SOLAR SYSTEM

THE ACHIEVEMENTS AND POTENTIAL OF ISO ARCHIVE FOR PLANETARY STUDIES

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ABSTRACT

The ISO observations of planetary objects have given several outstanding results. However, the potential from the ISO archive is still high as many observations, or some spectral ranges have not been analysed yet. The most striking example being the ISOCAM observations of Jupiter and Saturn. This situation is due to the difficulty to reduce and calibrate the high flux (up to 10^6 Jy) planetary observations, to the lack of spectroscopic data or numerical tools to accurately analyse the data, and also because the planetary community focused on the most unexpected observations. The achievements and potential from ISO archive encompasses the atmospheric isotopic composition, the oxygen and hydrocarbon stratospheric chemistry in the Giant Planets and Titan, the cloud structure of Jupiter and Saturn, and the composition of planetary surfaces.

Key words: ISO – Solar System; planets

1. INTRODUCTION

The ISO satellite granted the planetary community with many new and unexpected results. The results obtained with ISO were all the more remarkable that, for most of the planets, their infrared spectrum had already been explored by several dedicated interplanetary spacecraft. For example, different versions of the IRIS spectrometer had observed Mars (Mariner 9), the Giant Planets and Titan (Voyager 1 and 2) from 5 to 50 μm with a spectral resolution of 4.3 cm^{-1}. The near-infrared window had also been explored by low-resolution spectro-imagers such as ISM on Phobos (Mars) or NIMS on Galileo (Jupiter). However, if these instruments provided us with a broad view of the planetary infrared spectra, they were overpowered by ISO in terms of sensitivity and spectral resolution.

The potential of ISO archive for planetary studies must be analysed in a similar landscape, where interplanetary missions will continue to carry infrared spectrometers in the vicinity of planets such as Jupiter and Saturn (VIMS and CIRS aboard Cassini) or Mars (OMEGA and PFS aboard Mars Express). Yet, even for this new generation of dedicated instruments, the sensibility of ISO will give us a unique view on planetary spectra. The use of ISO archive for planetary studies must also take into account some specificities of planetary observations compared to other astronomical targets. For example, observing planets yielded very high fluxes (up to 10^6 Jy) ISO was not designed and calibrated to observe. Another aspect, is that each planet or satellite constitutes a class of object on its own. Therefore, we cannot use the ISO archive to merge different surveys of certain objects to improve our statistics on their physical states.

Each planet (except Venus and Mercury which were too close to the Sun) has been observed through its entire infrared spectrum by nearly each instrument of ISO. The future for the ISO archive thus rather resides in a complete analysis of all spectral regions, in particular those which have not been studied yet, or by combining information from different instruments in different spectral ranges. It will also relies on progress on the calibration of high flux observations, or on the release of new spectroscopic data whose lack has inhibited any interpretation up to now.

2. ISOTOPIC COMPOSITION

2.1. DEUTERIUM IN THE GIANT PLANETS

The D/H ratio in the Giant Planets constitutes one of the most useful tool to study their formation and evolution. The Giant Planets formed in the protosolar nebula composed of gas, mainly H_2 and He, and icy grains, enriched in D. Their current deuterium abundance thus reflects the relative fraction of presolar gas and grains that participated in their formation. In Jupiter and Saturn, the majority of the mass comes from the gaseous component of the presolar nebula. Their D/H ratio is therefore regarded as an estimate of the presolar D/H value. In contrast, Uranus and Neptune are predominantly composed of ices, which have enriched their atmospheres in deuterium. For this reason, measuring their D/H ratios could yield the deuterium abundance in the proto-uranus and proto-neptunian ices, and help to constrain the condensation processes in the presolar nebula.

Prior to the ISO mission, the deuterium abundance has been measured in Jupiter and Saturn from near-infrared lines of HD (Smith et al. 1989). However, the interpretation of these lines was complicated by some blending with absorptions from CH_4 and uncertainties on the cloud physical properties. Therefore, the most accurate value for Jupiter has been obtained from the *in-situ* measurements of the mass spectrometer aboard the Galileo probe (Niemann et al. 1998). For the three other Giant Planets, we had to rely on measurements of the CH_3D/CH_4 ratio, and on the knowledge of the fractionation coefficient f induced by the isotopic exchange reaction

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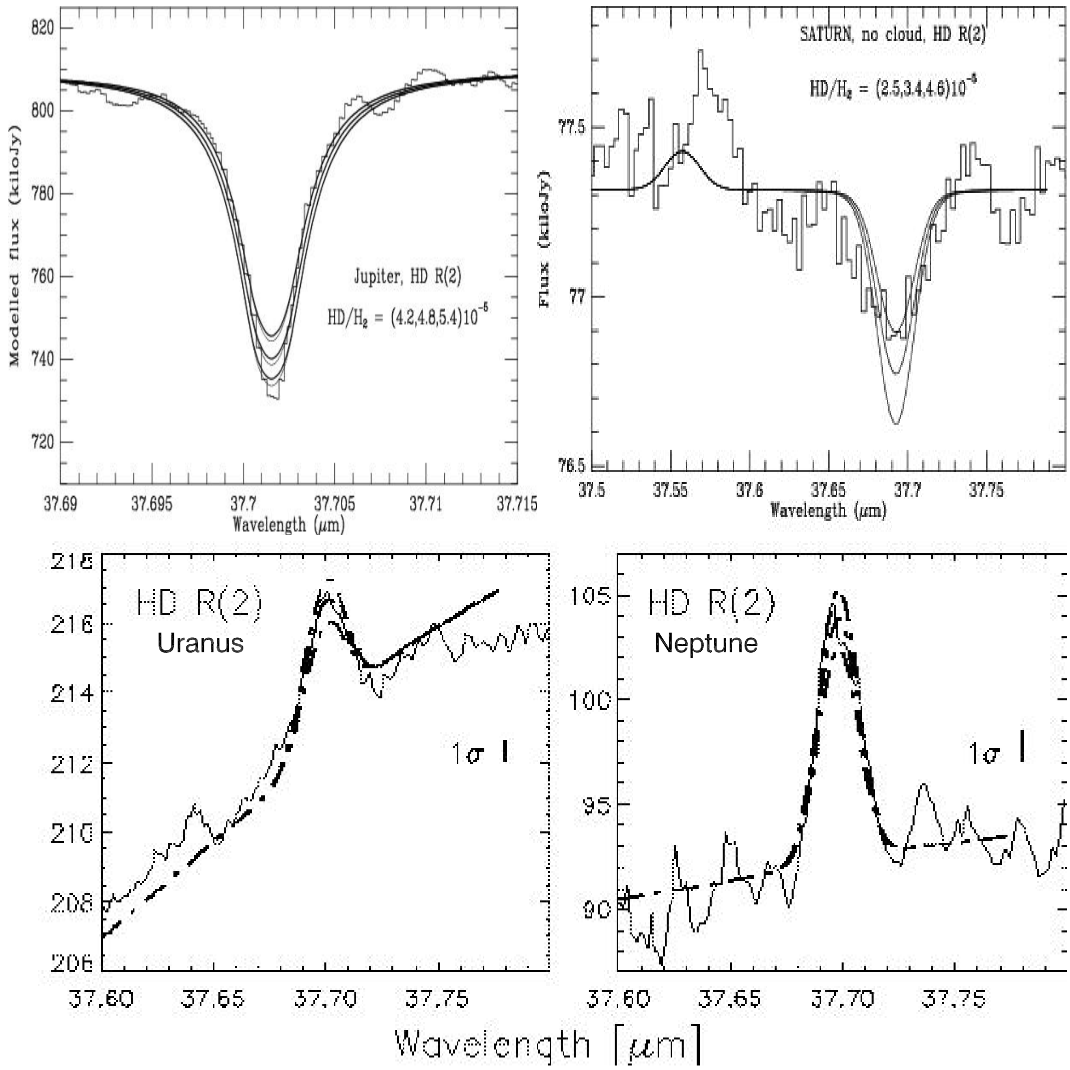

