and zodiacal light studies or included solar system science aspects. Surveys with observations close to the ecliptic plane, performed by ISOCAM and ISOPHOT, include many asteroids and several comets. In addition, the parallel and serendipity data –taken in non-prime instrument modes or while the satellite was

---

[*] Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

Space Science Review ISO Special Issue.

slewing from one target to the next– contain by chance many interesting solar system sources (Müller, 2001). Even standard background observations can be considered as absolute measurements of the zodiacal light and have been added to the database of dedicated studies of the dust in the solar neighbourhood.

First inventories of the ISO solar system contributions have been made by Encrenaz (2000), Fouchet (2003) and Müller (2003a). The latter two authors went through all solar system ISO projects and presented the proposed original ideas and compared them with the published scientific results (as of June 2002). They also identified promising future fields on solar system science with ISO. There, one can also find details on the proposals, target lists and instructions on how to search for specific moving objects in the ISO Data Archive.

The results on the "life-element" water in the universe - not least its unexpected discovery in large amounts in the higher atmospheres of all giant planets - together with other highlights on planet science are covered by the contributions by Cernicharo & Crovisier (2004) and Fouchet et al. (2004) in this volume. Different states of silicate dust under different conditions are the basis for the new research field on *astro-mineralogy*. Crystalline silicates are found around young and old stars, in proto-planetary disks and are also very common in our own solar system (e.g., in comet Hale-Bopp). The chapter on crystalline silicates (Molster & Kemper, 2004, this volume) touches therefore solar system science, but from a different point of view. Here, the remaining part of the solar system field is followed up and ISO's results on asteroids, comets and extended solar system structures are presented.

2. Comets

A total of 20 comets were observed with ISO (some of them with its four instruments): 2P/Encke, 7P/Pons-Winnecke, 22P/Kopff, 29P/Schwassmann-Wachmann 1, 30P/Reinmuth 1, 32P/Comas Solá, 43P/Wolf-Harrington, 45P/Honda-Mrkos-Pajdušáková, 46P/Wirtanen, 55P/Tempel-Tuttle, 65P/Gunn, 81P/Wild 2, 95P/Chiron, 103P/Hartley 2, 117P/Helin-Roman-Alu 1, 126P/IRAS, 128P/Shoemaker-Holt 1B, 133P/Elst-Pizarro, and the long-period comets C/1995 O1 (Hale-Bopp) and C/1996 B2 (Hyakutake).

A large part of the cometary programme was devoted to the exceptionally bright comet C/1995 O1 (Hale-Bopp), as a target of opportunity, resulting in a very rewarding scientific return. Unfortunately, ISO could not observe this comet at heliocentric distances smaller than 2.8 AU due to solar elongation constraints. Several observations of the fainter comets led to limited scientific results, which are still unpublished.

2.1. Spectroscopy of gas species

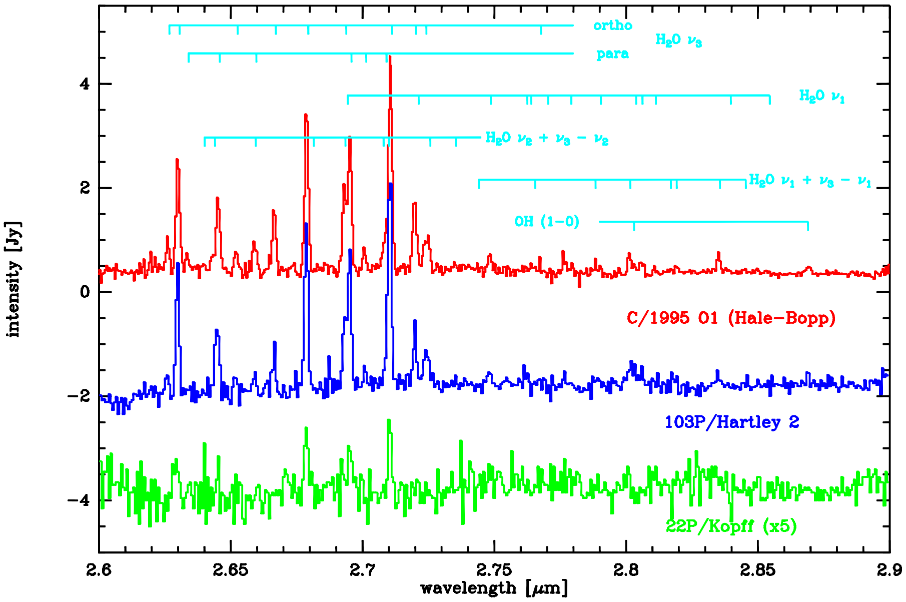

Figure 1. The SWS spectrum of water in the 3 μm region observed in comets C/1995 O1 (Hale-Bopp) at 2.8 AU from the Sun, 103P/Hartley 2 at 1.0 AU, and 22P/Kopff at 1.9 AU (scale expanded by ×5). Adapted from Crovisier et al. (1997b, 1999a).

The fundamental bands of vibration of volatile species released from the ices of comet nuclei are emitting in the mid-IR through fluorescence excited by the Sun.

High-resolution spectroscopy of comet Hale-Bopp (in September–October 1996, when it was at $r = 2.8$ AU from the Sun) with the SWS and LWS resulted in a detailed study of the water spectrum. The 6 μm band and several rotational lines (100–180 μm) of H_2O were observed for the first time in a comet. The bands around 2.7 μm could be studied in detail, resulting in estimates of the rotational and spin temperatures of water (Crovisier et al., 1997a, 1997b, 1999b; Fig. 1; see also Cernicharo & Crovisier, 2004).

Carbon monoxide and dioxide were also easily detected. These very volatile species are the only ones which are observed far from the Sun ($r = 4.6$ AU). CO_2 was very conspicuous from its strong ν_3 band at 4.26 μm in the ISOPHOT-S spectra. This detection of CO_2

by ISO (which was repeated in 103P/Hartley 2) is, besides the *in situ* observation in comet Halley, the only direct observation of this molecule in a comet. The Q-branch of the ν_3 band of CH_4 was also detected by the SWS at 3.31 μm (Crovisier, 2000a; Crovisier et al. *in preparation*). Evolution of the outgassing of H_2O, CO and CO_2 in comet Hale-Bopp could be investigated between 4.9 and 2.8 AU, pre- and post-perihelion, showing the transition from the CO-dominated to the H_2O-dominated sublimation regimes. (Crovisier et al., 1996, 1997b, 1999b; Crovisier, 2000b; Leech et al., 1999). H_2O, CO and CO_2 appear to be the most abundant volatile molecules, with relative production rates H_2O:CO:CO_2 equal to 100:70:20 at $r = 2.9$ AU in comet Hale-Bopp.

