ISO: THE MISSION AND ITS RESULTS

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Abstract

The *Infrared Space Observatory (ISO)* was the world's first true orbiting infrared observatory. Equipped with four highly-sophisticated and versatile scientific instruments, it was launched by Ariane in November 1995 and provided astronomers world-wide with a facility of unprecedented sensitivity and capabilities for a detailed exploration of the universe at infrared wavelengths (2.5–240 μm). Its 60 cm-diameter telescope was cooled by superfluid liquid helium to temperatures of 2–4 K. The mission was a great technical, operational and scientific success with most satellite sub-systems operating far better than specifications and with its scientific results impacting practically all fields of astronomy. During its routine operational phase, which lasted until April 1998 - almost a year longer than specified, ISO successfully made some 30000 individual imaging, photometric, spectroscopic and polarimetric observations ranging from objects in our own solar system right out to the most distant extragalactic sources. ISO's data archive – `www.iso.vilspa.esa.es` – opened to the community in December 1998 and, including data from calibration and auxiliary mode observations, contains about 100,000 data sets. A summary of the mission – including some of its highlights – is presented, followed by a description of current and future activities, focussing on those most relevant to the Herschel Space Observatory.

Key words: ISO – Telescopes – Instrumentation: miscellaneous – Space vehicles: instruments – Infrared: general

1. Introduction

ISO results from a proposal made to ESA in 1979. After a number of studies (assessment, 1979; pre-phase A, 1980; phase A, 1982), ISO was selected in 1983 as the next new start in the ESA Scientific Programme. Following a "Call for Experiment and Mission Scientist Proposals", the scientific instruments were selected in mid 1985. The two spectrometers, a camera and an imaging photo-polarimeter jointly covered wavelengths from 2.5 to around 240 μm with spatial resolutions ranging from 1.5″ (at the shortest wavelengths) to 90″ (at the longer wavelengths). The satellite design and main development phases started in 1986 and 1988, respectively with Alcatel (Cannes, F, formerly Aerospatiale) as prime contractor. ISO (Figure 1) was given a perfect launch in November 1995 by an Ariane 44P vehicle. All went very smoothly in orbit and, at a wavelength of 12 μm, ISO was one thousand times more sensitive and had one hundred times better angular resolution than IRAS. Routine scientific operations commenced in February 1996 and continued until April 1998. All data were re-processed with the 'end-of-mission' calibration to populate the first homogeneous ISO Data Archive, which opened to the community in December 1998. By August 1999, all data had entered the public domain. ISO is now in a post operations phase designed to maximise the scientific exploitation of its vast data set and to leave behind a homogeneous archive as a legacy to future generations of astronomers, especially those preparing and interpreting Herschel observations.

Figure 1. ISO Flight model in ESTEC Large Space Simulator.

Section 2 presents an overview of the ISO mission, while sections 3 and 4 address, respectively, its technical and scientific highlights.

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Table 1. Main characteristics of the ISO instruments

Instrument (Principal Investigator)	Wavelength Range and Main Function	Outline Description	Spectral Resolution	Spatial Resolution
ISOCAM (C. Cesarsky, CEA-Saclay, F)	2.5–17μm Camera and polarimeter	(i) 32 × 32 array for 2.5–5 μm (ii) 32 × 32 array for 4.5–17 μm	(i) 11 filters $2 \leq R \leq 20$ circular var. filter R∼40 (ii) 10 filters $2 \leq R \leq 14$ circular var. filter R∼40	Choice of 1.5, 3, 6 or 12″ per pixel
ISOPHOT (D. Lemke, MPI für Astronomie Heidelberg, D)	2.5–240μm Imaging photo-polarimeter	(i) Multi-aperture, multi-band photopolarimeter (3–110 μm) (ii) Far-infrared camera 30–100 μm: 3 × 3 pixels 100–240 μm: 2 × 2 pixels (iii) Spectrophotometer (2.5-12 μm)	(i) 14 filters $2 \leq R \leq 15$ (ii) 6 filters $1 \leq R \leq 3$ 5 filters $2 \leq R \leq 3$ (iii) grating, R∼90	(i) Choice of diffraction-limited to 3′ apertures (ii) 43″ per pixel 89″ per pixel (iii) 24 × 24″ aperture
ISO–SWS (Th. de Graauw, Lab. for Space Research, Groningen, NL)	2.38–45.2μm Short wavelength spectrometer	(i) Two gratings 2.38–45.2 μm (ii) Two Fabry-Pérot interferometers 11.4–44.5μm	(i) R∼1000–2000 (ii) R∼3×10^4	(i) 14 × 20″, 14×27″ 20×27″, and 20 × 33″ (ii) 10 × 39″, and 17 × 40″
ISO–LWS (P. Clegg, Queen Mary and Westfield College, London, UK)	43–196.7μm Long wavelength spectrometer	(i) Grating (ii) Two Fabry-Pérot interferometers	(i) R∼200 (ii) R∼10^4	1′.65 diameter aperture