Figure 1. SWS observations of the R(2) HD rotational line in the four Giant Planets. Adapted from Lellouch et al. (2001) and Feuchtgruber et al. (1999)

$\mathrm{HD} + \mathrm{CH}_4 \rightleftharpoons \mathrm{H}_2 + \mathrm{CH}_3\mathrm{D}$. The latter coefficient is quite uncertain as the reaction equilibrium constant and kinetics, and the planetary convection timescales are not well known.

ISO offered us to observe for the first time the rotational lines of HD. These lines enable a simple and consistent determination of the deuterium abundance in the four Giant Planets. The SWS instrument detected the R(2) (37.7 μm) in the four planets and the R(3) in Saturn (Fig 1). From Jupiter's SWS data, Lellouch et al. (2001) deduced a protosolar D/H ratio of $(\mathrm{D/H})_{\mathrm{ps}} = (2.1 \pm 0.4) \times 10^{-5}$. This is in agreement with the value derived from the $^3\mathrm{He}/^4\mathrm{He}$ measured in the solar wind (Geiss & Gloeckler 1998), and confirms the reliability of Jupiter as an indicator of the protosolar D/H ratio. Still from SWS data, Feuchtgruber et al. (1999) obtained D/H ratios of $(5.5^{+3.5}_{-1.5}) \times 10^{-5}$ and $(6.5^{+2.5}_{-1.5}) \times 10^{-5}$ respectively on Uranus and Neptune. From these measurements and the protosolar deuterium composition, Feuchtgruber et al. (1999) deduced a D/H value in the range (5.2–19.3)$\times 10^{-5}$ for the proto-uranian and proto-neptunian ices (under the assumption of a complete mixing between planetary cores and atmospheres). This is significantly different from the D/H ratio measured in comets (about 31×10^{-5}) and shows that the proto-uranian and proto-neptunian ices have formed latter than the comets in the protosolar nebula (Drouart et al. 1999).

Although already very impressive, the D/H determinations could be improved by using the ISO archive. Indeed, the latter results are based on the analysis of the SWS observations only, while two rotational lines, the R(0) (112.07 μm) and the R(1) (56.23 μm) lie in the LWS spectral range, and have been observed for the four Giant Planets (Davis et al. 2000). A complete analysis of these LWS observations have not yet been published [except a report on an early observation of the R(1) line on Saturn (Griffin et al. 1996)], but is currently undertaken by the LWS team. This work is complicated by the difficulty to accurately calibrate the LWS observations with the high flux levels yielded by planetary observations. In this area, there may be still some room to improve the existing calibration.

2.2. Mars isotopic composition

It is believed that Mars' atmosphere has suffered from an atmospheric escape since its formation. This view is supported by the high D/H ratio measured in water, about 6 times higher than the terrestrial D/H ratio. This is a result of the favoured escape of the lightest of the two isotopes, H. The atmospheric escape should also have left its signature in some other isotopic ratios. Since Mars' atmosphere is mainly composed of carbon dioxide (CO_2), it is especially interesting to measure its isotopic composition in ^{13}C, ^{17}O, and ^{18}O to understand its formation and evolution history compared to the Earth's atmosphere. The Viking mass-spectrometer found the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios to be equal to the terrestrial ratios within $\pm 5\%$ (Nier & McElroy 1977). However, a recent study based on ground-based high-resolution spectroscopy found a depletion rather than the expected enrichment in ^{18}O, with a ratio of $^{18}O/^{16}O = 0.87 \pm 0.08$ times the terrestrial ratio (Krasnopolsky et al. 1996).

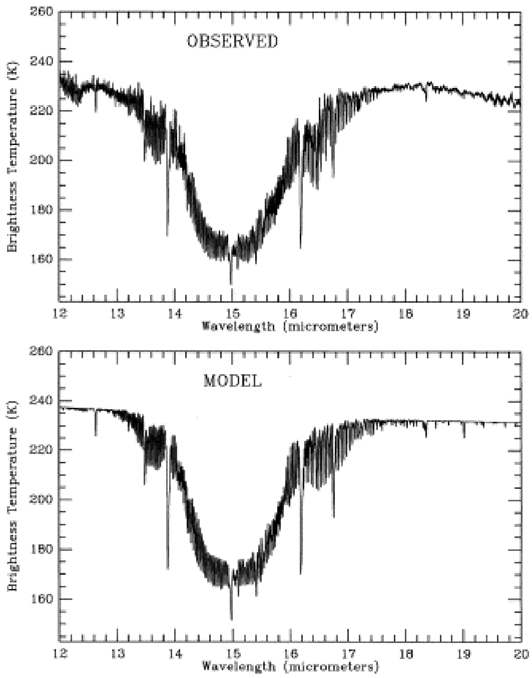

Figure 2. Comparison of Mars SWS observations in the ν_2 CO_2 band (upper panel) with a synthetic model assuming terrestrial isotopic ratios (lower panel). Adapted from Lellouch et al. (2000)

The latter measurement demonstrated the complexity of the Martian atmosphere evolution history, which was not only driven by atmospheric escape, but also by condensation, and interaction with the surface. Hence, the $^{18}O/^{16}O$ lower than the terrestrial ratio is regarded as an evidence for an isotopic equilibrium between water and silicates, and an isotopic exchange between the two major oxygen reservoirs, water and CO_2. To better constrain this evolution history, it would be valuable to obtain more accurate determinations of the carbon and oxygen isotopic composition. This is difficult to obtain from ground-based observations, due to the terrestrial CO_2. However, ISO observed the full ν_2 band of CO_2 at 15 μm. Lellouch et al. (2000) adjusted the observed spectra assuming a terrestrial isotopic composition (Fig 2). Although satisfactory, the detailed comparison reveals some mismatches that could be fixed by modifying the CO_2 isotopic abundance. However, to obtain a high accuracy on the measured ratios, one needs to model the spatially non-uniform Martian temperature field (the observations encompass the whole Martian disk, i.e. dawn and dusk limbs, winter and summer hemispheres). This work is feasible using the temperatures derived from the publicly available Martian General Circulation Model[1] (Lewis et al. 1999), which reliably predicts the atmospheric temperatures.