The spectrum of the Jupiter-family comet 103P/Hartley 2 was investigated by ISOPHOT, SWS and ISOCAM, allowing detection of H_2O, CO_2 (but not CO) and crystalline silicates (Colangeli et al., 1999; Crovisier et al., 1999a, 2000; Fig. 1). Long integration times were also spent on 22P/Kopff, but this comet was much fainter and only the water lines could be detected by the SWS (Crovisier et al., 1999a; Fig. 1).

The rotational temperatures retrieved for water in comets Hale-Bopp and Hartley 2 are 28 and 20 K, respectively. These cold temperatures agree with models of coma hydrodynamics and water excitation, which predict a rotational relaxation of water. The intensities of the ortho and para transitions in the ν_3 band of water also permit an evaluation of the ortho-to-para ratio and of the water spin temperature. $T_{\rm spin} = 28$ and 35 K were determined for the two comets, respectively. The meaning of the water $T_{\rm spin}$ is still to be understood (Crovisier et al., 1997b, 1999a, 1999b; Crovisier, 2000a; Cernicharo & Crovisier, 2004).

2.2. SPECTROSCOPY OF MINERALS

The 6–45 μm SWS spectrum of comet Hale-Bopp revealed emission features attributed to minerals in cometary dust (Fig. 2). A first look lead to the identification of crystalline, Mg-rich olivine (forsterite) (Crovisier et al., 1997b). A more thorough investigation showed that crystalline pyroxenes and amorphous silicates are also present (Crovisier et al., 2000). No PAH signature could be found. This ISO spectrum of comet Hale-Bopp was the subject of many studies, in comparison with complementary spectra observed from the ground at other heliocentric distances and with laboratory spectra of various minerals (e.g., Wooden et al., 1999; Brucato et al., 1999; Harker et al., 2002).

By probing the mid-IR spectroscopy of cosmic dust, ISO opened the new field of *astro-mineralogy*, allowing us to study the cycle of dust in

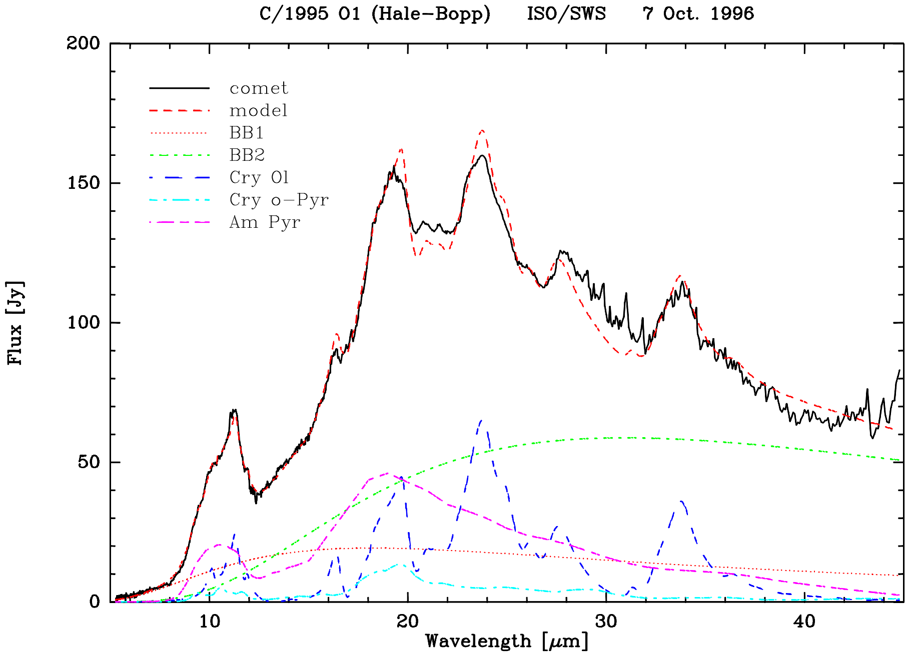

Figure 2. The 6–45 μm SWS spectrum of comet C/1995 O1 (Hale-Bopp) observed at 2.8 AU from the Sun, decomposed into several emission components: 22% of forsterite (Cry Ol), 8% of ortho-pyroxene (Cry o-Pyr), 70% amorphous silicates (Am Pyr), and two blackbody components (280 and 165 K). From Crovisier et al. (2000).

the Universe and in planetary systems. The resemblance between the spectra of cometary dust and of debris disks of young stars or of some Herbig Ae/Be stars observed by ISO was noted in many publications (e.g., Malfait et al., 1998; Molster et al., 1999; Waelkens et al., 1999; Crovisier, 2000b; Bouwman et al., 2003; Molster & Kemper, 2004). However, the origin of crystalline silicates in comets is still an open issue. Silicates observed in interstellar clouds are amorphous. Annealing could occur in the hot inner Solar Nebula, in regions where cometary ices could not be present. Turbulent diffusion within the primitive Solar Nebula might be an explanation (Bockelée-Morvan et al., 2002).

Crystalline water ice was shown to be present in the dust of comet Hale-Bopp at 2.9 AU from the Sun, from its signatures at 44 and 65 μm and possibly at 3.1 μm, observed by the LWS and ISOPHOT-S (Lellouch et al., 1998).

2.3. Photometry and imaging

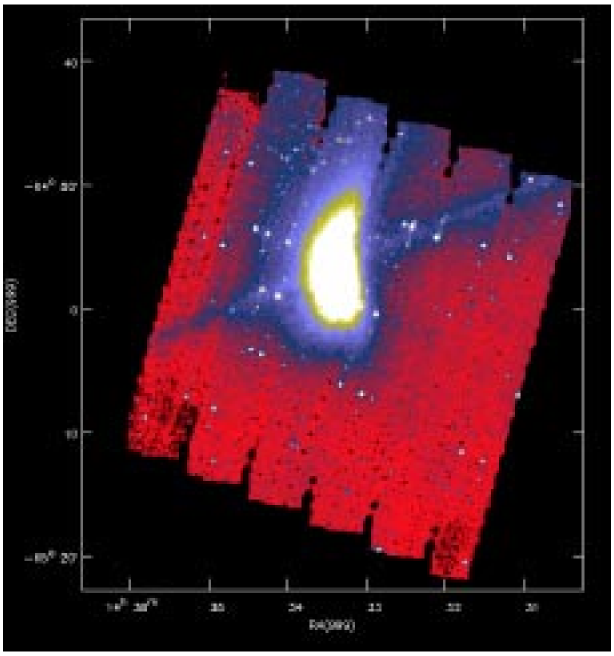

Figure 3. A mosaic image of comet 2P/Encke from ISOCAM. The comet tail shows up as a broad feature in the centre. The comet trail is the thin feature stretching diagonally from the lower left to the upper right. From Reach et al. (2000).

