# Parallel Modes and Serendipity Survey

# STATUS AND SCIENTIFIC POTENTIAL OF THE ISOCAM PARALLEL MODE SURVEY

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ABSTRACT

During most of ESA's ISO mission, the mid-infrared camera ISOCAM continued to observe the sky mainly around 6.7$\mu$m with a pixel field of view of 6″ in its so-called "parallel mode" while another instrument was prime.

This permitted an unbiased survey of limited areas of the infrared sky, albeit with varying depth and wavelength per field due to the different instrumental configurations used and the highly variable time spent per pointed observation.

Dedicated calibration, data reduction and source extraction methods were developed to analyse these serendipitously recorded data: 37000 individual pointings, taken during 6700 hours of observation. Using sophisticated merging algorithms, over 42 square degrees of the sky — roughly one per mill of the celestial sphere — are currently being processed and catalogued.

For the final catalogue around 30000 distinct point sources are expected. Their mid-infrared flux goes down to 0.5 mJy. Sources observed with the most sensitive instrumental configuration have a median flux of 2.7 mJy outside the galactic plane, and a median flux of 6.3 mJy inside the galactic plane.

We present an overview of the results of this recently finished data processing effort, outline the scientific potential of this data-set and present the first multi-wavelength cross-correlations.

Key words: ISO, ISOCAM, parallel mode, catalogue

## 1. OVERVIEW

During most of ESA's Infrared Space Observatory (ISO) mission (Kessler et al. 1996), the mid-infrared camera ISOCAM (Cesarsky et al. 1996), continued to observe the sky in its so-called "parallel mode" while another of the three instruments (LWS, ISOPHOT or SWS) was prime, during both normal pointed observations and satellite slews between targets (Siebenmorgen et al. 1996).

In parallel mode, routine use was made of broad band filters centred around 6$\mu$m with the 6″ pixel field of view (PFOV). As only a restricted telemetry band-width was available, 12 readouts with 2.1 seconds integration time were accumulated on board and down-linked as one image every 25 seconds. Depending on the prime instrument, ISOCAM observed the sky 12′ to 17′ from the prime target.

ISOCAM parallel data were taken as soon as ISOCAM's activation sequence was completed. Only interrupted by scheduled ISOCAM prime observations, ISOCAM parallel data were sent for up to 19 hours until the instrument was switched off before entering the radiation belts. In order to avoid saturation of the detector, the optical configuration was adapted to the expected flux level of field sources using one of several modes (see Table 1).

*Table 1. Standard ISOCAM parallel configurations.*

| PFOV | filter | wavelength | description |
|---|---|---|---|
| 6″ | LW2 | 5 - 8.5$\mu$m | extra-galactic mode |
| 6″ | LW4 | 5.5 - 6.5$\mu$m | galactic mode |
| 1.5″ | LW3 | 12 - 18$\mu$m | slew mode |
| 1.5″ | LW-CVF | 15$\mu$m | galactic centre mode |
| dark configuration | | | dark mode |

Effectively, this permitted an unbiased survey of limited areas of the infrared sky: Around 9700 hours of data were taken in the ISOCAM parallel mode; approximately 9500 hours during science observations, and 200 hours during engineering windows of other instruments (see Fig. 1). 400 hours were used for calibration measurements, with ISOCAM in dark configuration (Biviano et al. 2000). Additionally, 500 hours were taken during slews of the ISO satellite in parallel to the ISOPHOT serendipity mode (Bogun et al. 1996; Stickel et al. 2002).

For the work on the ISOCAM Parallel Catalogue only pointed observations lasting longer than 100 seconds were considered, i.e. such that at least four ISOCAM parallel readouts view the same part of the sky with the same instrumental configuration. Additionally, 617 hours of observation time had to be excluded for various reasons, e.g. data taken during the activation and deactivation phase of the other instruments, within the early revolutions of the spacecraft checkout phase or during the solar flare revolutions 722 and 723.

Overall 37000 pointings, representing in total 6700 hours of observation time, or 72% of all ISOCAM parallel data taken in pointed mode, could be processed. This makes the ISOCAM parallel survey the ISOCAM programme with by far the longest observing time. With an observed area of approximately 42 square degrees, it yields a sky-coverage double as large as any other ISO proposal for this wavelength range. Compared to IRAS (Beichman et al. 1988), areas covered by ISOCAM

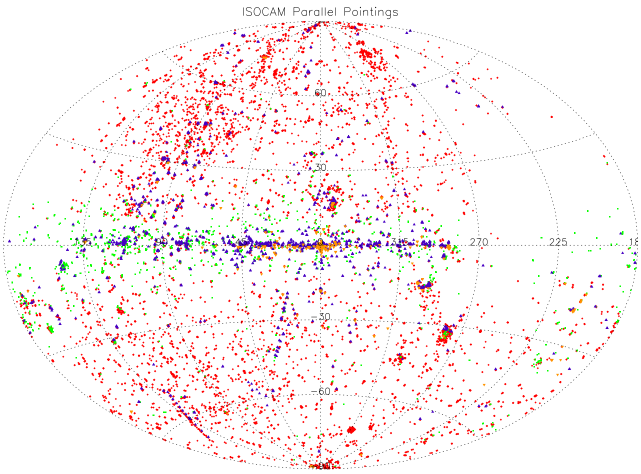


*Figure 1. Aitoff projection of an all-sky view of ISOCAM parallel pointings in galactic coordinates. Legend: red diamond: LW2, 6″ PFOV, green square: LW4, 6″ PFOV, blue up-triangle: LW3, 1.5″ PFOV, orange down-triangle: 15μm LW-CVF, 1.5″ PFOV*

parallel are surveyed with up to 500 times more sensitivity, and a 50 times higher spatial resolution.