3. EXOGENIC OXYGEN TO THE GIANT PLANETS

One of the most striking results obtained from ISO observations on planetary studies has been the discovery of H_2O in the stratospheres of the four Giant Planets (Feuchtgruber et al. 1997, 1998), and Titan (Coustenis et al. 1998), and of CO_2 in the stratospheres of Jupiter, Saturn and Neptune (Feuchtgruber et al. 1997, 1998). The presence of water — a highly condensible species in outer Solar System conditions — above the tropopause cold trap can only be explained by an external influx. CO_2 also condenses at the tropopause of Saturn and Neptune, and any internal sources in Jupiter are believed to be weak, since carbon-oxygen bonded species present in the planetary interior are effectively converted to CH_4 at shallow atmospheric levels. Therefore, the H_2O and CO_2 detections from ISO provided evidences for an exogenic supply of oxygen in the outer Solar System. Three different possible sources were proposed: (i) infall of interplanetary dust particles (IDPs), (ii) sputtering from icy rings and satellites, and (iii) rare impacts from kilometre-sized bodies.

All these results were based on SWS observations only. A recent study from Lellouch et al. (2002) combined the SWS and LWS observations of water. As shown in Fig. 3, the use of water lines with different intrinsic strength in the two instrumental ranges led to the conclusion that Jupiter stratospheric water is restricted to pressures less than 0.5 ± 0.2 mbar. If H_2O originated from a continuous source like infall of IDPs, it would be present in the whole stratosphere. Rather, the water must originate from an event recent enough for H_2O not to have diffused downwards, i.e. from the Shoemaker-Levy 9 impact, which occurred in 1994. This constitutes a remarkable achievement from a SWS and LWS combined analysis.

4. HYDROCARBON PHOTOCHEMISTRY

In the stratosphere of the Giant Planets and Titan, the ultraviolet solar flux photolysis CH_4 to produce CH, CH_2 and CH_3

[1] http://www-mars.lmd.jussieu.fr/mars/access.html

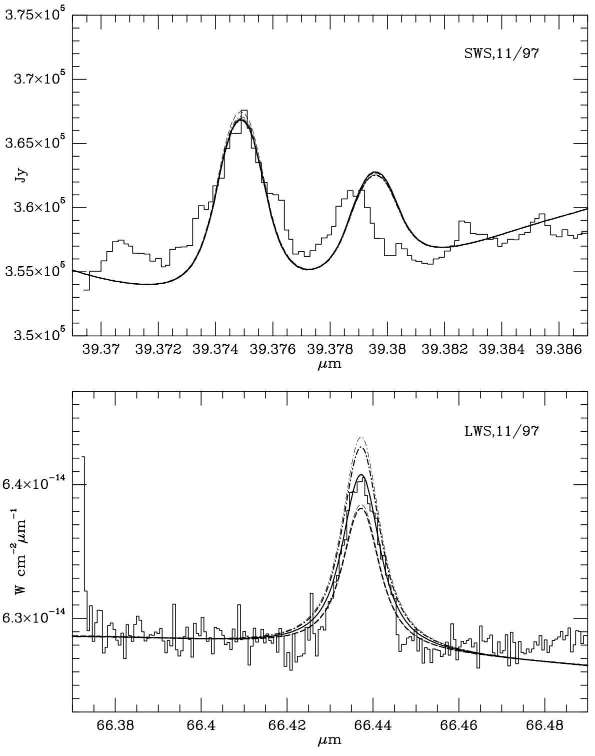

Figure 3. Comparison of SWS (upper panel) and LWS (lower panel) Jupiter observations in H_2O lines with three synthetic spectra: H_2O restricted to 0.5 mbar (solid line), 0.2 mbar (dashed line), and 0.8 mbar (dashed-dotted line). This shows the combined sensitivity of LWS and SWS data to the water vertical distribution. Adapted from Lellouch et al. (2002).

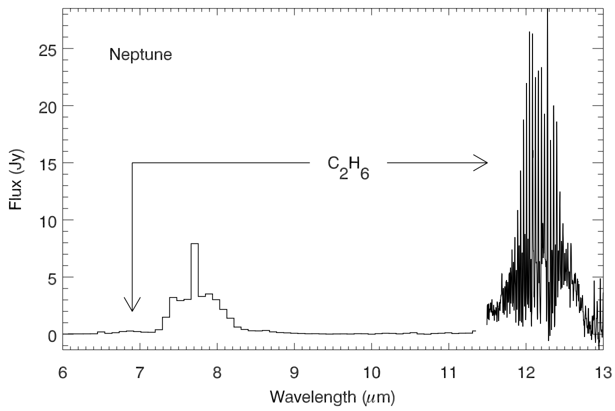

Figure 4. The ν_8 (6.9 μm) and the ν_9 (12.5 μm) C_2H_6 bands as observed by ISOPHOT ($\lambda < 11.4\,\mu$m) and SWS ($\lambda > 11.4\,\mu$m).

radicals in the upper stratosphere (1 μbar). These radicals then recombine to produce heavier hydrocarbons, such as C_2H_6, C_2H_4, C_2H_2, C_3- and C_4-species. The newly formed molecules are then transported to the whole stratosphere through eddy turbulent diffusion. The atmospheric column densities and vertical distributions thus result of two different processes, chemical production and eddy diffusion. Hence, in order to model the Giant Planet photochemistry, we must determine the relative abundance between hydrocarbon molecules, and how the abundance of an individual molecule evolve with altitude.

ISO-SWS observations led to many breakthroughs in the study of this hydrocarbon photochemistry, through the detections of many new species: CH_3 on Saturn and Neptune (Bézard et al. 1998, 1999), C_2H_4 on Neptune (Schulz et al. 1999), CH_3C_2H on Jupiter (Fouchet et al. 2000), CH_3C_2H and C_4H_2 on Saturn (de Graauw et al. 1997), and benzene (C_6H_6) on Jupiter, Saturn and Titan (Bézard et al. 2001, Coustenis et al. 2002). ISO-SWS also allowed us to determine the vertical distributions of C_2H_2 in Jupiter and Saturn (Fouchet et al. 2000, Moses et al. 2000). From these observations new photochemical models were developed (Moses et al. 2000, 2002).

The ISO observations could be further exploited, as some observed hydrocarbon emissions have not yet been interpreted. One example is the C_2H_6 ν_8 band at about 6.9 μm. This band shows an intensity different from the well-studied ν_9 band at about 12 μm. The two bands must then probe different atmospheric levels. A combined analysis could hence help to constrain the ethane vertical distribution, a highly valuable key to determine the strength of eddy mixing, as C_2H_6 is the most stable hydrocarbon product. On Jupiter and Saturn, it could be done from SWS data. On Neptune, the SWS-flux level is too low at $\sim 7\,\mu$m, but it is possible to combine the ISOPHOT and SWS data (Fig. 4). However, such an analysis will have to await for accurate spectroscopic data for the C_2H_6 ν_8 band.

CH_4 in Titan constitutes another illustration of a potentially highly fruitful combination between different emission bands. The methane abundance in Titan is not very well constrained, as quoted mixing ratios vary from 2 to 10%. This situation results from the degeneracy between atmospheric temperature and composition that has not yet been resolved from observations. With the level of uncertainty on the CH_4 abundance, it is difficult to accurately model Titan's photochemistry and thermal behaviour. ISOPHOT observations could help to further constrain Titan's CH_4 composition. Indeed, methane shows two different emission bands, the well-known ν_4 at 7.7 μm, and the ν_2 at 6.5 μm which cannot be observed from the ground. The two bands probe the same atmospheric pressure, and lie in a spectral region where the blackbody emission strongly varies with wavelength. Hence, a combined analysis of the two emission bands would help to determine simultaneously the atmospheric temperature and the CH_4 abundance.