The spectral energy distribution of several comets was observed by broad band photometry from 3.6 to 170 μm with ISOPHOT (Grün et al., 2001; Lisse et al., 2004). For comet Hale-Bopp, which was the subject of five observations between $r = 4.6$ and 2.8 AU, an extensive analysis was possible (Grün et al., 2001). The colour temperature, dust production, dust-to-gas ratio and their evolution with heliocentric distance could be studied. The 7.3–12.8 μm colour temperature is ≈ 1.5 times the expected blackbody temperature, pointing to the presence of small, superheated dust grains. Silicate features are always present and influence the emissions in the 10 and 25 μm region. Water ice grains are suggested at $r = 4.6$ AU from enhanced emission at 60 μm.

Cometary dust and its distribution was studied by ISOCAM imaging of comets 2P/Encke, 46P/Wirtanen, 65P/Gunn and 103P/Hartley 2 (Colangeli et al., 1998; Epifani et al., 2001), allowing the authors to model the comet tail, the evolution of dust coma, grain sizes and velocities and to infer implications for meteoroid streams .

Observations of comets in the thermal infrared with ISOCAM also allow one to separate the emission of the nucleus from that of dust. This was applied to C/1995 O1 (Hale-Bopp), 2P/Encke, 22P/Kopff, 46P/Wirtanen, 55P/Tempel-Tuttle, 95P/Chiron, 103P/Hartley 2 and 126P/IRAS (Fernández et al., 2000; Groussin et al., 2004a, 2004b; Jorda et al., 2000; Lamy et al., 2002). When it is possible to combine such data with HST observations in the visible, the albedo and size of the nucleus can be securely determined (this was possible for 2P/Encke, 22P/Kopff, 55P/Tempel-Tuttle and C/1995 O1 (Hale-Bopp)). Thus ISO significantly contributed to the database of cometary nuclei physical properties (Lamy et al., 2004).

Cometary trails were first discovered by IRAS. Their analysis in terms of mass loss rates and of dynamical evolution is crucial for our understanding of the origins of insterstellar dust particles and of meteoroids. ISO investigated the trails of 22P/Kopff (Davies et al., 1997) and 2P/Encke (Reach et al., 2000; Fig. 3). The trail of comet Hale-Bopp was even observed in the course of the ISOPHOT Serendipity Survey at 170 μm (Müller et al., 2002).

3. Asteroids

The ISO programmes included 40 different asteroids, among them 9 targets which are considered as transition objects between comets and asteroids. The whole asteroid programme was performed in less than 100 hours, using all four instruments of ISO. Details on the proposals, the targets and the observing strategies and goals can be found in Müller (2003a). The main goals of the asteroid observations were the identification of surface minerals, composition, the connection to meteorites and comets, surface alteration processes and the interpretation of taxonomic classes through the identification of mid-infrared features of well-known minerals and meteorites. The predominant observing technique in the asteroid programme was therefore spectroscopy.

3.1. SURFACE MINERALOGY

First results on ISOPHOT-S observations of bright main-belt asteroids (Dotto et al., 1999; Dotto et al., 2000; Müller et al., 2000) suggested the presence of silicates on the surface of all asteroids. Barucci et al. (2002) extensively studied 10 Hygiea and demonstrated the possible spectral similarity with CO carbonaceous chondrites at small grain sizes (Fig. 4).

Dotto et al. (2002) described the similarities between low-albedo asteroids and different meteorites which have been analysed in new

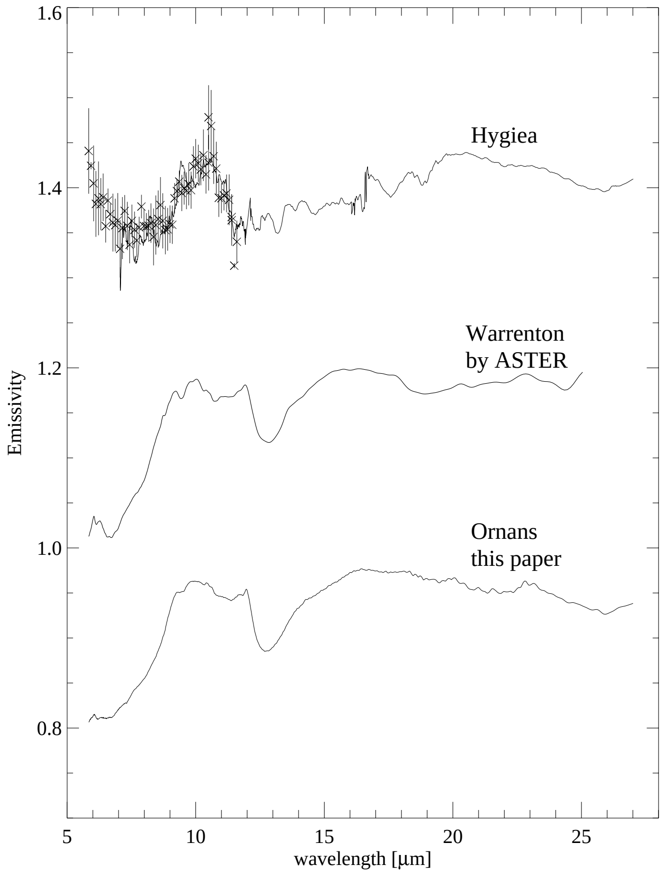

Figure 4. Comparison between the ISO spectrum of 10 Hygiea and different meteorite samples. Adapted from Barucci et al. (2002).

laboratory experiments. The ISOPHOT-S spectra seem to confirm the theories about the thermal history of C-type asteroids by the match between the spectrum of 511 Davida and the emissivity of the CM-type carbonaceous chondrite meteorite Murchison. Müller & Blommaert (2004) analysed the emissivity of 65 Cybele, which is a dark, very low albedo asteroid. Cybele shows an emissivity increase between 8.0 and 9.5 μm, which is close in wavelength to the Christiansen feature of CO and CO3 types of the carbonaceous chondrites. Very recent studies of the dark asteroid 308 Polyxo, which showed in earlier investigations similarities with the Tagish lake meteorite (Hiroi & Hasegawa, 2003), were carried out by Dotto et al. (2004). They suggest a tentative spectral similarity with the Ornans meteorite and cannot confirm the analogy with the Tagish Lake meteorite in the measured wavelength range between 7 and 26 μm.