## 2. PROCESSING STATUS

Dedicated data reduction and source extraction techniques, combined with major calibration, simulation and verification efforts, had to be developed to generate a catalogue of mid-infrared point sources candidates from data taken in the ISOCAM parallel survey (Ott, 2002).

The deglitching methods are based on improved sigma-clipping algorithms, adapted for ISOCAM observations and its temporal glitch distribution, and were particularly efficient to deglitch ISOCAM parallel data down to four readouts. Major calibration efforts led to the generation of 11 master flat-fields, which enabled the detection of true sources close to the array borders and significantly reduced the number of spurious detections at the same area. Fig. 2 demonstrates the improvement in the generation of calibrated exposures.

The source extraction method is based on an iterative, multi-step "search and destroy" algorithm, that combines source detection with classification into point- and extended sources. This technique was particularly powerful to detect point sources in crowded areas and within extended sources, without missing any significant sources.

A variety of simulations, performed at different flux levels, covered all aspects of the data processing. These validated the algorithmic approach, and permitted to predict the flux- and positional accuracy of the extracted sources, and the completeness limits for each pointing of the ISOCAM parallel survey.

Major efforts were spent on quality checks and source classification. Over 74000 source candidates and 24000 individual pointings were eye-balled. The manual classification of source candidates is used to determine the cut-off parameters in order to statistically clean the detected source candidates. In addition, this exercise demonstrated clearly the efficiency of the source extractor, and proved a powerful tool to identify observations with suspicious pointing information, which were consequently excluded.

Currently we are in the process to merge multiple detected sources into unique sources. We hope to complete the merging, and the simulation of bias effects, and an additional completeness estimate on the whole catalogue end 2002, so that the catalogue can be published and released to the community spring 2003.

## 3. DESCRIPTION OF THE CATALOGUE

For the final catalogue, we expect 30000 unique point sources, and a reliability of at least 99%. The detection threshold is limited by the flat-field noise. Using the most sensitive instrumental configuration (the broad band filter LW2 with 6″ PFOV), sources with a flux down to 0.5 mJy can be detected. The median flux of sources outside the galactic plane (galactic latitude outside $\pm 20^o$) is 2.7mJy. The vast majority of these sources are new detections in the infrared (see Fig. 3). 30 square degrees are mapped completely down to 4 mJy, while 0.4 square degrees could be mapped completely down to 1.0 mJy (See Fig. 4).

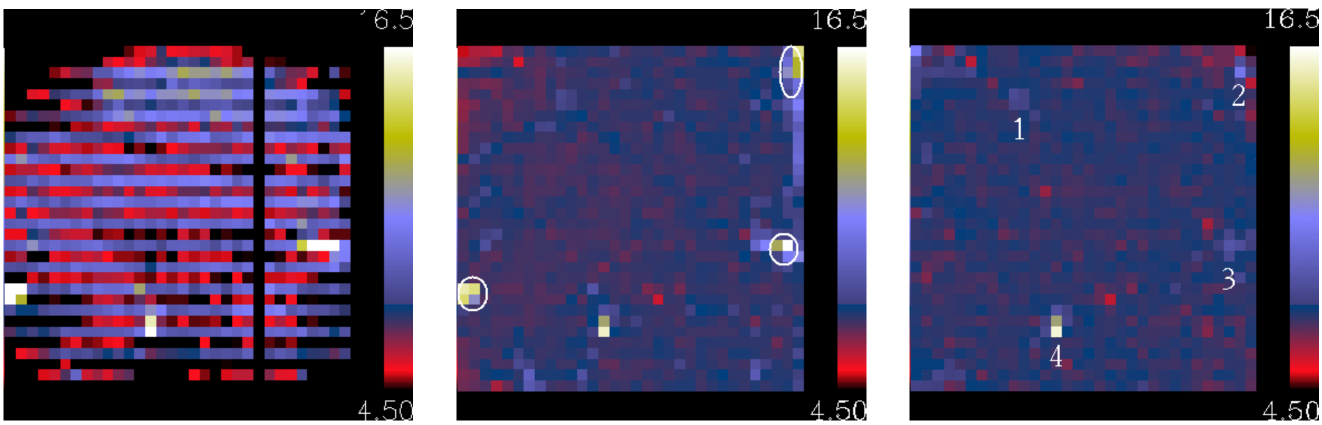


*Figure 2. Data processing of an ISOCAM parallel image.* **Left:** *Raw data.* **Middle:** *Standard data processing. Circles indicate remaining instrumental artifacts.* **Right:** *Parallel processing. Numbers mark the four detected sources from 2.5 to 19.5 mJy.*

