Figure 1. Asteroid Ida and its moon Dactyl in enhanced colour. This colour picture is made from images taken by the Galileo spacecraft just before its closest approach to asteroid 243 Ida on 28 August 1993. The moon Dactyl is visible to the right of the asteroid. The colour is ‘enhanced’ in the sense that the CCD camera is sensitive to near-infrared wavelengths of light beyond human vision; a ‘natural’ colour picture of this asteroid would appear mostly grey. Shadings in the image indicate changes in illumination angle on the many steep slopes of this irregular body, as well as subtle colour variations due to differences in the physical state and composition of the soil (regolith). There are brighter areas, appearing bluish in the picture, around craters on the upper left end of Ida, around the small bright crater near the centre of the asteroid, and near the upper right-hand edge (the limb). This is a combination of more reflected blue light and greater absorption of near-infrared light, suggesting a difference in the abundance or composition of iron-bearing minerals in these areas. Ida’s moon also has a deeper near-infrared absorption and a different colour in the violet than any area on this side of Ida. The moon is not identical in spectral properties to any area of Ida in view here, though its overall similarity in reflectance and general spectral type suggests that it is basically made of the same rock types.
(Credit: JPL, Galileo mission)

Figure 2. This image mosaic of asteroid 253 Mathilde is constructed from four images acquired by the NEAR spacecraft on 27 June 1997. The part of the asteroid shown is about 59 km by 47 km. Details as small as 380 m can be discerned. The surface exhibits many large craters, including the deeply shadowed one at the centre, which is estimated to be more than 10 km deep. The shadowed, wedge-shaped feature at the lower right is another large crater viewed obliquely. The angular shape of the upper left limb of the asteroid results from the rim of a third large crater viewed edge-on. The bright mountainous feature at the far left may be the rim of a fourth large crater emerging from the shadow. The angular shape is believed to result from a violent history of impacts.
(Credit: Johns Hopkins University Applied Physics Laboratory, NEAR-Shoemaker mission)

Figure 3. This picture of asteroid 951 Gaspra is a mosaic of two images taken by the Galileo spacecraft from a range of 5300 km just before closest approach on 29 October 1991. The resolution is about 54 m/pixel. Gaspra is an irregular body with approximate dimensions of 19 x 12 x 11 km. The portion illuminated in this view is about 18 km from lower left to upper right. The north pole is located at upper left; Gaspra rotates counterclockwise every 7 h. The large concavity on the lower right limb is about 6 km across, the prominent crater on the terminator, centre left, about 1.5 km. A striking feature of Gaspra’s surface is the abundance of small craters. More than 600 of them, 100-500 m in diameter, are visible here. The number of such small craters compared to larger ones is much greater for Gaspra than for previously studied bodies of comparable size such as the satellites of Mars. Gaspra’s very irregular shape suggests that the asteroid was derived from a larger body by nearly catastrophic collisions. Consistent with such a history is the prominence of groove-like linear features, believed to be related to fractures. These linear depressions, 100-300 m wide and tens of metres deep, are in two crossing groups with slightly different morphology, one group wider and more pitted than the other. Gaspra also shows a variety of enigmatic curved depressions and ridges in the terminator region at left.
(Credit: US Geological Survey, Galileo Orbiter)

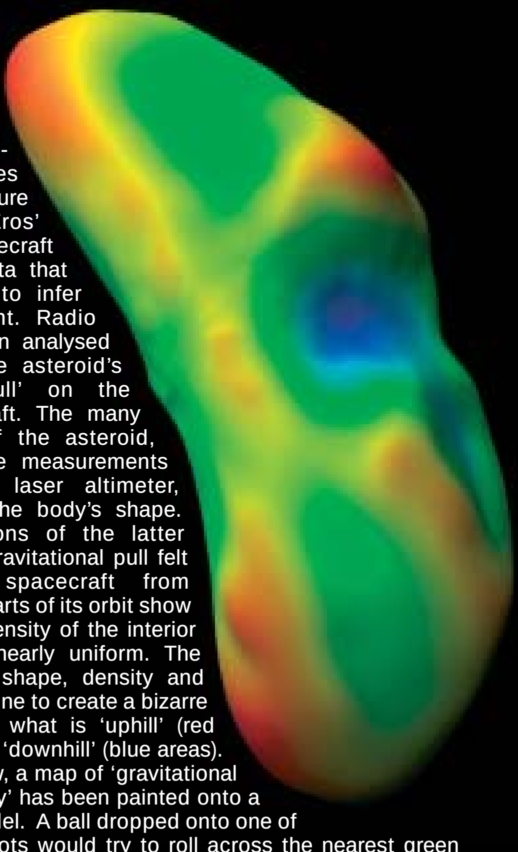

Figure 4. The ups and downs of Eros. While NEAR-Shoemaker does not directly measure gravity on Eros’ surface, the spacecraft gathers other data that allow scientists to infer this measurement. Radio tracking has been analysed to determine the asteroid’s gravitational ‘pull’ on the orbiting spacecraft. The many images of the asteroid, plus range measurements from the laser altimeter, measure the body’s shape. Comparisons of the latter with the gravitational pull felt by the spacecraft from different parts of its orbit show that the density of the interior must be nearly uniform. The asteroid’s shape, density and spin combine to create a bizarre pattern of what is ‘uphill’ (red areas) and ‘downhill’ (blue areas).
In this view, a map of ‘gravitational topography’ has been painted onto a shape model. A ball dropped onto one of the red spots would try to roll across the nearest green area to the nearest blue area.
(Credit: Johns Hopkins University Applied Physics Laboratory, NEAR-Shoemaker mission)

ISO and Asteroids

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We are currently at the end of ISO's 3.5 year Post-Operations Phase and the start of the 5 year Active Archive Phase. Final automatic bulk processing of the observations has concluded and all observations are publicly available from the ISO archive.

Here, in addressing ISO's observations of asteroids we attempt a complete overview, from the original scientific ideas – to the current results – to what can be expected in the future. ISO has delivered a wealth of new and unexpected results concerning asteroids, but the archive still has many hidden treasures. In the near future, ISO's mid- and far-infrared data, in combination with other observations, will provide new advances in our understanding of the Solar System and new insights into the interrelations between meteorites, asteroids, comets and interplanetary material, all of which play fundamental roles in the Solar System's history and evolution.

Introduction*

ISO was the world's first true orbiting infrared observatory. Equipped with four sophisticated and versatile scientific instruments, it provided astronomers with a facility of unprecedented sensitivity and capability for the exploration of the Universe at infrared wavelengths from 2.5 to 240 microns. The Solar System programme comprised only about 1.4% of all science observations made by the ISO mission, and the astronomical community's expectations were not very high in relation to asteroids, comets and planets. During the last decades many satellites have studied several of our neighbouring objects in great detail, both in-situ and during close flybys – so what could be expected from a 60-cm telescope circulating just outside the atmosphere?

Now, however, the ISO results are on their way to making a big impact on our knowledge of objects on our celestial 'doorstep'. Spectacular results regarding the 'life-element' water in the Universe – not least its unexpected discovery in large amounts in the higher atmospheres of all giant planets – were already presented in ESA Bulletin No. 104, in November 2000. Here we maintain the Solar System theme, presenting ISO's results on asteroids.