2. Mission design

2.1. Scientific Instruments

The scientific payload consisted of four instruments: an imaging photopolarimeter, ISOPHOT (Lemke and Klaas 1999, Lemke et al. 1996); a camera, ISOCAM (Cesarsky 1999, Cesarsky et al. 1996); a long wavelength spectrometer, LWS (Clegg 1999, Clegg et al. 1996); and a short wavelength spectrometer, SWS (de Graauw 1999, de Graauw et al. 1996). Each instrument was built by an international consortium of scientific institutes and industry, headed by a Principal Investigator, using national funding. Although developed separately, the four instruments were designed to form a complete, complementary and versatile common-user package.

Overall, the payload provided photometry and imaging (some polarisation) in broad and narrow spectral bands from 2.5–240 μm with spatial resolutions or fields of view from diffraction-limited to 3′. Full spectroscopic coverage (at medium and high spectral resolution) was available from 2.5–200 μm, providing a wealth of diagnostics for physical and chemical conditions in many regimes. Table 1 summarises the main characteristics of the instruments.

The instruments were mounted behind the primary mirror. Each one occupied an 80° segment of the cylindrical volume available. The 20′ total unvignetted field of view of the telescope was distributed radially to the four instruments by a pyramid mirror. Each experiment received a 3′ unvignetted field, centred on an axis at an angle of 8.5′ to the main optical axis, i.e. the instruments viewed separate areas of the sky. Switching between them involved repointing the satellite.

Only one instrument was operational in prime mode at a time. However, when the camera was not the main instrument, it was used in parallel mode to acquire extra astronomical data (Siebenmorgen at al. 2000, Ott et al. 2000). Whenever possible, the long-wavelength channel of the photometer was used during satellite slews. This serendipity mode (Stickel et al. 2000) led to a partial sky survey (sky coverage of approximately 15%) at wavelengths centred at 170 μm, a spectral region not covered by the IRAS survey. After launch, a parallel/serendipity mode was added for the LWS (Lim et al. 2000), in which narrow-band data were obtained at 10 fixed wavelengths in parallel with the main instrument and also during slews.

2.2. Satellite design

The ISO satellite (Kessler et al. 1996, Kessler 1999), shown in cutaway view in Figure 2) consisted of a payload module and a service module, which provided the basic spacecraft functions. The payload module carried the conical sunshade and the two star trackers. Overall, ISO was 5.3 m high, 2.3 m wide and had a mass of approximately 2500 kg at launch.

The payload module was essentially a large cryostat. Inside the vacuum vessel was a toroidal tank, which at launch was filled with over 2300 litres of superfluid helium. Some of the infrared detectors were directly coupled to the helium tank and were held at a temperature of be-

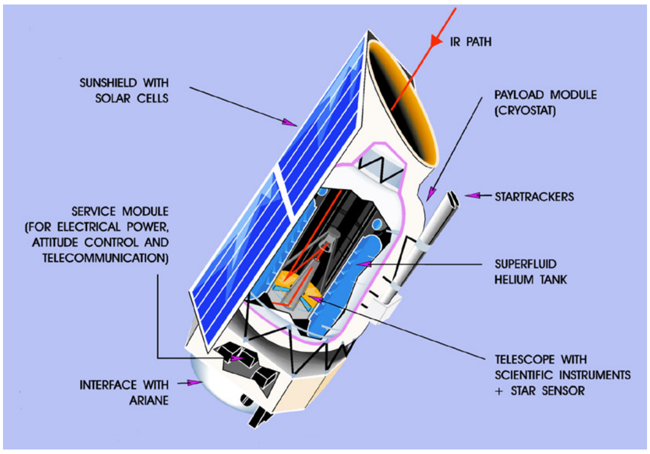

Figure 2. Schematic cut-away view of ISO.