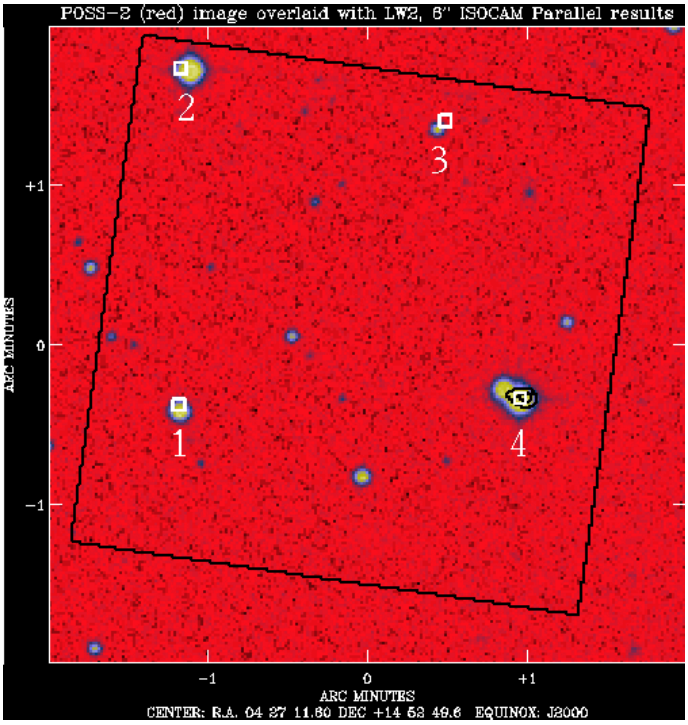


*Figure 3. Digital Sky Survey image overlaid with contours of the ISOCAM parallel exposure. Numbered squares mark the four verified sources. They are detected in six readouts and have a flux between 2.5 and 19.5 mJy — up to 100 times fainter than ISO's predecessor IRAS. Note the detection of the source #2 close to a corner of the ISOCAM detector. The elongated source #4 is a double star*

*Table 2. Observations done in standard ISOCAM parallel configurations.*

| number of pointings | pixel field of view | filter | overall duration | area covered (square degree) | average redundancy of pointings | maximum redundancy of pointings |
|---|---|---|---|---|---|---|
| 24036 | 6″ | LW2 | 3971 hours | 32.55 | 2.1 | 100 |
| 6203 | 6″ | LW4 | 1292 hours | 9.37 | 1.9 | 60 |
| 5108 | 1.5″ | LW3 | 1032 hours | 0.61 | 1.49 | 69 |
| 1686 | 1.5″ | LW-CVF (15$\mu$m) | 374 hours | 0.22 | 1.35 | 38 |
| 5018 | dark configuration | | 410 hours | | | |

Furthermore, as a by-product, we obtained 1697 extended source candidates. As we concentrated on point sources, this is a preliminary result, and could be refined in the future.

## 4. SCIENTIFIC POTENTIAL

Compared to ISO's predecessor, the all-sky surveying IRAS, areas covered by ISOCAM parallel are observed with up to 500 times more sensitivity, and a 50 times higher spatial resolution. With 42 square degrees of the sky inside and outside of the galactic plane surveyed, the detection of objects from a multitude of classes (besides stellar objects without infrared excess) can be expected:

- low-redshift starburst, elliptical and spiral galaxies
- ultraluminous and hyperluminous infrared galaxies
- Active Galactic Nuclei (AGNs)
- stellar objects with infrared excess, like
  - evolved AGB stars, (proto-)planetary nebulae, supergiants and binary systems
  - low-mass, young and embedded stars in nearby star-formation regions like Orion, Taurus, Perseus and Rho Ophiucus
  - brown dwarfs in the solar neighbourhood
- cold stellar populations even in the obscured regions throughout the inner galaxy
- asteroids, near-earth and Kuiper-belt objects

Many interesting results, affecting nearly all fields of astronomy can be expected, e.g.:

- mid-infrared extragalactic source counts, which will constrain cosmological model predictions
- a census of cold stellar populations, which will constrain stellar distribution models
- diameter and albedo determination of asteroids, which will permit a taxonomic classification