5. JUPITER AND SATURN CLOUDS

In the cold upper tropospheres of the Giant Planets, several atmospheric species condense. In Jupiter and Saturn, we expect H_2O, NH_4SH and NH_3 to form cloud layers between a few bars and a few hundred mbars. This theoretical view is supported by the aspect, especially cloudy, of the two planets. However, it has been very difficult to determine the clouds actual chemical composition, as the two main expected ices, NH_3

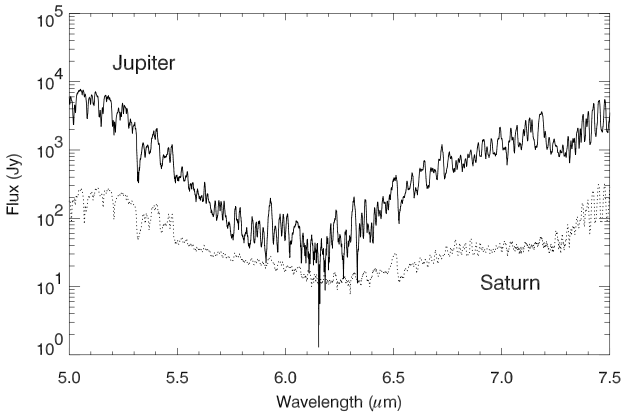

Figure 5. SWS observations of Jupiter (solid line) and Saturn (dotted line) in the 5–7-μm range.

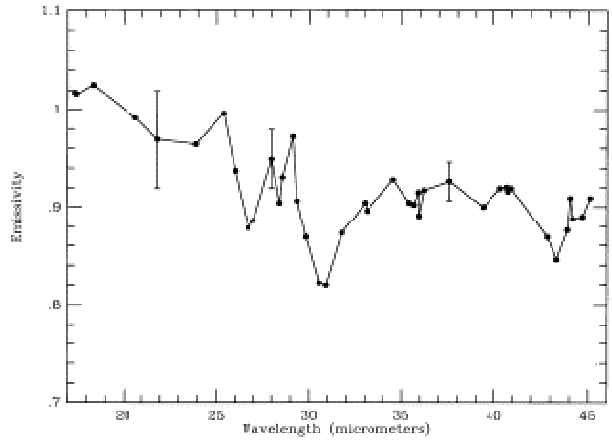

Figure 6. Emissivity spectra of the surface of Mars obtained from SWS observations. From Lellouch et al. (2000)

and H_2 ices, have eluded detection for a long time. ISO-SWS observations therefore provided a breakthrough, when Brooke et al. (1998) claimed the first detection of ammonia ice on Jupiter in the 3-μm range. However, this detection has been challenged by Irwin et al. (2001), since NH_3 ice exhibits absorption features at shorter wavelength than 3 μm which were not seen in Galileo/NIMS observations. More recently, Baines et al. (2002), also from Galileo/NIMS spectra, showed that NH_3 ice clouds do actually exist on the planet, but that they are very patchy, and represent only a small fraction of the planet's disk.

In the light of these latest results, the ISO-SWS observations of Jupiter at 3 μm should be reanalysed. The absorption present at this wavelength, initially attributed to NH_3 ice, could be the signature of another cloud component (H_2O and NH_4SH also absorb in this spectral region). Since solids usually exhibit broad absorptions, spectral features cannot be uniquely attributed to a given species. It is therefore necessary to simultaneously analyse different spectral regions where the suspected absorbent is active. For NH_3 ice, it would therefore be very valuable to conjointly analyse the 3-μm and the 6-μm spectral regions. The latter window is unaccessible from the ground, but, maybe for this very reason, the original ISO data in this spectral range have not been analysed at all. Thus a new study of Jupiter's cloud structure should be undertaken from the whole spectral range encompassed by ISO-SWS. This study could be coupled with the analysis of the same spectral range in Saturn's observations, since no result on Saturn's cloud structure from ISO observations has been released yet.

Clouds are intrinsically meteorological features, and hence vary in opacity and altitude with the different meteorological systems present on the planet. Therefore, spatially-resolved observations constitute the most fruitful way to analyse cloud structures. Such observations exist in the ISO database for Jupiter and Saturn, in the form of ISOCAM images. These observations are limited in terms of spatial resolution compared to that obtained from dedicated instruments aboard interplanetary missions (NIMS on Galileo or VIMS on Cassini), but they have some advantages too: a spatially uniform coverage (not achieved for Jupiter by NIMS) and a different wavelength range (2.5–11 μm for ISO against 0.7–5.2 μm for NIMS and VIMS). None of the ISOCAM observations has been analysed yet. They constitute a potential gold mine for planetary studies from the ISO archive.

6. Planetary Surfaces

6.1. Mars

It is believed that Mars' atmosphere has evolved through its history from a thick atmosphere of CO_2 to the currently thin ($\sim$ 6 mbar) atmospheric layer. A possible sink for the early Martian CO_2 is carbonate minerals. It is therefore interesting to look for carbonate spectral features in the ISO spectral range. Lellouch et al. (2000) conducted such a search from ISO-SWS data in the range 17-45 μm. Since Mars observations were highly saturated at these wavelengths, the absolute calibration of the spectrum becomes unreliable, and Lellouch et al. (2000) had to use an indirect method to estimate the surface emissivity. This method took advantage of the presence in the spectrum of several water rotational lines, whose relative contrast depends on both the water vapour abundance, and the surface emissivity. The resulting emissivity spectrum (Fig. 6) shows a strong minimum at 31 μm and two weak minima at 26.5 and 43.5 μm. These features may be compatible with the presence of carbonate minerals (see Fig. 13 of Lellouch et al. 2000). However, this result was viewed as very tentative by the authors, as the wavelength matches were not entirely satisfactory. In order to progress on this important issue for our understanding of Mars evolution, it would especially be interesting to improve the current data reduction for ISO-SWS high flux observations.

6.2. Titan

The near-infrared (1.0–5.0 μm) spectrum of Titan is shaped by methane absorptions. In the CH_4 bands centres, nearly all the solar flux is absorbed, while in the troughs between CH_4

bands, some sunlight reaches the surface and is reflected backward. In the last ten years, these atmospheric windows imaged from ground-based telescopes have revealed some geographical units of high and low albedo on Titan's surface [see for example Smith et al. (1996) or Combes et al. (1997)]. However, up to now, the reason for this difference in albedo has remained controversial. In particular, the chemical composition of the surface has not been determined, even if there are some hints for the presence of water ice. At 2.9 μm exists an atmospheric window which cannot be completely observed from the Earth, due to terrestrial atmospheric H_2O and CO_2 absorptions. However, it was observed in its full shape for the first time by ISO (Coustenis et al. 2000). Since water ice exhibits absorption features in this spectral range, these observations will be valuable to decipher the composition of Titan's surface.