*Units used in this article:
AU = Astronomical Unit, the average distance between Sun and Earth;
1 AU=149 597 870 km.
Jy = Jansky, flux density,
1 Jy = 1×10^{-26} Wm^{-2} Hz^{-1}.
Micron: wavelength unit,
1 micron = 1×10^{-6} m.

ISO was an ESA spacecraft launched on 19 November 1995 and operated in orbit until 16 May 1998, carrying instruments funded by the Agency's Member States (especially the countries of the instrument Principal Investigators (PIs): France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. Additional information on ISO, including results galleries and how to retrieve data, can be found by following links from the ISO Home Page (*www.iso.vilspa.esa.es*); news items are also posted at *www.sci.esa.int.*

Previous ESA Bulletin articles have addressed:
- The ISO Mission – A Scientific Overview (ESA Bulletin No. 84, November 1984)
- The First Results from ISO (ESA Bulletin No. 86, May 1996)
- Looking Back at ISO Operations (ESA Bulletin No. 95, August 1998)
- The ISO Data Archive (ESA Bulletin No. 98, June 1999)
- ISO's Astronomical Harvest Continues (ESA Bulletin No. 99, September 1999)
- ISO and Cosmic Water (ESA Bulletin No. 104, November 2000).

These small pieces of rock (by celestial standards) have diameters of up to several hundred kilometres, with the majority orbiting between Mars and Jupiter. Some asteroids collisionally and gravitationally scattered into Earth-crossing orbits have made it in recent years into the newspaper headlines. The ISO results are of less immediate journalistic interest, but appear more and more in scientific journals and at specialised conferences, by virtue of the fundamental contributions that they make to a deeper understanding of these important constituent bodies of the Solar System.

Asteroids receive light from the Sun and what we see of them through amateur telescopes (and under certain circumstances also with the naked eye) is purely reflected light. Typically, however, only 10% of the incident light is reflected by the asteroid, the rest being absorbed and re-emitted as thermal radiation in the infrared. If we could see with our eyes in the thermal infrared (and subject to the assumption that the atmosphere would be transparent at such wavelengths), we would see a completely unfamiliar sky: hardly any stars, but thousands of bright asteroids forming a nice band in the ecliptic plane – the plane in which the Sun moves against the sky and which intersects the plane of our galaxy near the bright galactic centre and at the anti-centre. ISO's sensitivity range spanned the wavelengths at which asteroids produce the vast bulk of their thermal emission, and so it was capable of detecting 99% of the thermal emission of asteroids including, at the shortest wavelengths, part of the reflected sunlight. The main goal of astronomers observing asteroids with ISO was to analyse, by all possible means, this 'heat radiation', which contains the fingerprint of the asteroids' surfaces, and therefore traces of the history of our Solar System.

ISO and its data

ISO's four instruments were a camera covering the 2.5 – 17 micron band (CAM), an imaging photo-polarimeter (PHT), and the short- and long-wavelength spectrometers (SWS and LWS), covering the 2.4 – 45 micron and the 45 – 196.8 micron bands, respectively. The satellite was a great technical and scientific success with most of its subsystems operating far better than their specifications and with its scientific results impacting practically all fields of astronomy. At a wavelength of 12 microns, ISO was one thousand times more sensitive, and had one hundred times better angular resolution than its predecessor the all-sky-surveying IRAS. During its routine operational phase (from the 4 February 1996 to 8 April 1998), ISO made over 26 000 scientific observations (plus about 4000 calibration observations) of targets ranging from objects in our own Solar System right out to the most distant extragalactic sources. In addition to the dedicated observations, ISO obtained other serendipitous data in parallel during slews of the satellite or during long pointed observations.

The accuracy of ISO's pointing system was at the arcsecond level and allowed the tracking of Solar System targets up to apparent velocities of 120 arcsec/hour with respect to equatorial coordinates. This covered most Solar System targets: only a few near-Earth asteroids and comets in certain constellations were too fast and had to be excluded.

The data processing and calibration methods are mature and the archive is approaching the final legacy of the ISO project (final archive pipeline processing products will be released early in 2002). The accuracy of the automatically processed archive products depends strongly on the brightness of a source, on the source-to-background contrast, and on the instrument observing mode. For Solar System objects in particular, special care was necessary due to the source movement, the changing background contributions and, in many cases, non-default instrument configurations. Therefore, most of the results on asteroids are based on manual data processing of basic archive products, performed with the instrument-specific interactive-analysis software packages.

ISO asteroid observations

The titles, Principal Investigators and the targets of all asteroid programmes performed with ISO are summarized in Table 1. In total, 173 proposals were implemented within the 'Guaranteed Time'[1] and 925 within the 'Open Time'[2]. The proposals included several asteroid categories: (a) near-Earth asteroids with closest approaches to the Sun (perihelion) of less than 1.3 AU; (b) Main-Belt asteroids between 1.8 and 4.0 AU from the Sun; (c) Trojan asteroids at the Lagrangian points around Jupiter; and (d) Kuiper-belt objects populating space beyond Neptune. The main scientific goals comprised

1 The various groups involved in the preparation and operation of the ISO mission received guaranteed observing time. These groups were: the four Principal Investigators and their teams, who built the ISO instruments; the five Mission Scientists; the Science Operations Team; the National Aeronautics and Space Administration (NASA), USA; and the Institute of Space and Astronautical Science (ISAS), Japan.

2 The majority of ISO's observing time was made available via two calls for observing proposals, which were open to the astronomical community.

studies of the chemistry and mineralogy of asteroid surfaces, but also of great interest were questions about the links between asteroids, comets, meteorites and other interplanetary material. ISO allowed detailed studies of all aspects of asteroid thermal emission, as reflected in the proposal titles and in the variety of recent scientific results. More details about the proposals, including their scientific abstracts, can be found in the ISO Data Archive at *http://www.iso.vilspa.esa.es*.

Calibration observations performed with ISO have mainly been used for technical studies, but have also proved useful for scientific investigations.