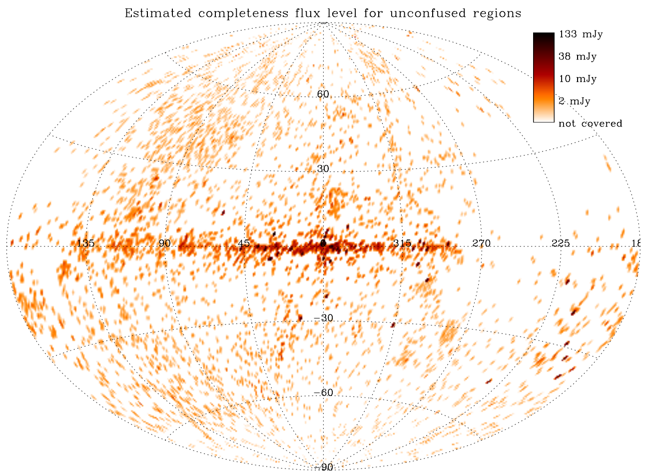


*Figure 4.* *All-sky view of expected completeness of ISOCAM parallel survey for not crowded regions. The completeness limit ranges from 0.9 mJy to 140 mJy per square degree sky-bin with a median of 2 mJy.*

To demonstrate this potential of the ISOCAM parallel mode survey in advance of the release of the final catalogue, to validate the processing by a first check against other catalogues, and to give an indication of the flux and astrometric accuracy achieved, a sub-sample of observations using the LW2 filter and the 6″ PFOV was selected. This sub-set had to fulfill the following criteria:

– observation has at least eight readouts (200 seconds integration time)
– pointing must be outside of the galactic plane (galactic latitude outside $\pm 20^o$)
– only the first pointing of a tracking observations is taken
– crowded regions (pointings showing extended structure or having more than six verified point sources) are excluded

These restrictions were introduced in order to minimise the number of spurious sources wrongly classified as good, to increase the reliability of cross-identifications and to reduce the effort needed to manually merge the results in advance of the final point source catalogue. Consequently, this sub-set consists of 9674 pointings, taken during 2300 hours and covers approximately 14 square degrees, i.e. around 45% of all LW2 observations with 6″ PFOV. The average redundancy of these pointings is 1.6, and the median completeness limit is 1.6 mJy.

7177 unmerged bona-fide point sources — point sources classified as good by eye-balling — with a median flux of 2.2 mJy were detected in this data-set. By using their *2 Micron All Sky Survey* (2MASS, Skrutskie et al. 1995) K-band counterparts, selected by a probability aperture (Derriere et al. 2003) they were merged into 4500 unique sources. For the vast majority (over 99%) of these sources optical (USNO astrometric standard catalogue, Monet et al. 1998) or near infrared (2MASS 2 $\mu$m) counterparts were identified.

Some results of the first multi-wavelength cross-correlations are:

– first infrared detection of the asteroid Watsonia. (See Fig. 5)

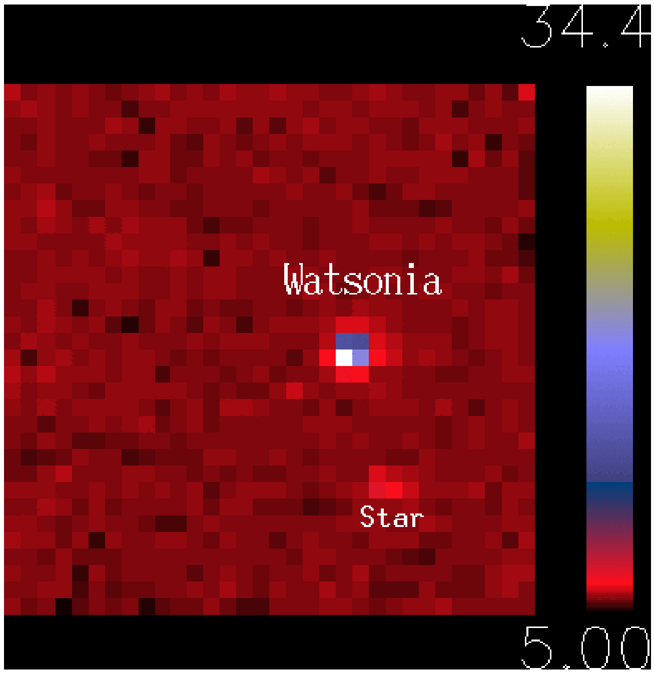


*Figure 5.* *ISOCAM parallel image showing the detection of the asteroid Watsonia. The ISOCAM flux is ≈ 57 mJy, in good agreement with the predictions of 54±6 mJy.*

– cross-correlations with other catalogues:
  – cross-identification with 2MASS counterparts gives the J, H and K colors for these sources. These colors are then used for sorting into stars and galaxies (Jarrett et al. 2000), resulting in a preliminary classification of 3500 stars and 1000 galaxies. While the majority are F and G stars, two additional object classes showing a high infrared excess are visible. They are expected to be stars with infrared excess and galaxies (See Fig. 6)
  – cross-correlation with the IRAS point and faint source catalogue (Beichman et al. 1988; Moshir et al. 1989) confirmed that all bona-fide IRAS 12$\mu$m sources are also detected by ISOCAM. IRAS sources without an ISOCAM parallel counterpart were sources with high IRAS astrometric uncertainty (see Fig. 7), IRAS upper limit detections or extended sources (and therefore not included in the ISOCAM parallel point source catalogue)
  – 20 matches with the bright and faint ROSAT catalogues (Voges et al., 1999; Voges et al. 2000) were found
  – cross-correlation with the Tycho 2 catalogue (Hog et al. 2000) yielded 500 matches. The detected objects are mainly F and G stars and M giants
  – cross-correlation with the catalogue of principal galaxies (PGC, Paturel et al. 1989) yielded 168 matches. All galaxies are low red-shift objects, with a maximum red-shift of 0.2
– In a *preliminary* analysis to deduce 7$\mu$m galaxy number-counts from ISOCAM parallel data, the J, H and K colours of their 2MASS counterparts are used to sort the ISOCAM