7. CONCLUSION

The ISO observations of planetary objects already yielded a worth of first class results. However, we can still expect many new results from the use of ISO archive. Indeed, several images and spectra have not yet been fully analysed up to publication, and the ISO data will not be outdated by current or future interplanetary missions neither in spectral resolution power nor in sensitivity. The new results will depend on improvements of the current calibration, new spectroscopic data, and the willingness of the planetary community to undertake tedious and difficult analyses.

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ISO OBSERVATIONS OF ASTEROIDS, COMETS AND INTERPLANETARY DUST: RESULTS AND UNEXPLOITED OBSERVATIONS

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ABSTRACT

The scientific programme of ISO included observations of 40 asteroids, 16 comets, 6 planets, and 8 planetary satellites. In addition, programmes were conducted on zodiacal light, comet tails and trails, solar system dust, planetary satellites and rings, zodiacal bands and the Earth's circumsolar dust ring. In large surveys many more asteroids and comets were seen by chance, some of which were not even discovered at the time of the observations. ISO's results contributed in many field of solar system research. A connection via crystalline silicates has been established between old stars, proto-planetary disks and our own solar system (astro-mineralogy). Thermal infrared spectroscopy allowed to see the interrelations within the solar system, between asteroids, comets and meteorites. In this context, many asteroid spectra have been taken and analysed. From additional photometry, the size, albedo and thermal properties have been derived through radiometric techniques. Most of the comet programmes concentrated on Hale-Bopp, Hartley 2 and Encke: Crystalline silicates, water ice, new parent molecules, dust production rates, development of coma, trail formation and other aspects have been studied in great details.

But large samples of photometric and spectroscopic asteroid observations remain to be analysed and interpreted. The comet studies and the modeling efforts could certainly be extended to fainter targets. The effects of space weathering and aqueous alteration of surface materials could be studied and a better understanding of the commonalities of asteroid near-IR taxonomy and mid-IR spectroscopy is possible, especially now that different laboratory studies of meteorites and mineral mixtures have become available.

But many of the key observations are still hidden in the ISO data archive and exciting results can be expected in the future.

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

1. INTRODUCTION

The solar system programme of ISO comprised about 6 % of the total ISO science time (only 1.4 % in terms of number of observations). The expectations from the astronomical community were not very high in relation to asteroids, comets and planets. During the last decades many satellites studied several of our neighbouring objects in great detail, in-situ and in close fly-bys. So what could be expected from a 60-cm telescope circulating just outside the Earth' atmosphere? Yet now, the ISO results are on their way to making a big impact on our knowledge of objects on our celestial "doorstep".

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 conference contribution by Fouchet. 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 and compared to the proposed original ideas as given in the publicly available abstracts through the ISO Data Archive (IDA). In the second part, ISO observations have been looked at from a different angle: What ideas are already covered by publications and which ones are not covered? Open topics are presented and possible obstacles in the data analysis are discussed. In the last part the promising future fields on solar system science with ISO data are summarised.

2. ISO'S SOLAR SYSTEM OBSERVATIONS

In the IDA one can find dedicated observations on Mars, Jupiter, Saturn, Uranus, Neptune and Pluto. In total, 8 planetary satellites have been seen: Deimos, Io, Europa, Ganymede, Callisto, Titan, Iapetus and Charon (Charon only together with Pluto). The comet programme consisted of 19 targets, in many cased accompanied by dedicated background observations: 29P/Schwassmann-Wachmann 1, 2P/Encke, 7P/Pons-Winnecke, 22P/Kopff, 30P/Reinmuth 1, 32P/Comas Sola, 43P/-Wolf-Harrington, 45P/Honda-Mrkos-Pajdusakova, 46P/Wirtanen, 55P/Tempel-Tuttle, 65P/Gunn, 81P/Wild 2, 103P/-Hartley 2, 117P/Helin-Roman-Alu 1, 126P/IRAS, 128P/-Shoemaker-Holt 1B, 133P/Elst-Pizarro, (1995 O1) P/Hale--Bopp, and (1996 B2) C/Hyakutake.

ISO observed 40 asteroids in dedicated programmes: 1 Ceres, 2 Pallas , 3 Juno, 4 Vesta, 6 Hebe, 9 Metis, 10 Hygiea, 13 Egeria, 20 Massalia, 46 Hestia, 52 Europa, 56 Melete, 65 Cybele, 77 Frigga, 106 Dione, 114 Kassandra, 150 Nuwa, 308 Polyxo, 313 Chaldaea, 336 Lacadiera, 498 Tokio, 511 Davida, 532 Herculina, 624 Hektor, 804 Hispania, 911 Agamemnon, 914 Palisana, 1172 Aneas, 1437 Diomedes, 1980 Tezcatlipoca, 2060 Chiron, 2062 Aten, 2201 Oljato, 2703 Rodari, 3200 Phaethon, 3671 Dionysus, 3840 Mimistrobell, 4015 Wilson-Harrington, 4179 Toutatis, and 5145 Pholus.

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Among the comet-asteroid group are 9 objects which are considered as "transition objects": Toutatis, Pholus, Dionysus, Tezcatlipoca, Chiron, Oljato, Phaeton, Wilson-Harrington, and Elst-Pizarro (the last 2 were part of a comet programme).

ISO also observed different extended structures: Solar system dust in form of zodiacal light, dust debris in the outer solar system and the Earth's dust ring, comet tails and trails and planetary rings.

Additionally, 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.

The solar system observations can easily be found in the IDA by specifying the target name given by proposer, for example `%ceres%` (the `%` sign is the IDA wildcard). There is one additional option for the search by name: Tracked ISO observations had a specific ISO generic number, which started with `20` for the planets, `21` for the asteroids and `22` for the comets. Examples: `200600` corresponds to Saturn, `200606` to Titan, `2100511` to the asteroid Davida and `220017` to the comet P/IRAS. To find all observations connected to an individual programme one can also specify the observer (`OBSID`) and/or proposal identification (`PROPID`), as given in the tables in the Appendix. Caution: The following targets have **not** been observed in *solar system tracking mode*: Zodiacal light, tails and trails of comets, some planets and satellite observations, the Earth's circumsolar dust ring, Kuiper belt objects, solar system background measurements and many calibration observations on asteroids. Background observations of moving targets were either taken at a neighbouring position or at the original position of the target, 1 or 2 days later when the source had moved out.