low 2 K. All other units were cooled by means of the cold boil-off gas from the liquid helium. This was first routed through the optical support structure, where it cooled the telescope and the scientific instruments to temperatures of around 3 K. It then passed along the baffles and radiation shields, before being vented to space. Above the main helium tank was a small auxiliary tank (of volume about 60 litres); this contained normal liquid helium and met all of ISO's cooling needs for the period immediately prior to launch. Mounted on the outside of the vacuum vessel was a sunshade, which prevented direct sunlight from entering the cryostat.

Suspended in the middle of the tank was the telescope, which was a Ritchey-Chrétien configuration with an effective aperture of 60 cm. The optical quality of its mirrors permitted diffraction-limited performance at a wavelength of 5 μm. Stringent control over straylight, particularly that from bright infrared sources outside the telescope's field of view, was necessary to ensure that the system's sensitivity was not degraded. This was accomplished by means of the sunshade, the Cassegrain and main baffles, a light-tight shield around the instruments and imposition of observing constraints (see section 2.3).

The load path to the launcher was provided by the service module, which also included the array of solar cells generating some 600 W mounted on the sun shield, and subsystems for thermal control, data handling, power conditioning, telemetry and telecommand, and attitude and orbit control. The last item provided the three-axis stabilisation to an accuracy of around an arc second, and also the raster pointing facilities needed for the mission. It consisted of sun and earth sensors, star trackers, a quadrant star sensor on the telescope axis, gyros and reaction wheels, and used a hydrazine reaction-control system. The downlink bit rate was 32 kbit/s, of which about 24 kbit/s was dedicated to the scientific instruments.

2.3. Orbit and Sky Coverage

ISO's operational orbit had a period of just under 24 hours, an apogee height of 70600 km and a perigee height of 1000 km. In this orbit two ground stations were needed to provide visibility of the satellite from the ground for the entire scientifically-useful part of the orbit – the nearly 17 hours per day spent outside the Earth's van Allen belts of trapped protons and electrons. ESA provided one ground station, located at Villafranca, Spain. The second ground station –located at Goldstone, California– and associated resources were contributed by the National Aeronautics and Space Administration (NASA), USA; and the Institute of Space and Astronautical Science (ISAS), Japan.

For thermal (protecting the spacecraft from sunlight) and power (illuminating the solar arrays) reasons and also to prevent straylight from reaching the instruments, there were constraints on the allowed pointing directions for the satellite. ISO always pointed only in a direction from 60°–120° away from the Sun. Additionally, it was neither pointed closer than 77° to the Earth limb, nor closer than 24° to the Moon. Jupiter was usually kept away from the optical axis by at least 7° unless, of course, Jupiter or one of its moons was the target of an observation. The sum of these constraints meant that, typically, only some 10-15% of the sky was available to ISO at any instant.

The orbit also precessed rather slowly. Thus, in the nominal 18-month long mission, there would have been an area of sky, centred on the Taurus-Orion region, inaccessible to ISO. Happily, the cryogen lasted longer than specified and almost all the sky was visible to ISO at some time during the mission.

2.4. Observing Time

Approximately 45% of ISO's time was reserved for those parties contributing to the development and operation of the scientific instruments and the overall facility, i.e. the instrument teams, the Mission Scientists, the Science Operations Team, and ESA's international partners, ISAS and NASA. Preparation of the programme for this guaranteed time started in the mid-80's. Two workshop-style meetings –each attended by about 100 guaranteed time astronomers– were held in Schloss Elmau in December 1989 and December 1990 to discuss and agree the content of the guaranteed time observations, which were published to the community in April 1994.

The other 55% of ISO's observing time –allocated on a 'per observation' basis– was distributed to the general community via two "Calls for Observing Proposals", one pre-launch (April 1994) and one post-launch (August 1996), each followed by peer review. Over 1500 proposals, requesting almost 4 times more observing time than available, were received in response to these Calls. The necessary flexibility for follow-up observations during the mission was provided by Discretionary Time proposals, with over 150 proposals being received, of which 40% were in the last 4 months of the mission. Additionally, in the extended lifetime, about 20 proposals on *specific* topics were solicited.