In addition to the intentional science and calibration observations of asteroids, ISO serendipitously observed Solar System objects that happened to be in the field of view during slews or were seen by instruments in one of the parallel modes. Many other programmes

Table 1. Dedicated asteroid programmes

Programme	P.I.	Asteroids
A. Guaranteed Time Observations		
Observations of Galilean Satellites and Asteroids	Encrenaz, Th.	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea, 52 Europa, 65 Cybele
The Mineralogy and Chemistry of the Major Asteroid Classes	Salama, A.	1 Ceres, 2 Pallas, 52 Europa
Vesta Lightcurve Observations	Schulz, B.	4 Vesta
B. Open Time Observations		
IR Observations of Rosetta Asteroidal Targets: Albedo and Diameter Measurements of the Rosetta Target Asteroids	Barbieri, C.	2703 Rodari, 3840 Mimistrobel
Dark, Volatile-rich Asteroids: Possible Relation to Comets	Barucci, A.	10 Hygiea, 77 Frigga, 114 Kassandra, 308 Polyxo, 511 Davida, 624 Hektor, 911 Agamemnon, 914 Palisana, 1172 Aneas, 1437 Diomedes
The Composition of D-Type Asteroids	Fitzsimmons, A.	308 Polyxo, 336 Lacadiera, 498 Tokio
Rosetta Target Asteroids	Fulchignoni, M.	3840 Mimistrobel
Cometary Activity in Asteroids	Harris, A.	1980 Tezcatlipoca, 3200 Phaethon, 3671 Dionysus, 4015 Wilson Harrington, 4179 Toutatis, 5145 Pholus
A Survey of Kuiper Belt Candidates	Ip, W.-H.	5145 Pholus, 1992 QB1, 1993 SB, 1993 SC, 1994 JQ1, 1994 TB, 1996 TL66
Spectroscopic Studies of Volatile-Rich Asteroids	Larson, H.	1 Ceres, 2 Pallas, 13 Egeria
Polarimetry of Asteroids	Mueller, T.	6 Hebe, 9 Metis
A Comprehensive Investigation of the Thermal Properties and Rotational Thermal Variability of the Pluto-Charon Binary and Chiron	Stern, A.	2060 Chiron
Asteroid Size Frequency Distribution	Tedesco, E.	4 Positions at around (22h38min — 08d34min, f.o.v. of 214″ x 214″, 17′ x 17′ and 19′ x 19′
C. Calibration Observations		
ISOCAM Calibration Observations	CAM Team	10 Hygiea, 20 Massalia, 46 Hestia, 56 Melete, 65 Cybele, 150 Nuwa, 804 Hispania, 2062 Aten
LWS Calibration Observations	LWS Team	1 Ceres, 2 Pallas, 4 Vesta, 10 Hygiea
ISOPHOT Calibration Observations	PHT Team	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea, 54 Alexandra, 65 Cybele, 106 Dione, 313 Chaldaea, 532 Herculina
SWS Calibration Observations	SWS Team	1 Ceres, 2 Pallas, 3 Juno, 4 Vesta, 10 Hygiea

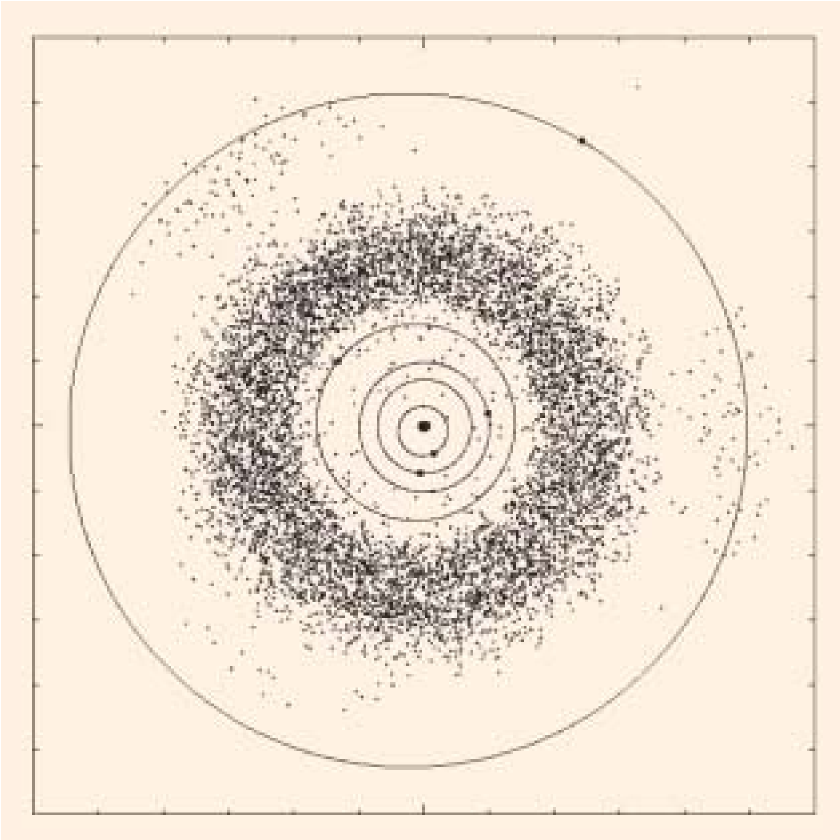

Figure 5. The positions of approximately 8000 asteroids and of the planets from Mercury through Jupiter, projected onto the ecliptic plane for 4 October 2000. The asteroid Main Belt between Mars and Jupiter is nicely visible. The two groups of Trojan asteroids are located at the Lagragian points in front of and behind Jupiter. We currently know the orbits of more than 100 000 asteroids.

provided indirect information on the asteroids, like those focussing on comets, on cometary transition objects (i.e. comets losing the last of their volatile substances and becoming asteroidal), on zodiacal light measurements, and on studies of the trails and tails of comets.

Scientific results

The ISO data archive contains spectroscopic, photometric, imaging and polarimetric measurements at infrared wavelengths between 2 and 240 microns of more than 40 different asteroids. Among the data are complete spectra from 2 to 200 microns of bright asteroids with spectral resolutions of 1000 – 2000 in the SWS range and about 200 in the LWS range. Imaging and photometric asteroid measurements are available and, for the first time, ISO also made polarimetric measurements of the disk-integrated thermal emission of asteroids at 25 microns. These observations and also those of the asteroids seen in parallel and serendipity modes, are the basis for current and future scientific investigations. The recent ISO results presented below are based both on data processed with the automatic-pipeline and with the interactive-analysis packages.

The special case of Vesta

Vesta is the third largest asteroid in the Main Belt. High geological interest arose from the discovery that howardite, eucrite and diogenite (HED) meteorites found on Earth could be samples excavated from its surface. These meteorites have spectral features common to Vesta and to a cluster of small (< 10 km diameter) V-type asteroids extending from the region surrounding Vesta to the edge of the 3:1 resonance[3] at 2.5 AU. Impacts may have excavated enough crustal material to form this widely scattered family of 'Vestoids': some of

[3] Objects with orbital periods close to a simple fraction (here 3:1) of Jupiter's 11.86-year period are in resonance due to the steady influence of Jupiter's huge gravitational attraction. Asteroids in these so-called 'Kirkwood gaps' have very unstable orbits.