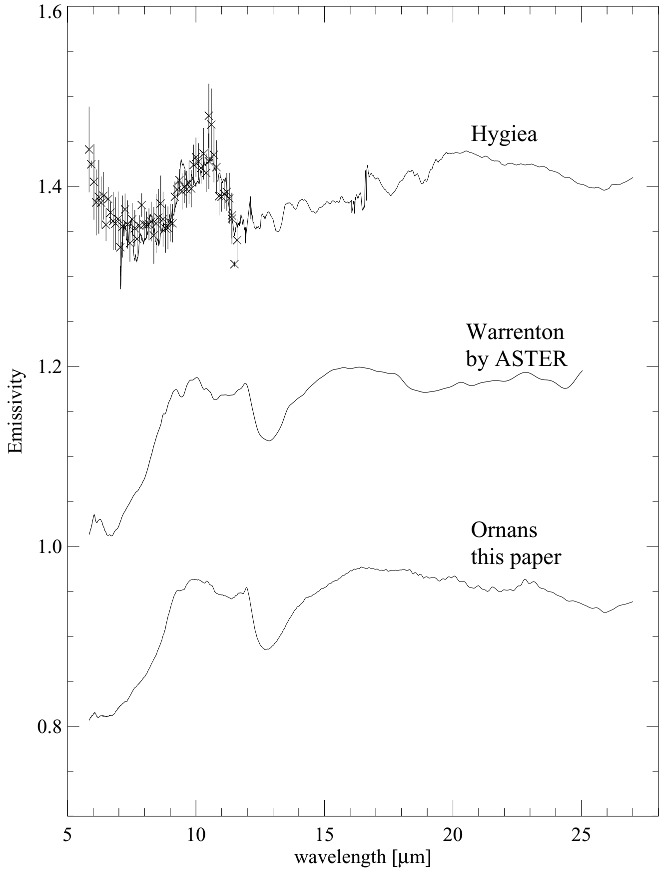

Figure 1. Comparison between the ISO spectrum of Hygiea and different meteorite samples (Barucci et al. 2002).

3. PROPOSALS AND RESULTS

3.1. ASTEROIDS

ISO spent 99.2 hours of observing time on dedicated asteroid programmes, based on 3 Guaranteed (GT) and 10 Open Time (OT) proposals. Data were taken with all 4 instruments and in many different observing modes. Asteroid spectroscopy included PHT-S, SWS, LWS and CAM-CVF measurements. The main goals were the identification of surface minerals, composition, 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.

First results on PHT-S observations of bright main-belt asteroids (Dotto et al. 1999, 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. 1). Dotto et al. (2002) described the similarities between low-albedo asteroids and different meteorites which have been analysed in new laboratory experiments.

From photometric results one can derive the asteroid size and albedo through radiometric techniques. A new thermo--physical model (TPM, Lagerros 1996, 1997, 1998) allowed the detailed characterisation of the thermal behaviour of the surface and the derivation of physical parameters, like cratering, surface roughness or porosity (e.g. Müller et al. 1999a). From large samples of photometric measurements at different wavelength and observing geometries it was also possible to determine the thermal inertia and thermal conductivity (Müller & Lagerros 1998). Recently, Müller & Lagerros (2002a) demonstrated that the new TPM matches all kind of thermal IR measurements from different observing geometries with a high accuracy. The TPM efforts resulted also in the establishment of asteroids as reliable calibrators for the far-infrared wavelength range (Müller & Lagerros 1998, 2002a, 2002b).

Deep ISOCAM observations at 12 μm in the ecliptic plane allowed for the first time the direct determination of the asteroid-size frequency distribution (Tedesco & Desert 2002). The study revealed 160$\pm$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 $1.2\pm0.5\times10^6$ kilometer-sized asteroids in our solar system, twice as many as previously believed.

The already published part of ISO's solar system programme included also studies on the cometary activity in asteroids (Harris & Davies 1999), a large programme on Kuiper-belt objects (Thomas et al. 2000) and a small programme on the derivation of asteroid surface parameters from thermal polarimetry measurements at 25 μm (Lagerros et al. 1999, Müller et al. 1999b).

3.2. Comets

ISO performed 153.2 hours of observing time on dedicated comet programmes, based on 4 GT and 16 OT proposals. More than half of the comet programme was dedicated to the target of opportunity Hale-Bopp.

The most spectacular results were derived from Hale-Bopp spectra, taken at different distances from the Sun (Crovisier et al. 1996; Crovisier et al. 1997; Leech et al. 1999): Pristine grains of Mg-rich pyroxenes were discovered from spectra taken at perihelion (Wooden et al. 1997). Wooden et al. (1999) presented also the general silicate mineralogy of the dust in the inner coma of Hale-Bopp pre- and post-perihelion. The observations of volatile molecules have been discussed by Crovisier (1997). The dust production rate at 2.9 AU from the Sun was analysed by Lellouch et al. (1998). They also presented evidence for water ice.

The thermal emission from the dust coma has been studied by Hanner et al. (1997) on the basis of photometric measurements. They determined the composition of the silicate grains through dust models. The possibilities and limitation of broad-band photometry together with sophisticated coma models are presented and discussed in Grün et al. (2001), based on large data sets of ISOPHOT observations from 2 to 200 μm. The authors determined the color temperatures, dust production rates, dust-to-gas mass ratios, analysed the silicate features and gave indications for crystalline water ice grains.

Through the Hale-Bopp spectrum a connection was established between our solar system, circumstellar dust and the interstellar medium (Waelkens et al. 1997). It was also named "The gemstone connection: ISO links comets to stars and Earth's origin" (Crovisier et al. 1997). Malfait et al. (1998) and Molster et al. (1999) even established the new field of "astro-mineralogy" which describes the different states of silicate dust under different conditions and connects the crystalline silicates which are found around young and old stars, in proto-planetary disks and which are also very common in our own solar system (see Fig. 2).

Three objects were analysed in the context of comet trails: Hale-Bopp (Peschke et al. 1997; Müller et al. 2002), P/Kopff (Davies et al. 1997) and P/Encke (Reach et al. 2000). The studies included also aspects like the description of mass loss rates, trail variations and the dynamical behaviour of small and large particles. For P/Encke also the physical properties of the nucleus, its size, rotation period, albedo and phase angle behaviour, were derived and presented by Fernández et al. (2000).

Further infrared spectroscopic observations (PHT-S) of comet Hartley 2 are included in the work by Colangeli et al.

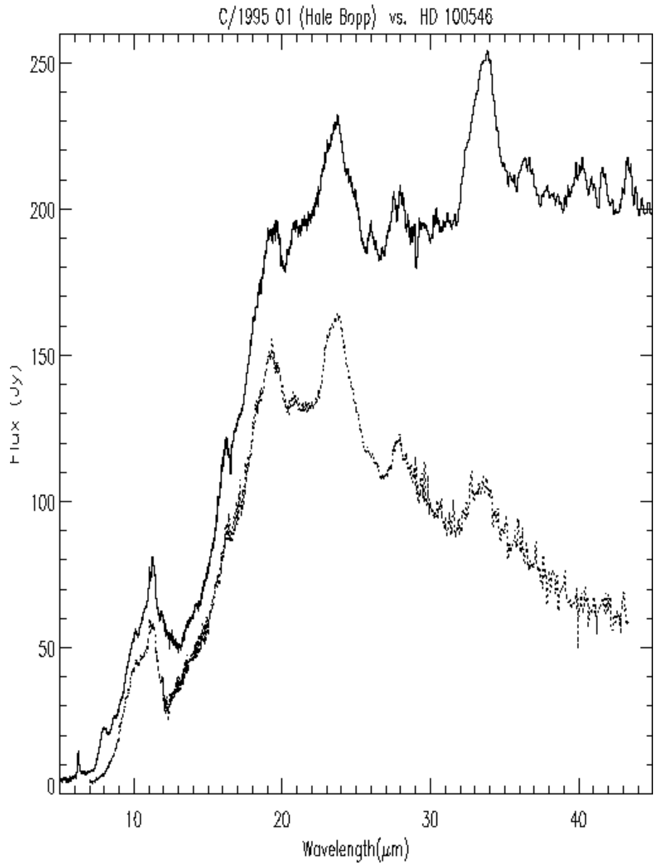

Figure 2. Comparison between the ISO-SWS spectrum from the comet Hale-Bopp (courtesy Crovisier et al. 1996, dotted line) with the spectrum of the young star HD 100546 (Malfait et al. 1998, full line).