During the in-orbit operations, observers were permitted to tune up their programmes via remote login to the Science Operations Centre. This widely-used facility allowed observers to take full advantage of results from previous observations and of improving knowledge of how best to use the instruments. It is strongly recommended that similar flexibility be available for Herschel observers.

Overall, about 10% of ISO's time was used for solar system studies, 23% for the ISM, 29% on stellar and circumstellar topics, 27% for extragalactic observations and 11% for cosmology.

2.5. Operations

Operations of ISO were conducted from ESA's Villafranca Satellite Tracking Station, located near Madrid in Spain. Two ISO teams were co-located there. One was responsible for the operations of the spacecraft. The other was responsible for community support and scientific operations ranging from the issue of the Calls for Observing Proposals, through the scheduling calibration and use of the scientific instruments, to the pipeline processing and distribution of the data products. Additional teams, based mainly at the PI institutes, supported the off-line operations of the instruments. The co-location of so many experts close to each other was a major factor in successfully carrying out ISO's complex operations.

The limited lifetime of ISO, the severe sky coverage constraints, the complexity of the scientific instruments, along with the necessity to make many short observations all dictated that all operations had to be pre-scheduled in order to maximise the time spent acquiring useful astronomical data. Thus, ISO was operated in a service observing mode with each day's observations being planned in detail and finalised up to 3 weeks in advance. This operational concept drove the design of the ground segment (Kessler et al. 1996, 1998).

ISO operations ran very smoothly from the start. They were well served by a superb spacecraft and by robust instruments which suffered only a few anomalies of relatively minor nature. The mission planning systems produced schedules with an average efficiency of 92%. During the routine operations phase, some 50,000 slews were executed in order to carry out over 31,000 observations (including astronomical calibration observations). In total, over 26,450 science observations were carried out successfully for nearly 600 Observers in over 1000 separate research programmes. About 400 hours of science observations were carried out per month with an average of 41 observations per day but ranging from 6 to 238. The average observation duration was 24 minutes.

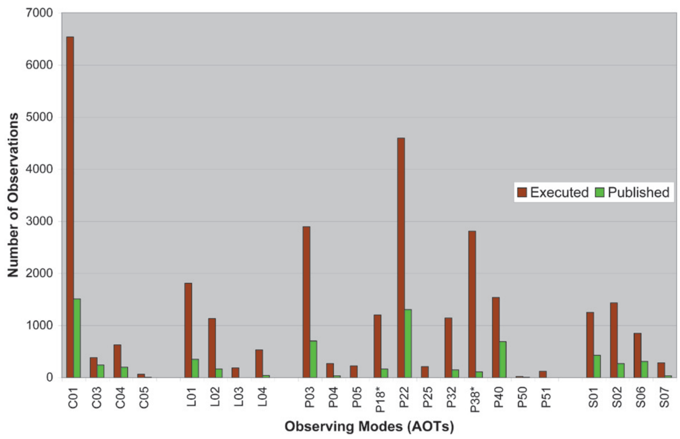

Figure 3. Observations executed and published as a function of observing mode (C for ISOCAM modes; L for LWS; P for ISOPHOT and S for SWS).

Between them, the ISO instruments had some some 23 main observing modes, the so-called 'Astronomical Observation Templates or AOTs'. Figure 3 shows the usage of these modes during the mission and also how many observations in each mode had been included in a refereed paper up to late 2000. It is interesting to note that 90% of the observations carried out and 90% of those published come from around 50% of the modes. Although it would not be correct to argue that doubling the number of modes doubles the total work, it is clear that significant resources were expended in the design, coding, test, commissioning, calibration, use and data analysis of modes that returned less than 10% of the science. In comparison, note that the SIRTF project has chosen a route of very few astronomical modes. This issue should be looked at very closely for Herschel but in a way driven by science. As discussed in section 2.4, there were already intensive activities on defining the ISO guaranteed time programmes some 6 years before launch. It is suggested that the equivalent programmes for Herschel be worked upon as soon as possible so as to define now the minimum set of observing modes necessary for the science return of the mission.