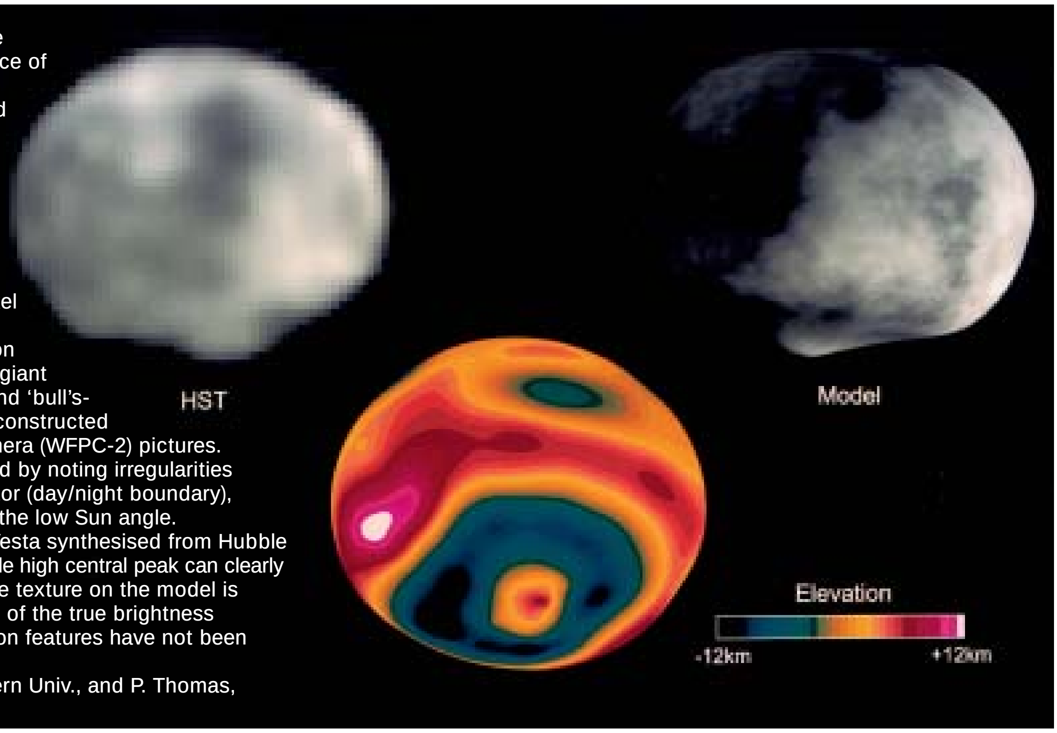

Figure 6. Hubble Space Telescope reveals a huge crater on the surface of Vesta.
Left: An HST image of the asteroid Vesta, taken in May 1996 when it was 110 million miles from Earth. The asymmetry of the asteroid and 'nub' and the south pole is suggestive that it suffered a large impact event. The image was digitally restored to yield an effective scale of six miles per pixel (picture element).
Centre: A colour-encoded elevation map of Vesta clearly showing the giant 285-mile diameter impact basin and 'bull's-eye' central peak. The map was constructed from 78 Wide Field Planetary Camera (WFPC-2) pictures. Surface topography was estimated by noting irregularities along the limb and at the terminator (day/night boundary), where shadows are enhanced by the low Sun angle.
Right: A 3-D computer model of Vesta synthesised from Hubble topographic data. The crater's 8-mile high central peak can clearly be seen near the pole. The surface texture on the model is artificial, and is not representative of the true brightness variations on the asteroid. Elevation features have not been exaggerated.
(Credit: B. Zellner, Georgia Southern Univ., and P. Thomas, Cornell Univ., NASA)

them approach the chaotic region associated with the 3:1 and v6 resonances[4], from which regions fragments can be rapidly transferred to Earth-crossing orbits. Based on HST images, a three-dimensional shape model was derived for Vesta, and mineralogical and albedo variegations on the surface were discovered.

Vesta has a large mountain on its south pole, surrounded by a ring of mountains stretching halfway to its equator (Fig. 6). This was interpreted as a huge crater with a large central peak rising 18 km above the crater floor. The discovery of substantial impact excavation on Vesta is consistent with the idea that the basaltic achondrite HED meteorites were excavated from its surface by impact processes. There are thus convincing observational and dynamical arguments to suggest that Vesta is the actual parent body for the suite of these meteorites, which represent about 6% of all meteorites falling on Earth. As such, Vesta would represent one of only four known Solar System bodies for which actual rock samples are available in terrestrial laboratories (Earth, Moon, Mars and Vesta).

The detailed studies of the high- and low-resolution ISO spectra of Vesta are still ongoing and are very promising. The observed structure at around 9.1 microns seems to be compatible with the presence of olivines on the asteroid's surface. However, material alteration, such as space weathering, aqueous alteration[5], and varying collisional history, complicate the unique identification of spectral features in the ISO data with laboratory spectra of HED materials. Here, the ISO data are expected to contribute significantly to our knowledge of the relationships between the meteorites that we have in our laboratories and their possible parent bodies.

The special case of Hygiea (courtesy of M. Barucci and co-workers)
Asteroid Hygiea (number 10 in the official asteroid numbering scheme) is the fourth largest asteroid in the Main Belt, with a diameter of more than 400 km. Hygiea rotates around its principal axis in a retrograde sense with an unusually long rotation period of 27.6 hours. Aqueous alteration products have been discovered in its near-infrared spectra, and also a compositional variation over the surface has been discussed. Hygiea was the only ISO target that was observed by all four ISO instruments on the same day. This provided interesting possibilities for intercomparison of the instruments' behaviours and for cross-calibration. It turned out that the overall thermal continuum emission has been nicely predicted by previous thermophysical modelling. However, the greatest interest arises when looking at the low-level spectral features, which are characteristic of the asteroid surface minerals. Hygiea is classified as a C-type asteroid with possible analogues in carbonaceous chondrite meteorites found on Earth. Extensive laboratory studies of different minerals and meteorites have revealed some similarities between ISO's Hygiea spectrum and Ornans and Warrenton meteorites (CO_3 meteorites) at small grain size (Fig. 7).