All mid-infrared spectroscopic studies clearly reveal the difficulties of identifying mineralogic features based on disk-integrated, mid-IR spectroscopy. A wide wavelength range with uniform data quality covering different rotation phases, a clean calibration and a careful modelling of the underlying thermal emission are necessary to recognise signatures of the surface material. In addition, laboratory spectra of different meteorites at various grain sizes are needed to identify the low level, broad band features. But even if all prerequisites are fulfilled, the spectroscopic interpretation still remains difficult.

3.2. THERMOPHYSICAL STUDIES

A new Thermo-Physical Model (TPM) for asteroids was developed during the ISO mission (Lagerros, 1996, 1997, 1998). This new TPM allows the detailed characterisation of the thermal behaviour of the surface and the derivation of physical parameters, like surface roughness or porosity from accurate thermal observations (e.g., Müller et al., 1999a; Müller, 2002). Through large samples of photometric measurements at different wavelengths and observing geometries it was also possible to determine the thermal inertia and thermal conductivity for a few large main-belt asteroids (Müller & Lagerros, 1998; Müller et al., 1999a): The thermal behaviour of many large asteroids can be explained by a regolith covered surface with a very low thermal inertia of about $\Gamma = 15\,\mathrm{J\,m^{-2}\,s^{-0.5}\,K^{-1}}$. Müller & Lagerros (2002) demonstrated that the TPM matches all kind of thermal IR measurements from different observing geometries with a high accuracy. This quality proof for a sample of well-known asteroids was the prerequisite for applying the model to arbitrary thermal measurements. Depending on the a priori knowledge on a specific asteroids, the TPM allows to derive a variety of properties: From a simple diameter and albedo determination up to a full characterisation of the surface regolith (Müller, 2003b). E.g., Müller et al. (2002) used 170 μm flux densities to derive simple size-albedo solutions for serendipitously seen asteroids which, apart from orbital elements and visual brightness, had no existing physical characterisation before. For 65 Cybele, on the other hand, a large database with visual and thermal observations was the basis for a sophisticated thermophysical analysis of the surface regolith (Müller & Blommaert, 2004). The authors derived a size of $302\times290\times232$ km ($\pm$ 4 %) and a geometric visible albedo of 0.050 ± 0.005 through a careful TPM analysis of the existing thermal observations. They also described the thermal behaviour in detail with respect to phase angle dependence, before/after opposition effects and wavelength dependencies. Figure 5 shows a comparison between the radiometric diameter-albedo determination using the TPM and the widely used Standard Thermal Model (STM; Lebofsky et al., 1986). The STM clearly shows unphysical, wavelength-dependent diameter and albedo values.

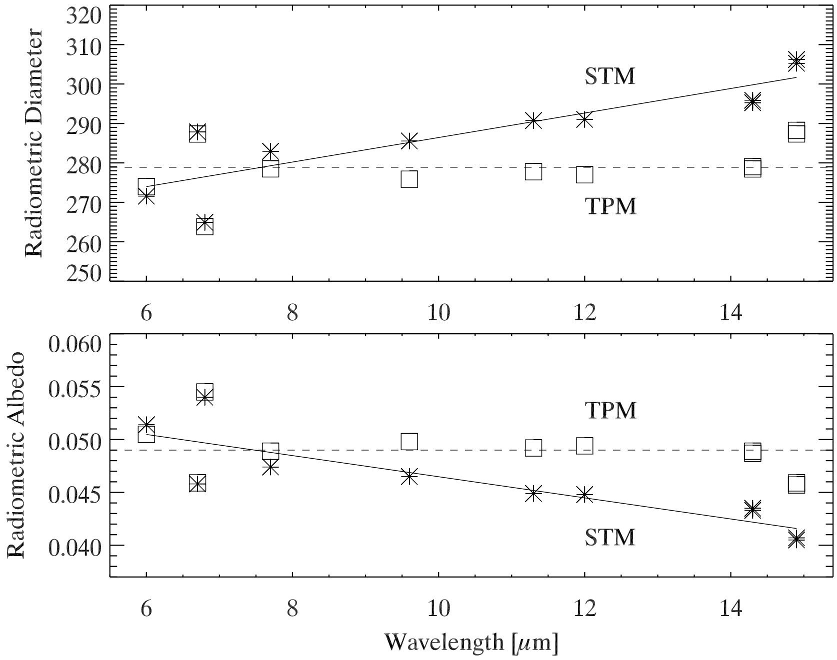

Figure 5. The radiometric diameter and albedo values for 65 Cybele calculated through the STM and the TPM. The observations are well-calibrated ISOCAM filter measurements. The STM results show clear trends with wavelength while the TPM produced a unique diameter/albedo solution. Adapted from Müller & Blommaert (2004).

The TPM efforts resulted in a convincing concept to use a few, well-known, large main-belt asteroids as new far-infrared photometric calibrators for ISO (Müller & Lagerros, 1998; 2002; 2003). The TPM predictions for 5-10 asteroids, which have large sets of independently calibrated infrared, submillimetre and millimetre observations, are now widely used to calibrate and characterise far-infrared and submillimetre instruments. Work is ongoing to extend this list to fainter targets in preparation for the Astro-F and Herschel missions.

3.3. MISCELLANEOUS PROGRAMMES

3.3.1. *Asteroid number density*

The superb mid-infrared sensitivity of ISO was used to determine the number of main-belt asteroids for the first time in a direct way (Tedesco & Desert, 2002). 22 moving sources appeared in a 15′ square field of repeated, deep ISOCAM observations at 12 μm in the ecliptic plane. Most of the asteroids detected have flux densities of less than 1 mJy, about 150 to 350 times fainter than any of the asteroids observed by IRAS. The study revealed 160±20 asteroids per square degree at a 0.6 mJy detection limit. Based on a statistical asteroid model, the authors concluded that there are about $1.2\pm0.5\times10^6$ asteroids ($\geq$ 1 km in diameter) in our solar system, twice as many as previously believed.