2.6. Post Operations and the Future

ISO is currently in a "post operations phase", with the goal of maximizing the mission's scientific return by facilitating widespread, effective and extensive exploitation of its data. This phase –lasting from August 1998 to the end of 2001– is a collaborative effort, co-ordinated by ESA's ISO Data Centre (IDC) in Vilspa, and involving 5 European 'National Data Centres' based around the groups that built the on-board instruments plus one centre (IPAC) in the USA. These 7 centres have a wealth of experience and expertise on ISO and its data and exist to help the community get the most out of the ISO data. Use them!

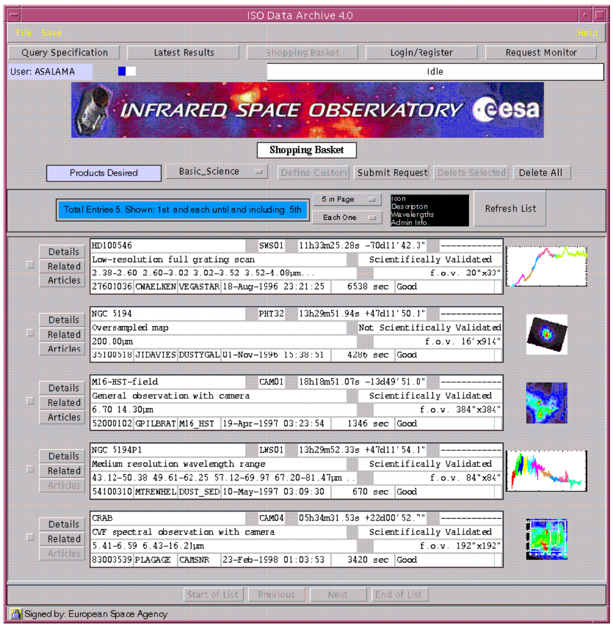

Figure 4. A panel from the ISO Data Archive, showing the first level of browse products – the icons on the right hand side.

In close conjunction with representative users, the IDC has developed the ISO Data Archive (Arviset and Prusti 1999). This archive has powerful facilities but is easily usable not only by experts, but also by astronomers without previous knowledge of ISO. It is one of the most technically-advanced astronomical archives currently available. A WWW- and Java-based interface permits easy access to the data archive, including new 'browse' products, designed to give users a quick but accurate impression of the scientific content of each observation in the data base (Figure 4). This archive is a key legacy from ISO and should be seen as one of the main tools available to help prepare observations for Herschel.

The ISO archive is intensively used by the astronomical community. In its first two years of use, the equivalent of 2.8 times the total number of scientific observations in the archive was downloaded, with the monthly retrieval rate ranging from 10% to over 30%. In total, there over 1100 registered users, still increasing at an average rate of about 1 per working day. About 100 users actually download data each month.

Looking further into the future, ESA activities at the ISO Data Centre for an "Active Archive Phase" have been approved. This phase will cover the period from January 2002 to December 2006, i.e. immediately following on from the current post operations phase, and will be used to consolidate the success of the mission by bringing the archive into its final shape. The main thrusts of the active archive phase are to support the community in their use of ISO data and to capture back into the archive as much as possible of the user knowledge so as to maximize the long-term value and usability of the archive. Several of the National Data Centres are also seeking funding to continue their activities into 2002 and beyond. The continuing activities of this network of ISO centres will help pave the way to a successful Herschel mission.

3. Technical Highlights

Due to excellent engineering and a fortunate combination of circumstances at launch, the liquid helium supply lasted over 10 months longer than the specified 18 months. The extra lifetime not only led to many more observations but also made it possible to observe the Taurus/Orion region – inaccessible in the nominal mission. By a combination of very good in-orbit performance, detailed analysis on the ground and a variety of tune-ups, the accuracy of the pointing system was improved to the arc second level. The absolute pointing error was reduced to around $1''$, ten times better than specified and the short term jitter was about five times better than the specification of $2.7''$ (2σ, half cone, over a 30 second period of time). The optical performance of the telescope and baffle system was excellent, with straylight being too low to measure.

All the scientific instruments, including many delicate cryogenic mechanisms, performed extremely well. As described in section 2.5, all elements of the ground segment also performed excellently, leading to an overall availability of the system during routine phase of 98.3% of the time scheduled for science. Taking into account all possible reasons for failure, only 4% of observations were lost. Over 98% of the highest-priority observations were successfully executed.