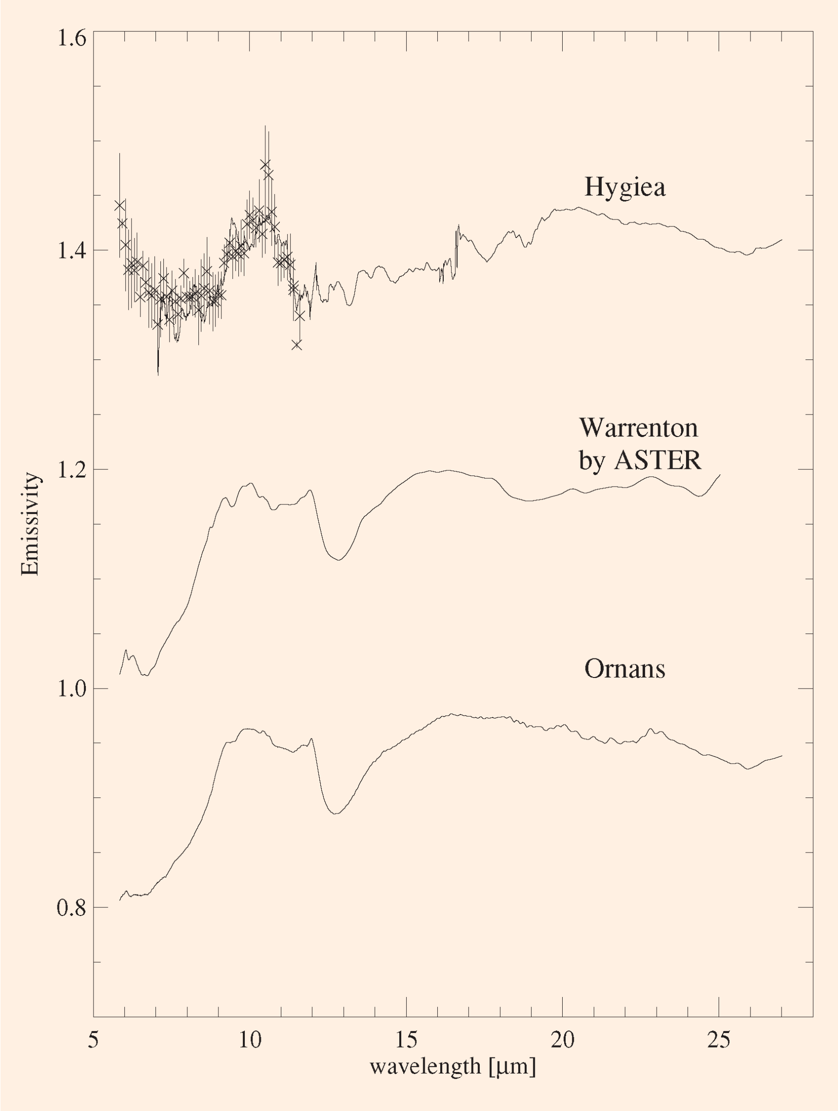

Figure 7. Comparison between 10-Hygiea emissivities measured by ISOPHOT-S and SWS, and laboratory emissivities of Ornans and Warrenton meteorites.
(Credit: M. Barucci & co-workers)

The most indicative feature for this kind of comparison is the Christiansen peak, which occurs around 9.3 microns in the ISO data and in the above-mentioned two carbonaceous chondrite meteorites. The analogy is also supported by the comparison of the transparency features around 13 and 26 microns. If Hygiea is really compatible with CO

[4] Specific secular resonances.
[5] Aqueous alteration is a low-temperature chemical modification of materials by liquid water.

meteorites, this would imply that it is a 'primitive' object which has undergone some metamorphosis. ISO's large database of spectroscopic observations will allow more detailed studies of mineralogy and chemical composition of asteroids to proceed in the near future. The questions of surface alteration processes and the interpretation of spectroscopic features in the infrared are of great interest in the Solar System expert community.

Spectroscopic and spectrophotometric observation of bright asteroids

Spectroscopic and spectrophotometric observations of asteroids have been carried out with all four ISO instruments. The sub-solar and black-body temperatures have been computed for all observed asteroids based on different models. The five bright asteroids 1-Ceres, 2-Pallas, 3-Juno, 4-Vesta and 52-Europa are among the brightest and best-known Main-Belt asteroids, with spin vector, shape and size computed to a good precision. Their thermal continuum has been modelled using a thermophysical model. The spectral features above the thermal-emission continuum have been analysed and discussed in terms of surface composition of the objects.

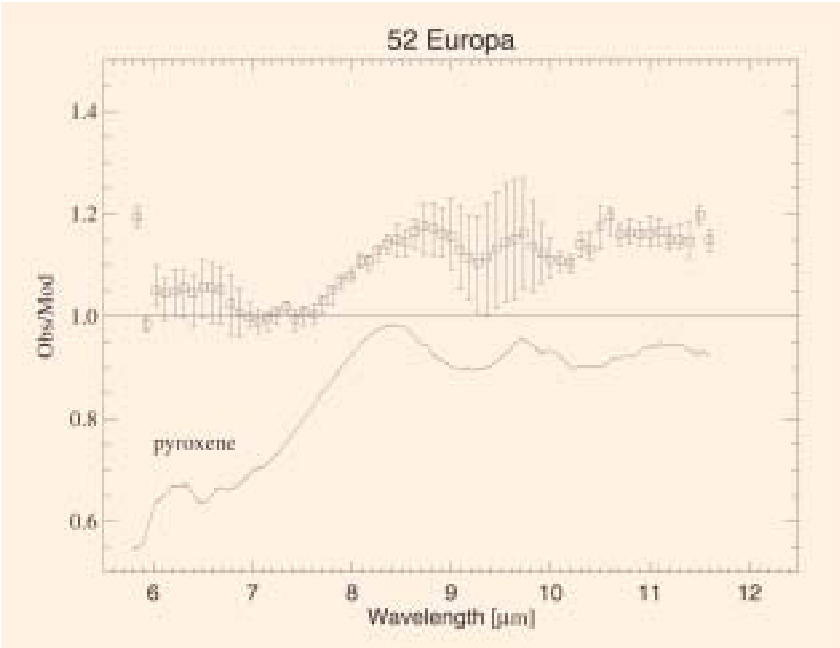

Figure 8. Comparison between 52-Europa emissivities measured by ISOPHOT-S and laboratory emissivities of typical asteroid minerals. (Credit: E. Dotto & co-workers)

The main features observable in the infrared spectral range, which are diagnostic of the mineralogical and petrologic assembly probably present on the surface of the observed asteroids, can be put into three classes: Reststrahlen, transparency and Christiansen features. The interpretation of these spectral features is neither easy nor unique. Since asteroid surfaces are composed of mixtures of minerals whose absorption features are combined following non-linear paths, asteroid spectra are affected not only by the chemical composition of the surface, but also by several undetermined physical parameters, such as density, mineralogy, particle size and packing. In order to investigate the surface composition of the observed asteroids, the spectra obtained have been compared with the emissivity of meteorites and minerals available in the literature, and with new laboratory spectra of a selected sample of minerals. The thermal emissivities of all of the five asteroids show a strong signature around 10 to 11 microns, suggesting the presence of silicates on the surface of these bodies. As an example, the observed emissivity of C-type asteroid 52-Europa and of pyroxenes and olivines obtained by laboratory experiments is shown in Figure 8.

The spectral behaviour between 8 and 11 microns suggests the presence of a mixture of pyroxenes and olivines on the surface of 52-Europa. In particular, the 8.8 micron maximum in the asteroid spectrum seems to be consistent with the Christiansen peak of olivine. At longer wavelengths, olivine and pyroxene exhibit two major reststrahlen bands separated by a band gap, which seems to be consistent with the ISO spectrum of Europa even though the error bars in this region are high.

Polarised thermal emission from asteroids

Depending on wavelength, refractive index and viewing geometry, the thermal-infrared emission from asteroids will originate at some depth below the surface. The radiation propagates through the porous regolith towards the surface, where it is refracted according to Fresnel's equations. As a consequence, the thermal emission becomes polarised. Due to symmetry, however, there can be no net polarisation in the disk-integrated flux from a circularly symmetrical temperature distribution. However, the non-zero thermal inertia of the asteroid, together with its rotation, causes an asymmetry in the temperature distribution. The effect increases with phase angle and for elongated asteroids. The contribution of subsurface emission to the total emission is wavelength-dependent, with the largest contribution at peak wavelength and beyond.