detections into stars and galaxies. The *preliminary* results are already in rough agreement with the ELAIS LW2 number-counts (Serjeant et al. 2000) and the Pearson & Rowan-Robinson models (Pearson & Rowan-Robinson, 1996), with approximately 40 galaxies having a flux of at least 2 mJy per square degree (See Fig. 8)

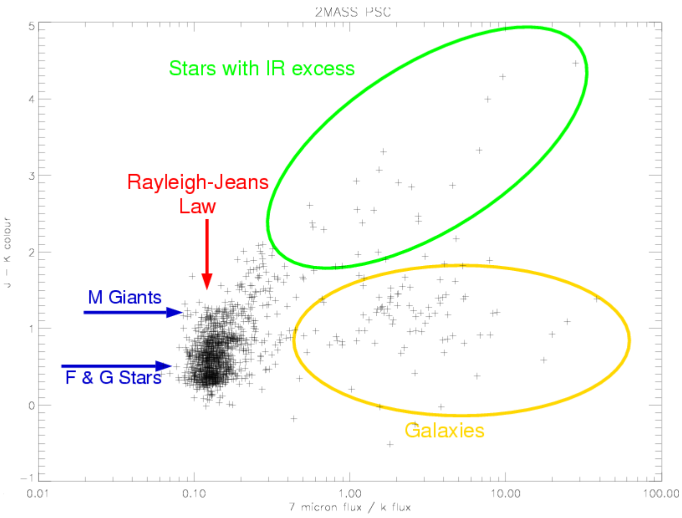


*Figure 6.* *Colour plot of detected ISOCAM parallel sources with 2MASS counterparts. The majority of detected objects are F and G stars and M giants. For these, the ratio of the ISOCAM parallel 6.7μm flux vs. the 2MASS 2.2μm flux is around 1/9, as expected from the Rayleigh-Jeans law, which indicates an excellent absolute flux calibration. The two additional object classes showing a high infrared excess are expected to be stars with infrared excess and galaxies.*

Currently, the following projects exploit ISOCAM parallel data:

- Solar System Objects (T. Müller et al.)
- LW2 (7$\mu$m) galaxy source counts (S. Ott et al.)
- Active Galactic Nuclei (N. Schartel et al.)
- Radio sources (R. Siebenmorgen et al.)
- Infrared excess stars (R. Siebenmorgen et al.)

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This research has made use of Digitized Sky Survey Archive Access provided by the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada.

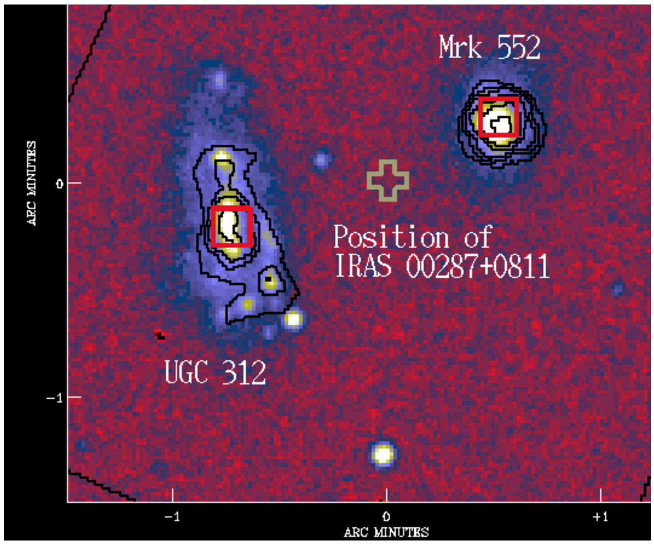


*Figure 7.* *ISOCAM parallel resolves confused IRAS 00287+0811 source. IRAS 00287+0811 (indicated by an olive cross) has a distance of 40″ between the two ISOCAM detections (UGC 312 and Mrk 552, both marked by a red square).*

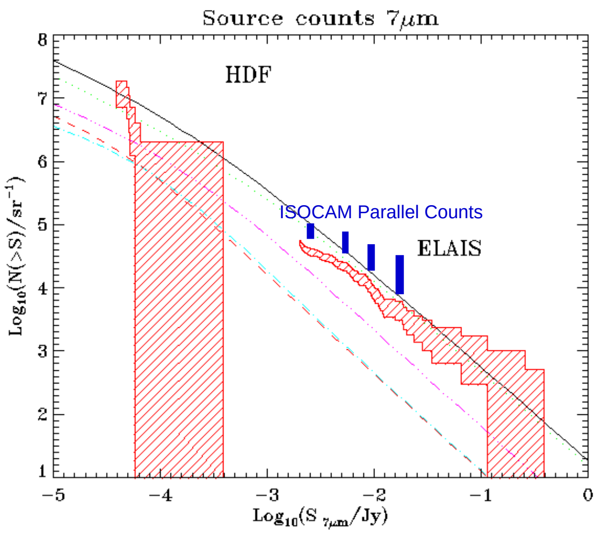


*Figure 8.* *First indication of ISOCAM parallel 7μm galaxy number-counts. The result falls well within the range of the proposed Pearson & Rowan-Robinson models.*

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This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

This research has made use of the VizieR database, operated at CDS, Strasbourg, France.