4. Scientific Highlights

ISO results are impacting most fields of astronomical research, almost literally from comets to cosmology. Some results answer questions; others open new fields of research and/or pose new questions. Some are already being followed up with existing telescopes; others have to await future facilities, such as the Herschel Space Observatory. There follows a smattering of some of ISO's scientific highlights. However, any and every selection is bound to be somewhat arbitrary. Thus, for a full overview, the reader is referred to the lists of the refereed literature maintained at `www.iso.vilspa.esa.es/science/publications.html`, to reviews such as Genzel and Cesarsky (2000) and to the many ISO-dedicated conferences such as: "ISO's View on Stellar Evolution" (Waters et al. 1997); "Star Formation with the Infrared Space Observatory" (Yun and Liseau, 1997); "ISO to the Peaks: First ISO Workshop on Analytical Spectroscopy" (Heras et al. 1998); "The Universe as seen by ISO" (Cox and Kessler, 1999); "ISO Polarisation Observations" (Laureijs and Siebenmorgen 1999); "Solid Interstellar Matter: The ISO Revolution" (d'Hendecourt et al. 1999); "2nd Austrian ISO Workshop: Atmospheres of M, S and C Giants" (Hron and Hoefner 1999); "ISO

Beyond Point Sources" (Laureijs et al 2000); "IR Space Astronomy" (Casoli et al., 2000); "ISO Beyond the Peaks" (Salama et al. 2000). Additionally, with a view to learning lessons from ISO, one may refer to the proceedings of the "ISO Detector Workshop" (de Graauw 2000) and of the "ISO Calibration Legacy Conference" (Metcalfe et al. 2001).

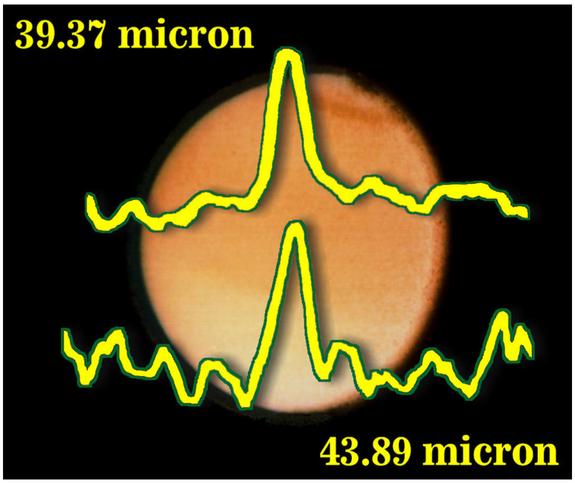

Figure 5. Detection of water vapour on Titan (Coustenis et al. 1998), superposed on a Voyager image

Results from ISO leading to new fields of study include:

- the identification of crystalline silicates in the atmospheres of young and old stars as well as in comet Hale-Bopp giving a link between interplanetary and interstellar dust;
- showing that water is ubiquitous in the cosmos. A wealth of water vapour transitions were measured in objects such as Mars, Titan (Figure 5), the giant planets, comets including Hale-Bopp, in shocks, in the cold interstellar medium, in circumstellar envelopes and in the ultra-luminous galaxy Arp 220. A determination of the abundance, spatial extent and distribution of water vapour is crucial to the modelling of the chemistry and physics of molecular clouds. Prior to ISO, most observations of water vapour had been via maser transitions making analysis of the data very difficult. The detections of water on Titan and in the atmospheres of the giant planets have implications for their sources of oxygen;
- the first detections of the lowest pure rotational lines of H_2 (giving access to gas at temperatures less than a few hundred K) in many sources such as young massive stars, HH-objects, PDR's, the diffuse ISM, outer parts of edge-on galaxies;
- detailed investigations of interstellar solid state features, e.g. CO_2 ices, leading to a very detailed interplay between observations and laboratory spectroscopy.