The disk-integrated mid-infrared polarisation parameters were computed by extending the new thermophysical model by J. Lagerros (Uppsala). The small-scale surface roughness was approximated by hemispherical segment craters covering a smooth surface. Analytical solutions were used for the multiply scattered solar and thermally emitted radiation inside the craters. The surface roughness enhances the emission in the solar direction, but lowers the polarisation due to a less sharp transition from the solid body to the vacuum. In general, the predicted degree of linear polarisation increases with higher refractive index, higher absorption coefficient, and a more elongated shape of the asteroid.

The asteroids 6-Hebe and 9-Metis were observed at a wavelength of 25 microns with ISOPHOT. The model absolute fluxes were in good agreement with the photometric results. Although no linear polarisation was detected, the upper limits, together with the extended model, allowed useful constraints to be placed on the regolith properties of the target asteroids. The derived detection limits were compared to model polarisation, by spanning a range in surface roughness, refractive index, and thermal-inertia parameter space. The Metis observations favour a low refractive index and high surface roughness, but the Hebe observations were inconclusive since they coincided with a minimum in the polarisation curve.

Fundamental thermal-emission parameters of Main-Belt asteroids

Based on a large, uniform, pre-ISO database of about 700 individual observations, ranging from 7 to 2000 microns, the thermophysical emission aspects of asteroids have been analysed. In this context, the ISO observations of the following objects have been studied in detail: 1-Ceres, 2-Pallas, 3-Juno, 4-Vesta, 10-Hygiea, 54-Alexandra, 65-Cybele, 106-Dione, 313-Chaldaea and 532-Herculina. A recent thermophysical model was applied to investigate surface roughness, heat conduction and emissivity over the thermal wavelength range. The model included aspects of observing geometry, illumination conditions, shape and spin vector and, if available, also the physical size and the albedo. The model parameters of thermal inertia and beaming were varied over a wide range in search of the best agreement between observations and model predictions. In a second step, the emissivity was determined as a function dependent on wavelength, to be fitted to the data.

The investigations indicated very rough surfaces, reflected in the beaming effect, and very low levels of heat conduction. These values were found to be much smaller than in the lunar case, mainly due to the different environment of the asteroid regolith (lower temperature, lower density) compared to the Moon. The derived thermal-infrared beaming model parameters in terms of 'surface slopes' and 'fraction of surface covered by craters' are in good agreement with theoretical considerations.

Due to scattering processes in the porous regolith, the emissivity varies significantly with wavelength. At the peak of the thermal emission at around 20 microns, the objects emit almost perfectly, and with a significantly lower efficiency at longer wavelength. In the case of Vesta, emissivities as low as 0.6 in the far-infrared/submillimetre region were found. Redman and co-workers suggested that this is an indication of the presence of a dusty, porous regolith. Scattering processes by grains within the regolith reduce the emissivity in a wavelength-dependent fashion. However, the interpretation of the results in terms of grain-size distribution, regolith structure and material is still ongoing.

The excellent agreement at all flux levels over the full thermal-emission spectrum of Ceres at different epochs confirms that the derived values for the thermal properties are well-determined. Figure 9 shows SWS and LWS observations of Ceres taken at different times. The thermophysical model predictions are over-plotted.

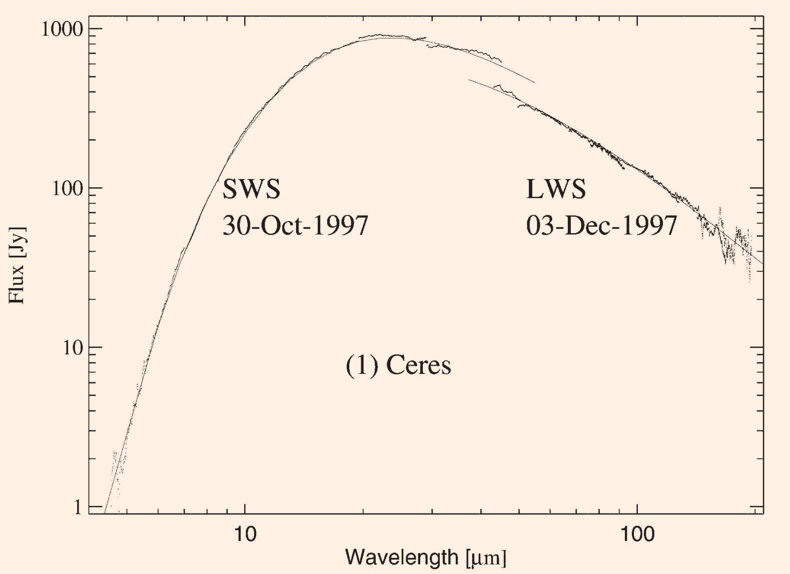

Figure 9. The asteroid 1 Ceres, observed by ISO's short- and long-wavelength spectrometers SWS and LWS. The TPM predictions are over-plotted as solid lines.

Further preliminary tests of these values against other asteroid observations show that the thermal description of Ceres is also valid for other Main-Belt asteroids. This means that the thermophysical model parameters allow a prediction of the thermal emission with a high accuracy for all Main-Belt asteroids where the shape and reflected-light properties are known.

Cometary activity in asteroids

Five near-Earth asteroids have been observed in dedicated programmes with ISOCAM to search for cometary activity. A preliminary analysis of the region around 1980-Tezcatlipoca, 3200-Phaethon, 3671-Dionysus, 4015-Wilson-Harrington and 4179-Toutatis showed no extended emission. It was expected, at least for some of the targets, that weak cometary activity would be seen in the form of dust comas. The non-detection of activity has implications for our understanding of the transition between asteroids and comets, and for the possible scenarios for extinct comets. The CAM photometry was very useful. It has been employed to improve the physical characterisation of these objects, and their albedos and diameters have been derived from a model recently developed especially for near-Earth objects (courtesy of A. Harris, Berlin).

Asteroid size-frequency distribution (courtesy of E. Tedesco, TerraSystem Inc., USA)
Two deep maps of a 12 arcminute square field on the ecliptic using the ISO 12 micron 'IRAS' filter (ISOCAM LW10 band) were made in June 1996, and another four in June 1997. The positions of the fields and the timing between the exposures had been chosen to enable recognition of moving sources with typical Main-Belt apparent velocities below 1 arcmin/hour.

Based on the Minor Planet Center's database, as of October 2000 two known asteroids had been identified in the 1996 field, but none in the 1997 field. Of the seven probable asteroids identified in this field, the two that appear to correspond to 1999-AQ23 and 1999-JZ50 are the brightest and third-brightest in the field. The apparent velocities of the sources are appropriate for Main-Belt asteroids (as seen from ISO).

As an upper limit, it was found that there are about 400 asteroids per square degree at the ecliptic plane above the 12 micron detection threshold of the observations. This threshold is about 0.9 mJy, i.e. it corresponds to diameters greater than about 1.1 km at mid-belt. To put these results into perspective, the IRAS limiting sensitivity was about 150 mJy at 12 microns, whereas most of the asteroids detected by ISO are more than 100 times fainter than that!