3.3.2. *Surface properties through thermal polarimetry*

In a small programme Lagerros et al. (1999) and Müller et al. (1999b) investigated the surface properties of the asteroids 6 Hebe and 9 Metis through thermal polarimetry at 25 μm. Solid upper limits were interpreted through an extended version of the TPM to cover also polarimetric aspects. The Metis observations favored a low refractive index and high surface roughness, but the Hebe observations were inconclusive since they coincided with a minimum in the polarization curve.

3.3.3. *NEOs and TNOs*

Two asteroid programmes performed observations on asteroids outside the main-belt-Jupiter region. Harris & Davies (1999) combined ISOPHOT observations with mid-infrared ground-based observations to investigate radiometric diameter and albedo values for three near-Earth asteroids. The original idea to search for cometary activity in near-Earth asteroids with ISOCAM turned out to be too ambitious. The best achieved sensitivity corresponds to a mass-loss rate of above 0.1 kg/s, which is the expected upper limit for near-Earth cometary asteroids. The second programme with almost 28 hours of ISO time was dedicated to 7 Kuiper-belt objects (Thomas et al., 2000). The authors reported marginal detections of the two trans-Neptunian objects (TNO) 1993 SC and 1996 TL_{66}. Their radiometric modelling attempts indicated that the TNOs are large, spherical and very dark objects. The outcome of this programme was clearly limited by the ISOCAM and ISOPHOT sensitivities.

3.3.4. *Serendipitous observations*

Additionally to the dedicated asteroid programmes, many comets and asteroids have been seen serendipitously in the ISOCAM Parallel Survey, in the ISOPHOT Serendipity Survey and in large survey programmes, like e.g. the galactic plane survey ISOGAL (Müller, 2001). The ISOPHOT Serendipity slews went over 16 different bright asteroids, 2 planets and 7 comets (Müller et al., 2002). The resulting 170 μm fluxes served two purposes: (i) improvement of the flux calibration through a few well-known asteroids and planets; (ii) scientific investigations in terms of diameter-albedo determination and comet modelling. The nine slews over comet Hale-Bopp showed that the large particles are concentrated in the nucleus-trail transition region. The extraction of solar system targets for several other surveys is ongoing and interesting results can be expected.

4. Zodiacal Light

During its 71.9 hours of dedicated programmes, ISO observed different extended structures of the solar system: zodiacal light, dust debris in the outer solar system and the Earth's dust ring, comet tails and trails and planetary rings (for an inventory see Müller, 2003a). Three main goals were set by the observers: (i) refinement of the post-DIRBE picture on the global structure of the Interplanetary Dust Cloud; (ii) study of sub-structures in the zodiacal light; and (iii) reliable determination of the mid-infrared spectrum of the Zodiacal emission.

4.1. SPATIAL STRUCTURES

Technically, point (ii) is the least challenging, since differential – rather than absolute – photometric measurements, as well as images, can be utilised. With the aim of exploring how comets release fresh dust into the interplanetary space, Reach et al. (2000) observed comet 2P/Encke with ISOCAM (see Fig. 3). They detected a long, straight dust trail composed of large cm-sized grains following the orbit of the comet. These grains will become part of the Encke meteoroid stream, and – on longer term – of the zodiacal cloud. Computing the total mass loss from the 1997 apparition of Encke, the authors predict a limited (several thousands years) lifetime for the comet. Ábrahám et al. (2002) observed a similar trail of 22P/Kopff at longer wavelengths with ISOPHOT, and detected its emission at 0.25° behind the comet at 12 and 25 μm but not at 60 μm, consistent with a temperature of 215 K. The trail was only marginally seen at larger distances, showing that its intensity

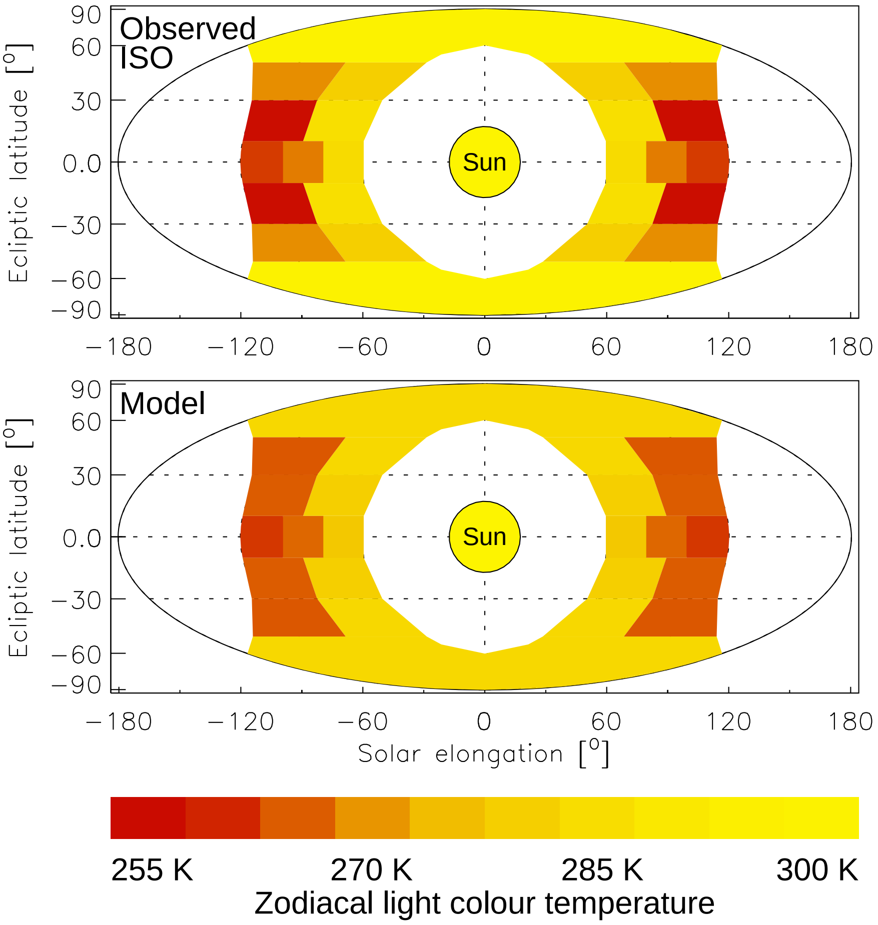

Figure 6. Upper panel: Colour temperatures derived from the ISOPHOT-S templates using single temperature blackbody fits. Lower pannel: Colour temperatures predicted by a model in the spectral range of ISOPHOT-S. Adapted from Leinert et al. (2002).