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# THE SCIENTIFIC POTENTIAL OF THE LWS PARALLEL AND SERENDIPITY MODES

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ABSTRACT

ISO LWS was one of the two ISO instruments able to operate in parallel mode i.e. taking by scientific data while another ISO instrument was active. In parallel mode the LWS diffraction grating remained in a fixed position allowing the spectrometer to act like a 10 channel photometer with bandwidths of 0.3 microns (one resolution element in second order) for the five short wavelength detectors and 0.6 microns (one resolution element in second order) for the five long wavelength detectors. This paper describes the LWS parallel mode and gives details on the data obtained. The paper will also describe the automated processing developed for the parallel mode data and the calibration strategy employed. Areas for further scientific study are proposed and one example will illustrate a sparse coverage map at one wavelength in in the Rho Oph region and a temperature map which was derived from fitting all 10 channels.

Key words: ISO – LWS

## 1. INTRODUCTION

The LWS parallel and serendipity modes were additional to the standard observing modes of the LWS instrument (Clegg et al. 1996) and were in operation during those times when LWS was not the prime instrument. Parallel data were obtained when another ISO instrument was operating and serendipity data was obtained when ISO was slewing. These modes were not used until revolution 237 and continued until the end of the ISO mission with a gap between revolutions 380 and 442 when the LWS instrument was switched off due to a problem with its interchange wheel. In all more than 100,000 individual pointings were made in parallel mode in over 17,000 individual observations with a total sky coverage of about 1%.

The actual configuration of the LWS instrument for both the parallel and serendipity modes was identical, the grating was not powered and hence the ten detectors were only receiving flux over one grating resolution element corresponding to the grating rest position. The parallel and serendipity data was downlinked through the ’essential’ housekeeping telemetry which was a part of the telemetry stream used by all the instruments on the satellite to downlink data for health monitoring purposes. Those parts of the housekeeping telemetry which was not necessary when the instrument was not prime were replaced with detector signal values calculated on board.

The use of the housekeeping data meant that the data could only be inserted into the downlink telemetry stream at a greatly reduced rate, up to a factor of about 80, compared with prime mode. The space available provided for two values from each detector to be placed in each telemetry format (every 2 sec.). Prime mode data was downliked as samples on each ramp output from integrating amplifiers. Generally 1/2 sec ramps were used and for bright sources 1/4s ramps. For parallel and serendipity modes the detector integration time on board was adjusted to 1 sec. The on-board software calculated the slope of each ramp and it was this slope that was downlinked instead of individual ramp samples.

In the next section we outline the offline processing steps with reference to the processing done on prime mode data and then we give the status of the calibration of both modes followed by a comparison with other instruments. The use of parallel mode data for scientific investigation is also discussed.

## 2. STANDARD PROCESSED DATA

The approach to the processing of parallel and serendipity data is essentially the same as for the prime data and, whenever possible, the same algorithms and calibration files are applied (Burgdorf et al. 1998, Lim et al. 1998). The main difference occurs in the determination of the individual ramp slopes which was done on-board. The parallel mode ramp slopes are determined with a simple algorithm which simply takes the last point in each ramp, subtracts the first and divides by time. Hence the curve fitting and within ramp glitch detection, which is done on prime mode ramps no longer takes place. The same engineering conversions as prime mode are applied to convert the raw slope value to a photocurrent. The detector ramps when observing strong sources are non-linear due to the detectors debiasing, hence an empirical calibration for the non-linearity is also applied, and the photocurrent adjusted. As the parallel and serendipity mode ramps are longer in time, the effect of debiasing is greater and a further calibration is then applied to adjust for the difference in slopes of the parallel and prime mode ramps to account for the length difference. This correction allows the prime mode derived calibration to be used in the processing.

The photocurrents are then written to the standard processed data (LPSP) file. Each LPSP file contains all the photocurrents obtained by LWS during one observation. Each observation time period is defined by the prime ISO instrument and is allo-

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cated the same eight digit 'TDT number' as the prime instrument observation.

## 3. AUTO ANALYSIS

Once the photocurrents have been obtained, the next stage is to remove the dark current. Each prime mode observation was preceded and followed by a standard measurement of the LWS illuminators. The beam was blanked and a dark current measurement was taken before the illuminators were switched on. These dark current values prior to the illuminator flashes from the start and end of each observation were then determined and an average of the two values was subtracted from each photocurrent value.