The same sky areas were simulated with the Statistical Asteroid Model developed by Tedesco and co-workers. The model gives only lower limits, because it does not include the near-Earth asteroids or asteroids beyond the Hilda group and it terminates abruptly at an asteroid diameter of 1 km. It predicted values of around 200 asteroids per square degree at the ecliptic plane above the 12 micron detection threshold. If smaller asteroids were included, some of these would have 12 micron flux densities greater than 1 mJy if they were close to the Earth. Nevertheless, the ISO data imply that the actual number of kilometre-sized asteroids is significantly greater than previously believed, and in reasonable agreement with the Statistical Asteroid Model.

Asteroids serendipitously seen by ISO
During the ISO mission many surveys and large observing programmes were conducted. Surveys with observations close to the ecliptic plane, performed by CAM and PHT, include many asteroids. The detection of asteroids at thermal wavelengths has many applications. For well-known objects, thermal-model predictions can be tested against the measured infrared brightness. In all cases, radiometric diameters and albedos can be determined and compared, if available, with direct size determinations and/or IRAS results. The mid-infrared CAM observations allow further studies of beaming and surface structure properties, while the far-infrared measurements provide clues about the so far unknown emissivity behaviour of asteroids.

A first analysis of the approximately 40 000 CAM parallel observations between 6 and 15 microns revealed infrared fluxes for about 50 asteroids, most of them not seen by IRAS. Many additional objects are expected to be included in other CAM surveys, with some of the deep observations being sensitive enough to detect 1 km-diameter objects in the asteroid mid-belt.

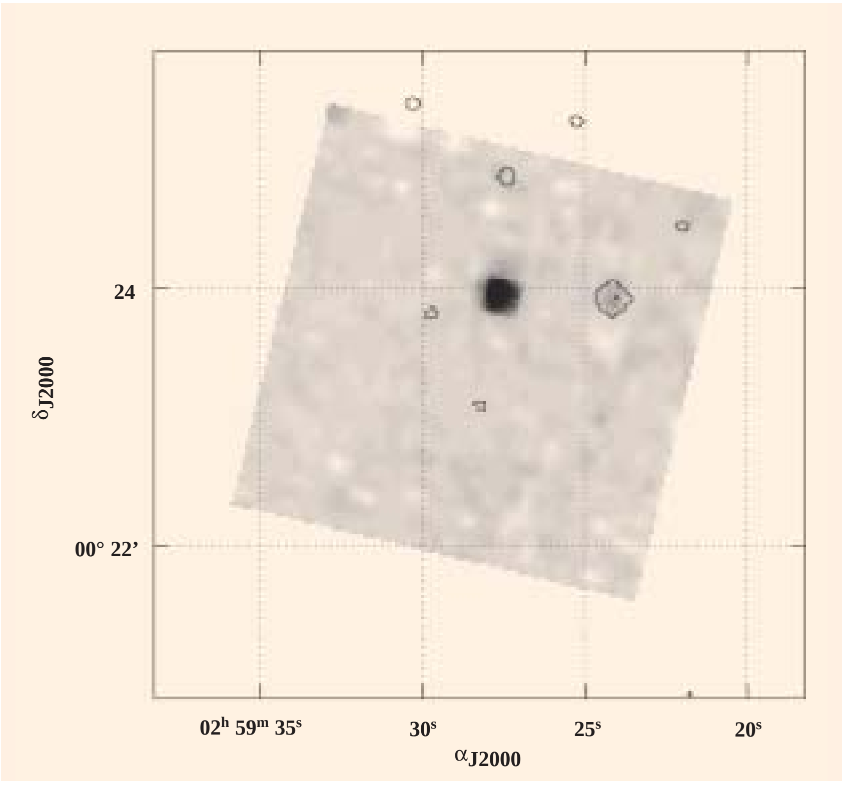

Figure 10. Asteroid 729 Watsonia as serendipitously observed in the ISOCAM parallel mode.

PHT performed observations at 170 microns while the ISO satellite was slewing from one target to the next. This so-called 'PHT Serendipity Survey' covered approximately 15% of the sky, with a limiting sensitivity of 1 Jy. A total of 56 asteroids were predicted to be bright enough to be seen in the slew data. However, an accurate flux determination was not possible in all cases, mainly due to the structured and bright celestial cirrus background. Nevertheless, the new 170 micron fluxes allowed thermophysical model analysis and improvements of the PHT serendipity calibration through reference to well-known asteroids. For some objects, diameter and albedo estimates became possible for the first time.

The ISO database can now be searched systematically for Solar System objects with known orbits. The flux determination will allow thermophysical investigations and the derivation of surface parameters. However, ISO also saw moving targets for which no counterpart in the Minor Planet Database is known so far. For these objects, only a statistical analysis is possible at the moment, at least as long as the orbits and the visual brightness are not known.

Asteroids as new standards in the thermal infrared

Celestial standards play a major role in astronomy. They serve as references for all kinds of measurements where absolute values of physical properties are investigated. In the visible, many stellar sources are available, with Sirius and Vega as main references. In the mid-infrared (i.e. at wavelengths shorter than 35 microns), a 'self-consistent radiometric all-sky network of absolutely calibrated stellar spectra' was recently established (courtesy of M. Cohen, P. Hammersley and co-workers). At submillimetre and radio wavelengths, observers usually use planets as primary standards and H II regions and planetary nebulae as secondary standards. With the launch of ISO in 1995 the far-infrared window was opened, and for the first time observations out to 200 microns were possible. At the same time, it became necessary to establish a set of new celestial standards for the photometric calibration of instruments in the far-infrared.

The extension of stellar reference spectra to the far-infrared provided for the calibration of faint objects, while the planets covered only the very brightest targets. The gap between the two types of calibrators had to be filled by new objects. A set of asteroids fulfilled all requirements:

- they filled the brightness gap between stars and planets in the far-infrared
- at least a few of them were always available during the ISO mission
- they have a smooth thermal-continuum spectrum with only minor emission and absorption features
- the flux changes due to rotation and changing observing geometry can be modelled
- the absolute-brightness predictions are accurate to better than 10% in most of the cases.

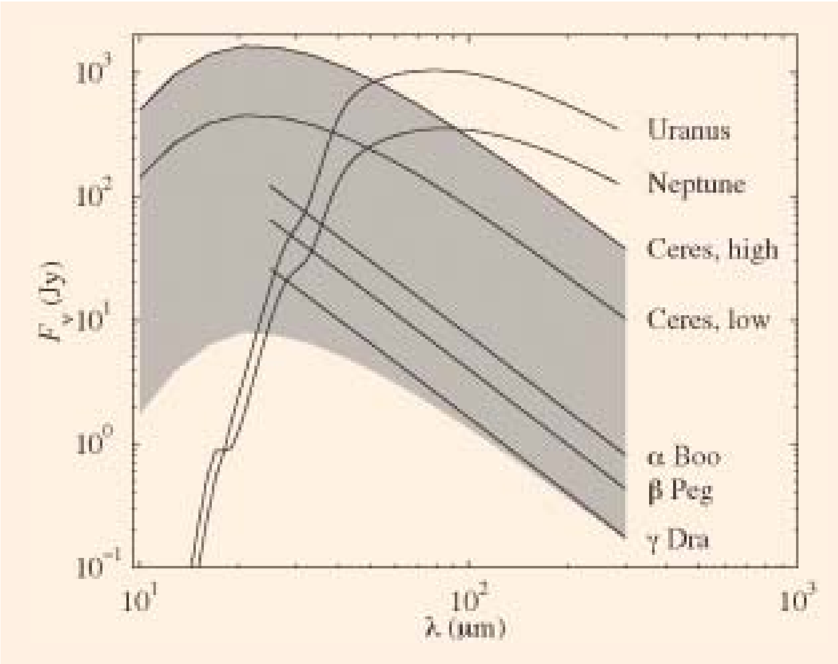

Figure 11. The brightness of different celestial standards. The shaded area indicates the range covered by the selected asteroids. The predictable flux variations of the asteroid, due to rotation, are in the order of 5-30% on time scales of several hours. The changing Earth-asteroid distance can cause a flux increase or decrease of one order of magnitude on a yearly scale (see Ceres: high and low). Uranus and Neptune cover the upper flux range.