drops quickly behind the head. Ábrahám et al. (2002) also studied the brightness profiles of the asteroidal bands parallel to the Ecliptic, and determined an upper limit for the intrinsic arcminute scale brightness variations of the bands. Searching for similar variations in the general zodiacal light distribution may also be interesting, since if the interplanetary dust was replenished from discrete sources – asteroids, comets – a structureless zodiacal light is difficult to explain. From ISOPHOT measurements at 25 μm, however, Ábrahám et al. (1997b) deduced an upper limit for the underlying r.m.s. brightness fluctuations of ±0.2 %, which corresponds at high ecliptic latitudes to ±0.04 MJy/sr.

4.2. SPECTRAL CHARACTERISATION

The mid-infrared spectrum of the zodiacal light, not known before ISO, was measurable with both ISOCAM-CVF and ISOPHOT-S. However, the technical difficulties involved are indicated by the fact that both instrument groups needed to revise their first results due to straylight contamination (ISOCAM) and to incorrect beam profile (ISOPHOT). The spectra derived from 29 ISOPHOT-S observations (Ábrahám et al., 1997a; Leinert et al., 2002) could be well represented by blackbody radiation in the 255–300 K range (see Fig. 6). No spectral features in the $6-12\,\mu$m range were visible at the 10-20% level. With the ISOCAM-CVF, Reach et al. (1996, 1997, 2003) also found blackbody-shaped spectra – though their temperatures are somewhat lower than those from ISOPHOT-S – indicating large ($>10\,\mu$m radius), low-albedo, rapidly rotating grey particles. Comparison to theoretical models provided acceptable fits only for 'astronomical silicates', ruling out many other potential components of the zodiacal light. The ISOCAM spectra give also a hint for a 9-11 μm emission feature with an amplitude of 6% of the continuum. This feature might indicate the presence of a mixture of small ($\sim 1\,\mu$m) amorphous, crystalline and hydrous silicates grains. The large scale temperature distribution on the sky was derived consistently from both instruments' data sets: the temperature value increases with the ecliptic latitude and decreases with the distance from the Sun (Fig. 6). This result can be understood in terms of the geometry of the interplanetary dust cloud.

4.3. ABSOLUTE SURFACE BRIGHTNESS

The most challenging part of ISO's zodiacal light programme is no doubt the analysis of the absolute surface brightness measurements. This is still an on-going project involving determination of the photometric zero points of the instruments, linearity and beam profile issues. Ábrahám et al. (2002) discussed the possible advantages of ISOPHOT measurements of this type in refining the present picture on the large scale structure of the Zodiacal cloud produced by DIRBE (e.g. small beam avoiding point sources; observations from Sep–Dec when DIRBE was not cooled; more far-infrared filters). They demonstrated that the ISOPHOT and DIRBE observations can be transformed to each other's photometric systems (see also Holmes & Dermott, 2000). Thus once the absolute calibration of ISOPHOT is set, large samples of dedicated and serendipitous observations of the sky at different latitudes and at different solar elongations contained in the ISO Data Archive could be analysed. Improvements of the existing zodiacal light models might be possible and new structures, like asteroidal bands, could still be hidden in the observations. And it is also worth to mention that an accurate determination of the absolute level of the Zodiacal light is a strong prerequisite to extract the value of the infrared extragalactic background light, and that many of the absolute photometric data of ISO will not be superseded by the coming new infrared satellites.

Acknowledgements

This work was partly supported by the grant OTKA 037508 of the Hungarian Research Fund. P. Á. acknowledges the support of the Bolyai Fellowship.

References

Ábrahám, P., Acosta-Pulido, J.A., Klaas, U. et al.: 1997a, ISOPHOT-S Measurements of the Zodiacal Light: A Calibration Tool, in *First Workshop on Analytical Spectroscopy*, A.M. Heras, K. Leech, N. R. Trams, and M. Perry (eds.), ESA SP-419, 119–123

Ábrahám, P., Leinert, C., & Lemke, D.: 1997b, Search for brightness fluctuations in the zodiacal light at 25 micron with ISO, *A&A* **328**, 702–705

Ábrahám, P., Leinert, C. & Lemke, D.: 2002, Zodiacal light observations with the Infrared Space Observatory, in *Dust in the Solar System and Other Planetary Systems*, S.F. Green, I.P. Williams, J.A.M. McDonnell & N. McBride (eds.), COSPAR colloquia series, Vol. 15., 111–126

Barucci, M.A., Dotto, E., Brucato, J.R. et al.: 2002, 10 Hygiea: ISO Infrared Observations, *Icarus* **156**, 202–210

Bockelée-Morvan, D., Gautier, D., Hersant, F., Huré, J.-M., and Robert, F.: 2002, Turbulent radial mixing in the Solar Nebula as the source of crystalline silicates in comets, *A&A*, **384**, 1107–1118.

Bouwman, J., de Koter, A., Dominik, C., Waters, L.B.F.M.: 2003, The origin of crystalline silicates in the Herbig Be star HD 100546 and in comet Hale-Bopp, *A&A* **401**, 577–592

Brucato, J. R., Colangeli, L., Mennella, V., et al.: 1999, Silicates in Hale-Bopp: hints from laboratory studies, *P&SS* **47**, 773–779

Cernicharo, J., and Crovisier, J.: 2004, Water in Space – The Water World of ISO, *this volume.*

Colangeli, L., Bussoletti, E., Pestellini, C.C. et al.: 1998, ISOCAM Imaging of Comets 65P/Gunn and 46P/Wirtanen, *Icarus* **134**, 35–46

Colangeli, L., Epifani, E., Brucato, J. R. et al.: 1999, Infrared spectral observations of comet 103P/Hartley 2 by ISOPHOT, *A&A* **343**, L87–L90

Crovisier, J., Brooke, T.Y., Hanner, M.S. et al.: 1996, The infrared spectrum of comet C/1995 O1 (Hale Bopp) at 4.6 AU from the Sun, *A&A* **315**, L385–L388