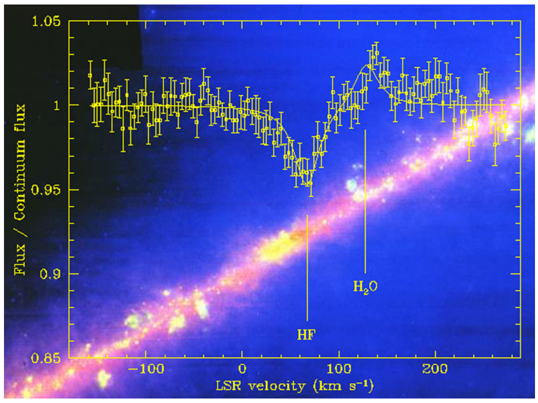

Figure 6. Detection of Hydrogen Fluoride towards the Galactic centre (Neufeld et al. 1997), superposed on an IRAS image

Some specific discoveries include:

- finding carbon-bearing species such as the methyl radical and benzene, giving insight into the complex organic chemistry, which may also build larger molecules;
- discovering the OH absorption feature (at a wavelength of 35 μm) in the ultraluminous galaxy Arp 220 which had long been predicted to provide the excitation and line inversion responsible for powering this galaxy's megamaser emission;
- the first detection of a fluorine-bearing molecule (HF) in interstellar space (Figure 6).

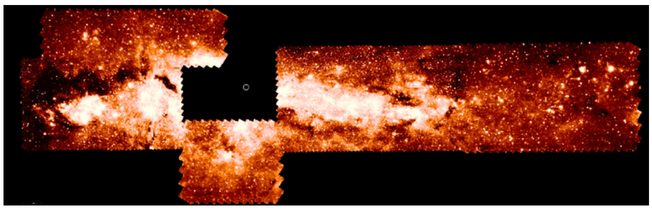

Figure 7. The Inner Galaxy as imaged by ISOCAM (Ganesh, Omont et al. 2001)

Some other fields in which ISO has made significant contributions include:

- demonstrating with its wealth of results, the worth for solar system studies of a relatively-small telescope in Earth orbit even in the age of remote exploration. Examples include the first coherent detection of the D/H ratio in the giant planets and the study of the Pluto/Charon system;
- probing details of the dusty disks around main sequence stars. One intriguing result came when the ages of these stars were correlated with the presence or absence of a disk. It was found that all stars in a particular sample younger than 300 million years had a disk while very few older than 400 million years had one. This age of 300 - 400 Myr for the apparent loss

of the dusty disk is very similar to the age of our Sun when it was forming its planetary system, including the comets in the Oort cloud. Thus, the disks of the older stars may have been removed as a result of the formation of planets;
- detailed investigations of star-forming regions in our own and external galaxies, including detections of pre-stellar cores and determinations of initial mass functions showing substantial numbers of objects in the brown dwarf mass range;
- surveying 22 square degrees of the inner galaxy (Figure 7) at 7 μm and 15 μm to give the first view of global stellar populations and study of the history of this region, as well as information on the onset of mass loss on the AGB and the discovery of globules optically thick even at 15 μm;
- mapping nearby galaxies in unprecedented detail and showing that there could be up to x10 more dust in some galaxies than deduced from IRAS measurements alone, thereby bringing dust-to-gas ratios closer to galactic values;
- distinguishing between central engines and starbursts as the energy sources for ultra-luminous infrared galaxies;
- finding dust between galaxies in a distant cluster;
- making deep cosmological surveys at near- and far-infrared wavelengths (Figure 8), the results from which show: early star formation hidden by dust, the need for evolutionary models, resolution of part of the cosmic infrared background (CIB) into discrete sources, and detection of fluctuations in the CIB.

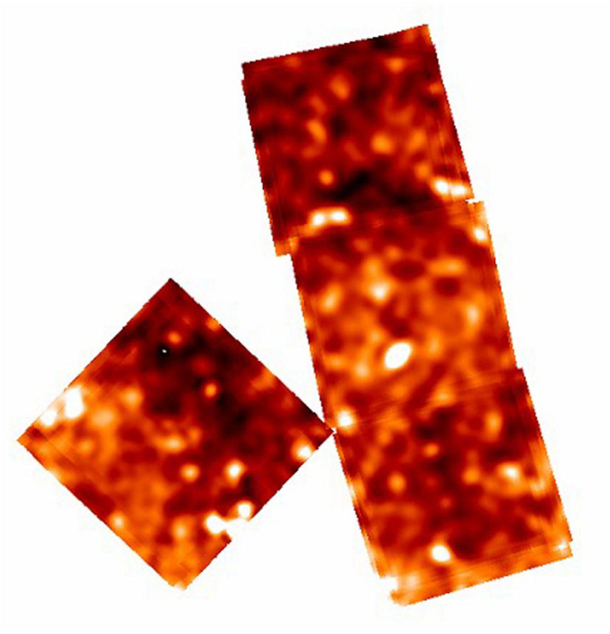

Figure 8. 175 μm image of the Marano Fields (Lagache and Puget 2000)