(1999). From ISOCAM imaging mode the comets Gunn and Wirtanen (Colangeli et al. 1998) and Hartley 2 and Encke (Epifani et al. 2001) have been studied. They modeled the comet tail, the evolution of dust coma, grain sizes and velocities and they gave implications for meteoroid streams.

3.3. Extended Structures

The 4 GT and the 5 OT proposals in this field required 71.9 hours of ISO time. The main goals were related to zodiacal light: Global mapping, seasonal variations, the search for arcminute structures in the zodiacal dust cloud, the search for sub-arcminute structures in the zodiacal bands, general properties and mineralogy of the solar system dust. Specific topics were covered in additional programmes, like the search for dust debris in the outer solar system, observations of the Earth's circumsolar dust ring, mapping of specific COBE or ecliptic pole regions.

An ISOCAM CVF mid-infrared spectrum of the zodiacal light (Reach et al. 1996) showed no spectral features brighter than 15 % of a blackbody fit with 261.5$\pm$1.5 K. The comparison to models revealed acceptable fits only for 'astronomical silicate', ruling out many other potential components of the zodiacal light. They also presented a hint of a 9-11 μm feature, which was so far not confirmed by the large database of PHT-S measurements (Ábrahám et al. 1997a & Ábrahám, priv. comm.). The results from a large ISOPHOT programme were presented by Ábrahám et al. (1997b; 1999b; 1999c). The measurements at 25 μm resulted in 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. Ábrahám et al. (1999a) also determined the blackbody-like spectral shapes with no obvious spectral features. The fitted black body temperatures increase with ecliptic latitude and decrease with distance from the Sun in the range 260-290 K.

3.4. Serendipitous Observations

During the ISO mission many surveys and large observing programmes were conducted. Additionally, the parallel and serendipity data –taken in non-prime instrument modes or while the satellite was slewing from one target to the next– contain by chance many interesting sources (Müller 2001). Surveys with observations close to the ecliptic plane, performed by ISOCAM and ISOPHOT, include asteroids, comets and zodiacal light measurements. 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: improvement of the flux calibration through a few well-known asteroids and, planets and scientific investigations in terms of diameter and albedo determination and comet modeling. The nine slews over Hale-Bopp showed that the large particles are concentrated in the nucleus-trail transition region.

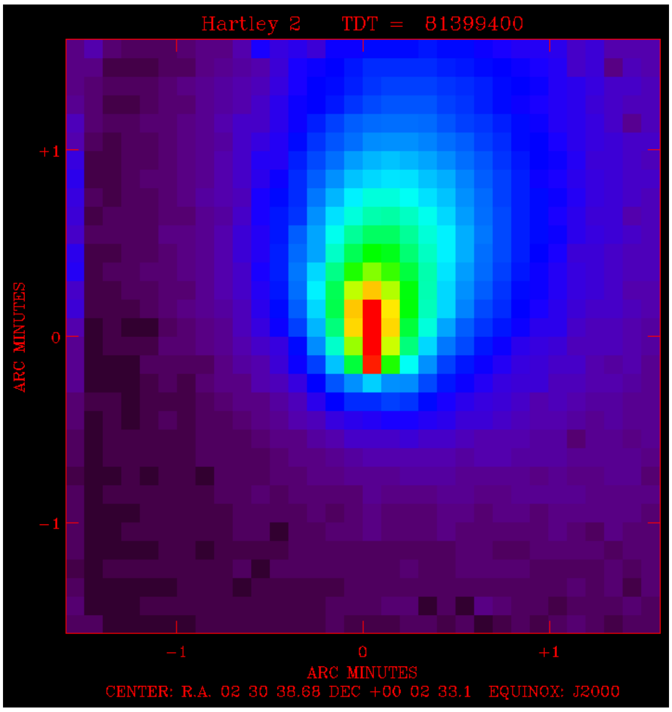

Figure 4. Comet Hartley-2, serendipitously observed in the ISOCAM parallel mode at 6.7 μm.

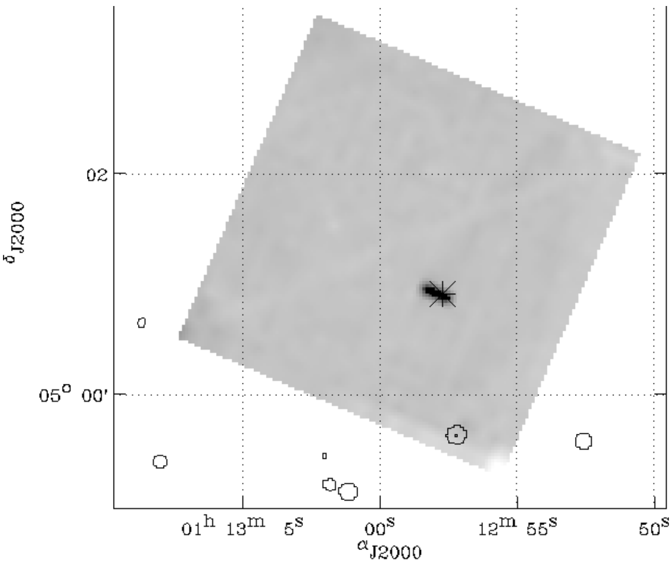

Figure 3. Asteroid 272 Antonia, serendipitously observed at 6.7 μm in the ISOCAM parallel mode.

4. UNEXPLOITED OBSERVATIONS

4.1. Asteroids

Several bright asteroids have been observed many times for calibration purposes. These observations contain scientifically useful information, but the data analysis is more difficult and needs expert support. But well-elaborated asteroid models are available to convert even individual thermal fluxes into scientific quantities or to combine ISO data with information from other programmes.

The most promising field is the asteroid spectroscopy. CAM-CVF, PHT-S, SWS and LWS have measured more than 10 different asteroids in different wavelength regions and resolutions. Combined with recent laboratory data, this is the basis for surface mineralogy, to establish better connections to comets, to meteorites and to the solar system dust cloud, and to analyse space weathering and surface alteration processes. Difficulties in the spectroscopic analysis are related to the faint low-contrast emission and absorption features which extend in many cases over 2 or more wavelength bands of the spectrometers. The cross-identification with laboratory spectra is also a non-trivial task. Grain-size distributions and deviating physical conditions modify the spectral features in a complicated way and allow often only a qualitative comparison.

4.2. Comets

Up to now, only 6 out of 19 observed comets appear in literature. One of the "missing" targets –Temple-Tuttle– was even part of a target-of-opportunity programme. About 10 comets are listed in the context of nucleus and coma studies. Based on these observations one could derive radiometric sizes and/or dust production rates. In addition to Hale-Bopp, 6 comets have spectroscopic data, which have so far not been analysed. Information on composition, parent molecules, silicates, carbonaceous material and much more is still hidden in the spectra. The IDA contains data of 4 additional targets which are mentioned in the programmes of tail and trail studies and several comets have still unpublished ISOCAM images.