Crovisier, J., Leech, K., Bockelee-Morvan, D. et al.: 1997a, The Spectrum of Comet Hale-Bopp (C/1995 O1) Observed with the Infrared Space Observatory at 2.9 Astronomical Units from the Sun, *Science* **275**, 1904–1907

Crovisier, J., Leech, K., Bockelée-Morvan, D., Brooke, T.Y., et al.: 1997b, The infrared spectrum of comet Hale-Bopp, in First ISO Workshop on Analytical Spectroscopy, A.M. Heras, K. Leech, N.R. Trams and M. Perry (eds.), ESA SP-419, 137–140

Crovisier, J., Encrenaz, T., Lellouch, E., et al.: 1999a, ISO observations of short-period comets, in The Universe as seen by ISO, P. Cox and M.F. Kessler (eds.), ESA SP-427, 161–164

Crovisier, J., Leech, K., Bockelée-Morvan, D., et al.: 1999b, The spectrum of comet Hale-Bopp as seen by ISO, in The Universe as seen by ISO, P. Cox and M.F. Kessler (eds.), ESA SP-427, 137–140

Crovisier, J., Brooke, T.Y., Leech, K., et al.: 2000, The thermal infrared spectra of comets Hale-Bopp and 103P/Hartley 2 observed with the Infrared Space Observatory, in Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths, M.L. Sitko, A.L. Sprague and D.K. Lynch (eds.), ASP Conf. Series 196, 109–117

Crovisier, J.: 2000a, Observations of gas and dust in comets with the Infrared Space Observatory, in Astrochemistry: From molecular Clouds to Planetary Systems (IAU Symp. 197), Y.C. Mihn and E.F. van Dishoeck (eds.), ASP, 461–470

Crovisier, J.: 2000b, Circumstellar, cometary and interplanetary dust, in ISO Beyond the Peaks, A. Salama, M.F. Kessler, K. Leech and B. Schulz (eds.), ESA SP-456, 23–28

Davies, J. K., Sykes, M. V., Reach, W.T. et al.: 1997, ISOCAM Observations of the Comet P/Kopff Dust Trail, *Icarus* **127**, 251–254

Dotto, E., Barucci, M.A., Crovisier, J. et al.: 1999, ISO observations of asteroids, in The Universe as Seen by ISO, P. Cox & M. F. Kessler (eds.), ESA SP-427, 165–168

Dotto, E., Müller, T.G., Barucci, M.A. et al.: 2000, ISO results on bright Main Belt asteroids: PHT-S observations, *A&A* **358**, 1133–1141

Dotto, E., Barucci, M.A., Müller, T.G. et al.: 2002, ISO observations of low and moderate albedo asteroids. PHT-P and PHT-S results, *A&A* **393**, 1065–1072

Dotto, E., Barucci, M.A., Brucato, J.R. et al.: 2004, 308 Polyxo: ISO-SWS Spectrum up to 26 micron, *A&A*, **427**, 1081–1084

Encrenaz, T.: 2000, ISO Observations of Solar-System Objects, in Infrared space astronomy, today and tomorrow (École de Physique des Houches). F. Casoli, J. Lequeux, and F. David (eds.), EDP Sciences, Paris, p. 89–149

Epifani, E., Colangeli, L., Fulle, M. et al.: 2001, ISOCAM Imaging of Comets 103P/Hartley 2 and 2P/Encke, *Icarus* **149**, 339–350

Fernández, Y.R., Lisse, C.M., Käufl, U.H. et al.: 2000, Physical Properties of the Nucleus of Comet 2P/Encke, *Icarus* **147**, 145–160

Fouchet, T.: 2003, The achievements and potential of ISO archive for planetary studies, in Exploiting the ISO Data Archive – Infrared Astronomy in the Internet Age, C. Gry, S. B. Peschke, J. Matagne et al. (eds), ESA SP-511, 41–46

Fouchet, T., Bézard B., Encrenaz, T.: 2004, The planets and Titan observed by ISO, *this volume.*

Groussin, O., Lamy, P., Jorda, L.: 2004a, Properties of the nuclei of Centaurs Chiron and Chariklo, *A&A*, **413**, 1163–1175

Groussin, O., Lamy, P., Jorda, L., Toth, I.: 2004b, The nuclei of comets 126P/IRAS and 103P/Hartley 2, *A&A*, **419**, 375–383

Grün, E., Hanner, M.S., Peschke, S.B. et al.: 2001, Broadband infrared photometry of comet Hale-Bopp with ISOPHOT, *A&A* **377**, 1098–1118

Harker, D.E., Wooden, D.H., Woodward, C.E., and Lisse, C.M.: 2002, Grain properties of comet C/1995 O1 (Hale-Bopp), *ApJ.*, **580**, 579–597.

Harris, A. W. & Davies, J. K.: 1999, Physical Characteristics of Near-Earth Asteroids from Thermal Infrared Spectrophotometry, *Icarus* **142**, 464–475

Hiroi, T. & Hasegawa, S.: 2003, Revisiting the search for the parent body of the Tagish Lake meteorite –Case of a T/D asteroid 308 Polyxo, *Antarct. Meteorite Res.* **16**, 176–184

Holmes, E. K.; Dermott, S. F.: 2000, Comparison of ISO and COBE Observations of the Zodiacal Cloud, in *ISO Beyond Point Sources: Studies of Extended Infrared Emission*, ESA-SP 455, p. 67–70.

Jorda, L., Lamy, P., Groussin, O., et al.: 2000, ISOCAM observations of cometary nuclei, in *ISO Beyond Point Sources*, R.J. Laureijs, K. Leech and M.F. Kessler edts, ESA-SP 455, 61–66.