The majority of the results described above have come from observations made in specific ISO programmes and have been published by the PIs of the proposals. However, with all data public, a wide range of archival research becomes possible. As an example of these new possibilities, relevant for preparation of Herschel programmes, look at Figure 9. This shows an example of large-scale use of the ISO archive, where 600 observations of 400 sources from 100 proposals have been analysed to produce evolutionary sequences for the transition from AGB stars to PNe for C- and O-rich chemistry.

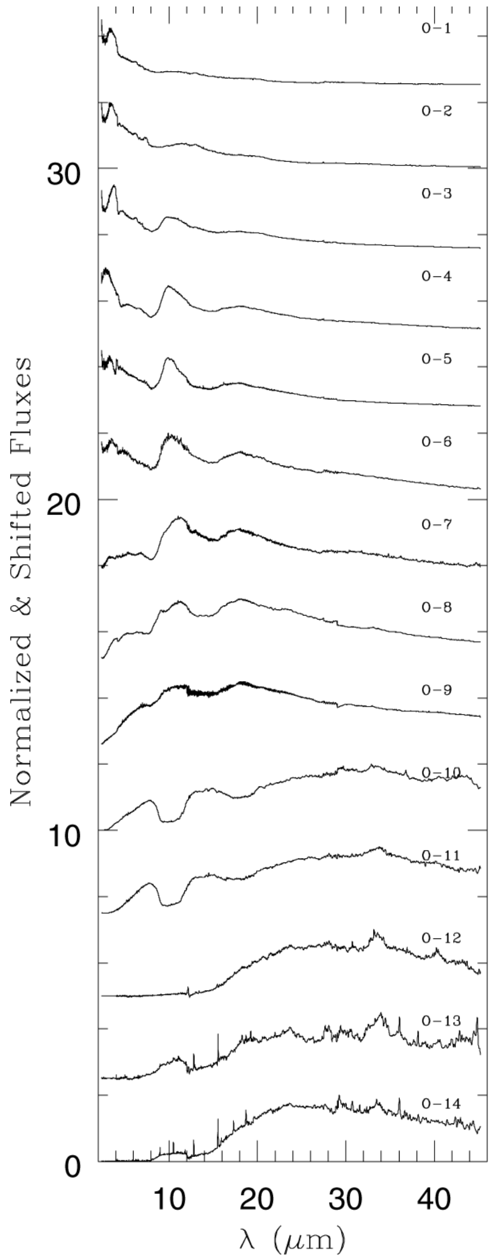

Figure 9. O-rich evolutionary sequence from AGB stars to PNe (Garcia-Lario and Perea 2001)

Since late 1996, nearly 700 papers – 330 in the years 1999-2000 – on ISO results have appeared in the refereed scientific literature and many more in conference proceedings. The publication rate does not seem to have peaked yet. Around 15% of all ISO observations (25% by time) have been published at least once in the refereed literature. Many more results are in the pipeline!

5. Conclusions

ISO's technical and operational successes provide a firm foundation on which the Herschel project is already building. The process of drawing lessons from the ISO experience and applying these to future missions is well underway, with good emphasis on those areas where ISO 'could have done better'! ISO's scientific results, impacting astronomical research fields from comets to cosmology, are consolidating, extending and completing the overall success of the mission. With all the data now public, with the ISO data archive rapidly establishing itself as a general astronomical research resource and also as an important tool for planning future missions – such as Herschel, with activities continuing on refining the calibration and data reduction algorithms, many more astronomical surprises and discoveries from ISO are still expected. These inputs and results will help us fully realise the 'Promise of Herschel'.

Acknowledgements

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During the history of ISO, countless engineers and scientists have contributed to its development, launch and operation and scientific use. They are too numerous to name individually but without their expertise, enthusiasm, dedication, professionalism and sheer hard work, the success of ISO, the results discussed in this article and the data contained in the archive would not have been possible. This paper has been written on their behalf.

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