In support of ISOPHOT, a set of 10 asteroids was intensively studied and established as new calibrators. Figure 11 shows the three brightest stellar reference sources. It shows Uranus and Neptune (at the upper end of the ISO brightness scale) and also a shaded area representing the selected set of asteroids. Ceres, as the brightest one, is shown at opposition and at conjunction to demonstrate the flux increase or decrease on a time scale of a year.

To establish asteroids as photometric standards, it was necessary to model geometric and illumination effects, surface structures and porosity, and the thermal behaviour for non-spherical objects. The essential model input parameters were derived from many ground-based observations at mid-infrared and submillimetre wavelengths, from Kuiper Airborne Observatory data and from special ISO measurements.

The following parameters are crucial for accurate flux predictions: asteroid size, shape and spin vector; the infrared beaming behaviour caused by surface roughness; the thermal inertia, and a wavelength-dependent emissivity. A comparison of thermophysical

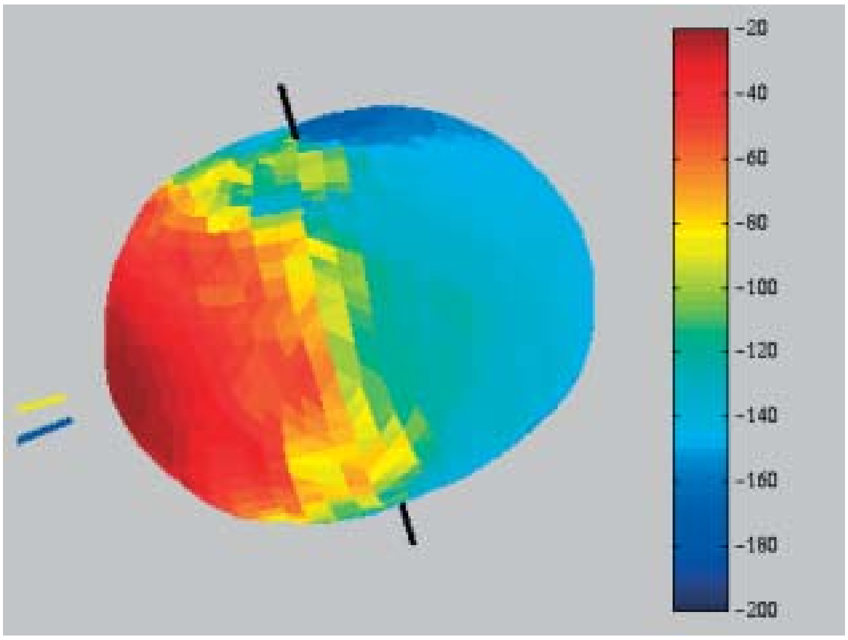

Figure 12. The asteroid 4 Vesta on 6 May 1996 (produced by J. Lagerros). The shape was derived from HST observations (by N. Thomas and co-workers), the temperature coding is in centigrade, the spin vector is marked with a black line, the direction to the Sun with a yellow line and the direction to the Earth with a blue line.

model predictions against spectroscopic data from 5 to 200 microns showed an excellent agreement. The uncertainties of the absolute calibration depend on the individual object and the wavelength interval. In the far-infrared ISOPHOT wavelength range (50 – 200 microns), an accuracy of between 5 and 20% has been achieved. One result of the thermophysical modelling is shown in Figure 12, where the surface temperature of Vesta has been calculated.

Asteroids were widely used later on for calibration purposes for all four ISO instruments. Future applications for ground-based submillimetre, airborne and spaceborne experiments are expected.

Outlook

Only a small fraction of the ISO archive has been exploited in terms of asteroid research. There are still several dedicated programmes for which the astronomers involved have not yet announced their results. The final archive will facilitate this work in the future, and support to the ISO user community is assured for the next five years through provision for an Active Archive Phase for the mission. Nevertheless, the main directions of ISO asteroid research can be seen from the previous overview section: ‘astro-mineralogy’ is the new topic in the astronomical world. Based on ISO’s spectroscopic data from mid- to far-infrared and the corresponding laboratory analysis, many research groups have started to investigate asteroid surface compositions, their interrelation with meteorites, with comets, with the interplanetary and the interstellar medium, and with protoplanetary systems. ISO not only provides the ‘key’ observations to connect meteorites to asteroids, it also provides means to study the alteration of surface minerals in space.

ISO has also shown the high potential of thermal-infrared observations for the analysis of physical properties of asteroids through thermophysical modelling. The understanding of the thermal behaviour is a prerequisite for the interpretation of surface-mineral signatures in the thermal spectra. As in ISO’s case, an excellent understanding of the thermal behaviour of well-known asteroids can be used to calibrate instruments in the far-infrared, where celestial calibrators are extremely rare.

Since the majority of the targets are Main-Belt objects, that is where the biggest improvements can be expected. Moreover, the few dedicated measurements of near-Earth objects will provide new clues to help answer important questions like the fate of extinct comets, or the real sizes and albedos of objects in Earth-threatening orbits. The serendipitous and parallel observations most likely include near-Earth objects, and surprises are not impossible.

It can be imagined that the ISO Data Centre and Archive might become involved with broad initiatives within the astronomical community, such as the Astrophysical Virtual Observatory (AVO), which will allow new and spectacular ways of using ISO observations together with observations at other wavelengths. In terms of the discovery of objects on Earth-crossing orbits, ISO’s infrared observations, in combination with information from the visible, lead to an accurate diameter determination, which allows a better judgement of the impact risk and, if necessary, to evaluate mitigation scenarios.

ISO spent less than 100 hours in total on asteroid observations, or about 0.7% of the total available observing time. However, due to the uniqueness of the data and the great spectroscopic and polarimetric possibilities of ISO, these observations will remain state-of-the-art for many years to come, and future projects like SIRTF, SOFIA, ASTRO-F, and Herschel will benefit greatly from the ISO results. Our knowledge about the formation and evolution of asteroids has changed with ISO, and the picture of our Solar System will, from now on, retain many nuances injected by ISO.

Acknowledgement

The results described above are the work of a large number of astronomers, who for reasons of space could not all be individually credited throughout the article.