Obstacles in the data reduction can be expected in cases of faint comets. Very faint extended emission and difficulties in some observing modes and instrument configurations add to the complexity of these data.

4.3. Extended Structures

The IDA contains large samples of dedicated and serendipitous observations of the sky at different latitudes and at different solar elongations. Improvements of the existing zodiacal light models might be possible and new structures, like asteroidal bands, could still be hidden in the observations. The combination of all spectroscopic programmes from all instruments on solar system dust could be used to clarify the question about spectroscopic features in the zodiacal light spectrum. The variety of observing modes, difficulties in calibration of extended emission and faint flux levels require in some cases instrument experts to solve still existing calibration problems for extended faint structures.

4.4. Serendipitous Observations

Similar to the analysis of the ISOPHOT Serendipity Survey, the extraction methods are currently applied to the ISOCAM Parallel survey (see Fig. 3 and 4) and to the galactic plane survey ISOGAL. But many observations in the IDA still contain SSOs, serendipitously located in ISO's field-of-view and measured at wavelengths inaccessible from ground.

5. CONCLUSIONS

The most promising future fields of solar system science from existing ISO data on asteroids, comets and zodiacal light are:

- Analysis of serendipitous observations
- Analysis of asteroid spectra in comparison with laboratory measurements
- Analysis of intermediate and faint comets
- Data base of zodiacal light measurements and final spectroscopic analysis

Further unexpected results on solar system science might still be hidden in the large collection of high quality data in the IDA.

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APPENDIX: Performed Solar System Proposals

In the following all performed solar system proposals on asteroids, comets and extended structures are listed. The tables include the original title of the proposal, the OBSID, the PROPID (the % sign is the IDA wildcard), total observing time (in sec.) and the number of observations in the archive. The proposals are separated in `Guaranteed Time` (first part) and `Open Time` (second part).

Guaranteed Time Proposal Title	OBSID	PROPID	time	no.
Observations of Galilean Satellites and Asteroids with ISO	THENCRE	GALSAT	4214	16
The Mineralogy and Chemistry of the Major Asteroid Classes	ASALAMA	AST_MIN	17679	7
Vesta Lightcurve Observations	BESCHULZ	VESTALC1	18925	39
Mapping of Dust and Parent Molecules in Periodic Comets with ISOCAM	FSIBILLE	COMETCAM	23525	20
Spectroscopic Observations of Periodic Comets with LWS and SWS	JCROVISI	COMETS	80656	26
Comet Observations with ISOPHOT: Study of Bare Nuclei, Onset of Activity, Composition of Comets and Dust Production	EGRUEN	COMETS%	86080	145
On the Trail of Tails: Imaging the Trails of Comets P/Kopff, P/Gunn and P/Churyumov-Gerasimenko with CAM	JDAVIES	JKDTRAIL	43644	12
Is There Sub Arc Minute Structure in the Zodiacal Bands?	JDAVIES	JDKBANDS	3434	1
Global Mapping, Seasonal Variation and Search for Arcminute Structure of Zodiacal Light	CLEINERT	PG4L3B_A, GLOBAL%	69948	283
Properties of Solar System Dust	CLEINERT	PROPERT%	104296	144
SWS Observations of the Zodiacal Light: Solar System Mineralogy	PMORRIS	GLASHAUS	8779	1

Open Time Proposal Title	OBSID	PROPID	time	no.
IR Observations of Rosetta Asteroidal Targets: Albedo and Diameter Measurements of the Rosetta Target Asteroids	CBARBIER	ROSAST	1976	4
Dark, Volatile-Rich Asteroids: Possible Relation to Comets	MBARUCCI	ASTEROI%	74127	51
The Composition of D-Type Asteroids	AFITZSIM	DTYPE	2888	6
Rosetta Target Asteroids	MFULCHIG	AROSETTA	7368	8
Cometary Activity in Asteroids	AHARRIS	ASTEROID	17952	21
Survey of Kuiper Belt Candidates	WIP	KUIPER%	100326	66
Spectroscopic Studies of Volatile-Rich Asteroids	HLARSON	ASTEROID	22478	7
Polarimetry of Asteroids	TMUELLER	AST_POL%	4691	2
Comprehensive Investigation of the Thermal Properties and Rotational Thermal Variability of the Pluto-Charon Binary and Chiron	ASTERN	CHIR_PL	7360	14
Asteroid Size-Frequency Distribution	ETEDESCO	ASTSFDIS	77003	10
Study of Carbonaceous Matter in Comets	DBOCKELE	COMET_CC	18114	3
Cometary Nuclei and Trails Study: Analysis of Comets also in Preparation to Rosetta	LCOLANGE	CONTRAST	18122	13
Extended Remote Analysis of Coma and Trails: Analysis of Comets also in Preparation to Rosetta	LCOLANGE	EXTRACT	23116	11
ToO: Observations of Unexpected Comets	JCROVISI	NEWCOMET	82747	24
ToO: Spectroscopic Observations of Comets	JCROVISI	NEWCOM_2	25486	8
ToO: ISOPHOT Observations of a Bright Comet Coma: Composition and Dust Production	EGRUEN	TOOCOMBA	24019	101
ToO: ISOPHOT Observations of a New Comet: Coma Composition and Dust Production	EGRUEN	TOOCOM_2	8732	26
Observation of Cometary Nuclei	PLAMY	COMETNU%	24878	102
ToO: The Nucleus of a New Bright Comet	PLAMY	COMETNU%	18054	28
Large-Scale Observations of Scattered Sunlight and Thermal Emission in the Tails of Bright Periodic Comets	CLISSE	PERBRCO	21261	6
Spectral Analysis of "Carbon-Chain Depleted" Comets	DOSIP	PROP_COM	10027	4
Spectral Analysis of "Carbon-Chain Depleted" Comets: Spectral Studies of P/Wolf-Harrington	DOSIP	COM_SPEC	11797	6
ToO: Cometary Comae in the IR: Dimensions, Structures and Composition	SPESCHKE	FIRCOMAE	3120	3
Imaging the Source of Cometary Dust Trails	WREACH	COMTRAIL	9629	2
Distributed Sources in Cometary Comae: Column Density Profiles of Potential Parent Molecules	RSCHULZ	D_SOURCE	2362	2
Characterization of the Size of Short-Period Comet Nuclei: Short-Period Comet Nuclei	JSCOTTI	COMNUC	6180	5
Search for Dust Debris in the Outer Solar System: Mapping and Fluctuation Search	SVWB	3KBMAP	7374	6
Observations of the Earth's Circumsolar Dust Ring	SDERMOTT	ETRING_1	8361	43
Probing the Zodiacal Cloud by Observing the Ecliptic Poles	SDERMOTT	ZCPOLES1	6666	20
Mapping of Cobe Fields	CLEINERT	PROP_MAP	28334	23
Spectrum of the Zodiacal Light	WREACH	ZODYSP	21827	6