Trend analysis of these prime mode dark current measurements indicated that the dark current remained at a stable value throughout each revolution of the ISO mission. The rare exception being that transient effects which occur after observing bright sources sometimes led to higher than normal values. As the serendipity data was often taken when LWS was pointing at areas of sky below the detection limit, dark current values were defined as the minimum photocurrents consistently obtained in this mode. The values obtained were slightly lower than those obtained in prime mode and these 'serendipity darks' were implemented as one standard dark current value per detector and applied to the parallel and serendipity data for the whole mission.

The next stage of processing corrected for a drift in the detector responsivity. The responsivity slowly increased between detector curings which took place at the start of each revolution just after ISO emerged from the Earth's radiation belts and at perigee. The correction uses the simple ratio between the response to the illuminators found at the time of a particular observation and that used as a reference based on an observation of the Uranus primary standard. Both the parallel and the serendipity observations did not have dedicated illuminator flashes, therefore the responsivity correction could not be derived in the same way as for prime mode. For each half revolution all illuminator flashes were linearly fitted to obtain responsivity drift coefficients for that revolution. The parallel and serendipity data were then calibrated by using the interpolated response of the detectors. For revolutions where there are no prime mode observations, a standard responsivity drift defined by averaging all revolutions, was applied.

In prime mode the grating is moving constantly hence each detector receives a constantly changing signal. In parallel mode the grating remains at a fixed position and it was therefore possible to apply a transient correction to the data. The transient correction applied was based on fitting a double exponential to the data, and then using this fit to correct the data.

The wavelength determination was done by a look-up table as all the data were taken at the grating rest position and this remained stable throughout the ISO mission (Gry et al. 2002). Each data point has a bandwidth of one grating resolution element and the units of parallel mode auto-analysis products are $\mathrm{W\,cm^{-1}\,\mu m^{-1}}$ and serendipity products are $\mathrm{MJy\,sr^{-1}}$, as a correction is made for the beam profiles (Lloyd et al. 2002).

The final fluxes are then written to the auto-analysis data (LPAR) file. Each LPAR file contains all the fluxes obtained by the LWS during each observation by another ISO instrument and is allocated the same eight digit 'TDT number' as the standard processed data. The LPAR file is equivalent to the prime mode LSAN file and the units are $\mathrm{W\,cm^{-}2\,\mu mm^{-1}}$. Note at this point no account has been taken in the data processing for the LWS beam (Lloyd et al. 2002) and this must be done either manually or using data reduction software after processing. As the data consists of a time series at a fixed pointing (or set of pointings in the case of a raster), a further product is produced, the LPAD file, where the data at each pointing is averaged. All parallel mode product files are available in FITS format from the ISO Data Archive at
http://www.iso.vilspa.esa.es/ida/index.html

## 4. DATA REDUCTION

Generally the benefit of the parallel mode data lies in the sparse maps produced at the ten detector wavelengths. Fig. 1 shows an example of a parallel mode map. In this example the prime instrument had been doing a large area survey and LWS parallel data was also obtained. The map is generated by combining several rasters. Several data reduction tools have been developed in IDL and these form the LWS parallel interactive analysis package which is available at:
http://jackal.bnsc.rl.uk/isouk/lws/software/parallel/parallel.html.

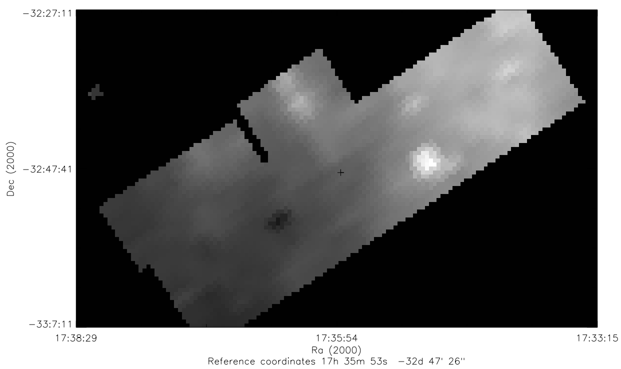


*Figure 1. An example parallel mode map produced from several raster observations*

The main parallel mode map generation tool is a GUI which allows users to select an area of interest on the sky by zooming in from a whole sky map. A list of observations within that area is displayed. When satisfied the user can download the appropriate LPAD files from the ISO Data Archive and then use the GUI to automatically generate a map of the selected area. When the map is generated the LWS effective beam sizes, which are different for each detector, are taken into account, and the fluxes are converted to $\mathrm{MJy\,sr^{-1}}$. Although the beam