Lagerros, J.S.V.: 1996, Thermal physics of asteroids. I. Effects of shape, heat conduction and beaming, *A&A* **310**, 1011–1020

Lagerros, J.S.V.: 1997, Thermal physics of asteroids. III. Irregular shapes and albedo variegations, *A&A* **325**, 1226–1236

Lagerros, J.S.V.: 1998, Thermal physics of asteroids. IV. Thermal infrared beaming. *A&A* **332**, 1123–1132

Lagerros, J.S.V., Müller, T.G., Klaas, U. & Erikson, A.: 1999, ISOPHOT Polarization Measurements of the Asteroids (6) Hebe and (9) Metis at 25 μm, *Icarus* **142**, 454–463

Lamy, P. L., Toth, I., Jorda, L. et al.: 2002, The Nucleus of Comet 22P/Kopff and Its Inner Coma, *Icarus* **156**, 442–455

Lamy, P.L., Toth, I., Fernández, Y.R., and Weaver, H.A.: 2004, The sizes, shapes, albedos, and colors of cometary nuclei, in *Comets II*, M. Festou H.U. Keller & H.A. Weaver edts, Univ. Arizona Press, Tucson, *in press.*

Lebofsky, L. A., Sykes, M. V., Tedesco, E. F. et al.: 1986, A refined 'standard' thermal model for asteroids based on observations of 1 Ceres and 2 Pallas, *Icarus* **68**, 239–251

Leech, K., Crovisier, J., Bockelée-Morvan, D. et al.: 1999, The Infrared Spectrum of Comet Hale-Bopp as Seen by the Infrared Space Observatory, *Earth Moon and Planets* **78**, 81–83

Leinert, Ch., Ábrahám, P., Acosta-Pulido, J., Lemke, D., Siebenmorgen, R.: 2002, Mid-infrared spectrum of the zodiacal light observed with ISOPHOT, *A&A* **393**, 1073–1079

Lellouch, E., Crovisier, J., Lim, T. et al.: 1998, Evidence for water ice and estimate of dust production rate in comet Hale-Bopp at 2.9 AU from the Sun, *A&A* **339**, L9–L12

Lisse, C. M., Fernández, Y. R., A'Hearn, M. F et al.: 2004, A tale of two very different comets: ISO and MSX measurements of dust emission from 126P/IRAS (1996) and 2P/Encke (1997), *Icarus* **171**, 444–462

Malfait, K., Waelkens, C., Waters, L.B.F.M. et al.: 1998, The spectrum of the young star HD 100546 observed with the Infrared Space Observatory, *A&A* **332**, L25–L28

Molster, F.J., Yamamura, I., Waters, L.B.F.M. et al.: 1999, Low-temperature crystallization of silicate dust in circumstellar disks, *Nature* **401**, 563–565

Molster, F.J., Kemper, C.: 2004, Crystalline Silicates, *this volume.*

Müller T.G. & Lagerros J.S.V.: 1998, Asteroids as far-infrared photometric standards for ISOPHOT, *A&A* **338**, 340–352

Müller, T.G., Lagerros, J.S.V., Burgdorf, M. et al.: 1999a, Fundamental thermal emission parameters of main-belt asteroids derived from ISO, in The Universe as Seen by ISO, P. Cox & M.F. Kessler (eds.), ESA SP-427, 141–144

Müller, T.G., Lagerros, J.S.V. & Klaas, U.: 1999b, Polarisation Measurements of Asteroids at 25 μm with ISOPHOT, in Workshop on ISO Polarisation Observations, R.J. Laureijs & R. Siebenmorgen (eds.), ESA SP-435, 31–36

Müller, T. G., Dotto, E., & Barucci, A.: 2000, ISO Observations of Bright Asteroids with Pht-S, in ISO beyond the peaks: The 2nd ISO workshop on analytical spectroscopy, A. Salama, M.F. Kessler, K. Leech & B. Schulz (eds.), ESA-SP 456, 33–36

Müller, T.G.: 2001, Asteroids in the infrared-Serendipitous observations with ISO, *Planetary and Space Science* **49**, 787–791

Müller, T.G., Hotzel, S. & Stickel, M.: 2002, Solar system objects in the ISOPHOT 170 mu m serendipity survey, *A&A* **369**, 655–679

Müller T.G. & Lagerros J.S.V.: 2002, Asteroids as calibration standards in the thermal infrared for space observatories, *A&A* **381**, 324–339

Müller, T.G.: 2002, Thermophysical analysis of infrared observations of asteroids, *M&PS* **37**, 1919–1928

Müller T.G.: 2003a, ISO Observations of asteroids, comets and interplanetary dust: results and unexploited observations, in Exploiting the ISO Data Archive – Infrared Astronomy in the Internet Age, C. Gry, S. B. Peschke, J. Matagne et al. (eds), ESA SP-511, 47–52

Müller, T.G.: 2003b, ISO: Asteroid Results and Thermophysical Modelling, in Physical Properties and Morphology of Small Solar System Bodies, IAU JD 19, 29

Müller T.G. & Lagerros J.S.V.: 2003, Asteroids as Calibration Standards in the Thermal Infrared – Applications and Results from ISO, in The Calibration Legacy of the ISO Mission, L. Metcalfe, A. Salama, S. B. Peschke and M. F. Kessler (eds.), ESA SP-481, 157–163

Müller T.G. & Blommaert, J. A. D. L.: 2004, 65 Cybele in the thermal infrared: Multiple observations and thermophysical analysis, *A&A* **418**, 347–356

Reach, W.T., Abergel, A., Boulanger, F. et al.: 1996, Mid-Infrared spectrum of the zodiacal light, *A&A* **315**, L381–L384

Reach, W.T.: 1997, The structured zodiacal light: IRAS, COBE, and ISO observations, in *Diffuse Infrared Radiation and the IRTS*, H. Okuda, T. Matsumoto, and T. Rollig (eds.), ASP Conference Series **124**, 33–40

Reach, W.T., Sykes, M.V., Lien, D., & Davies, J.K.: 2000, The Formation of Encke Meteoroids and Dust Trail, *Icarus* **148**, 80–94

Reach, W.T., Morris, P., Boulanger, F., Okumura, K.: 2003, The mid-infrared spectrum of the zodiacal and exozodiacal light, *Icarus* **164**, 384–403

Tedesco, E. F. & Desert, F. X.: 2002, The Infrared Space Observatory Deep Asteroid Search, *AJ* **123**, 2070–2082

Thomas, N., Eggers, S., Ip, W.-H. et al.: 2000, Observations of the Trans-Neptunian Objects 1993 SC and 1996 TL66 with the Infrared Space Observatory, *ApJ* **534**, 446–455

Waelkens, C., Malfait, K., Waters, L.B.F.M.: 1999, Comet Hale-Bopp, Circumstellar Dust, and the Interstellar Medium, *Earth Moon and Planets* **79**, 265–274

Wooden, D.H., Harker, D.E., Woodward, C.E. et al.: 1999, Silicate Mineralogy of the Dust in the Inner Coma of Comet C/1995 01 (Hale Bopp) Pre- and Post-perihelion, *ApJ* **517**, 1034–1058