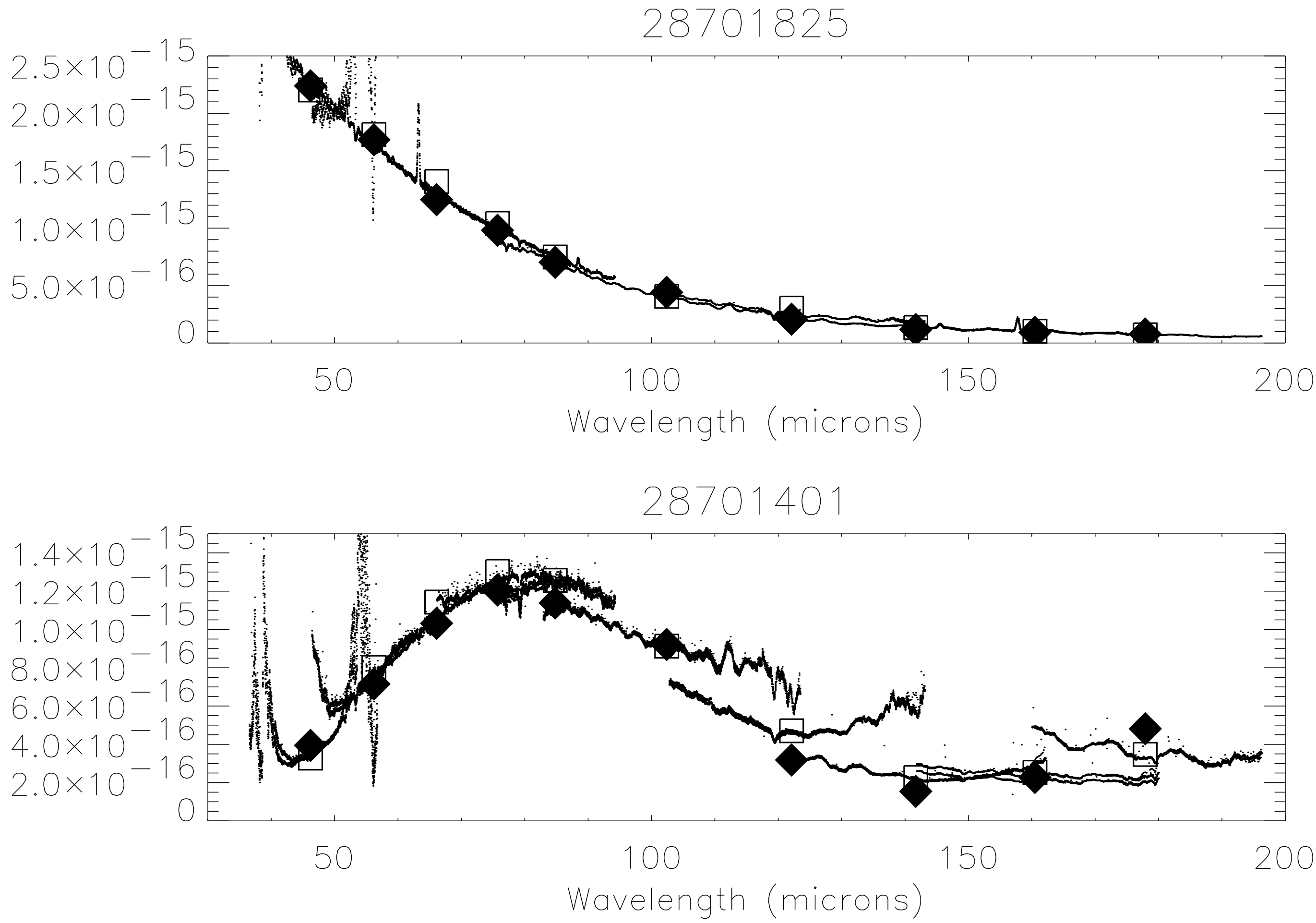


*Figure 2. Comparison of parallel mode fluxes with prime mode L01 observations. The top panel shows a well calibrated observation of a point source on axis and the bottom panel shows a case of high flux and extended emission.*

is actually asymmetric, for simplicity a symmetric beam is assumed.

Although many maps such as the example in Fig. 1 have good flat-fielding, some maps have poor flat-fielding between the constituent rasters due to the relatively poor determination of the detector responsivity at the time the raster was taken. The flat-fielding within an individual observation is not affected by this and is generally good. The generated map can either be saved as a FITS file or in an IDL save set. Other LPIA routines, run from the command line can then be used for map visualisation and for comparing with maps taken by other instruments. These also allow the map to be saved in postscript format.

## 5. COMPARISON WITH THE PRIME MODE

We were able to verify the calibration scheme for the data processing by comparing the parallel mode data to prime mode data i.e. when a prime mode observation occured within a parallel raster and/or at the same pointing as a parallel position. Several L01 observations were selected to provide a direct cross check between parallel and prime mode. All the L01 positions lie within the parallel rasters and some pointings are exactly coincident with one of the raster positions.

Fig. 2 shows two cases where prime mode observations are coincident with Parallel mode maps. The full spectrum shown in each panel is that from a prime mode full grating scan at a single pointing. In both cases, two adjacent pointings (a few arc seconds away) were made in parallel mode and these fluxes are shown as the open squares and filled diamonds on each panel.

The upper panel in Fig. 2 is for a pointing where a point source is on axis. This is an example of LWS producing well calibrated prime mode data. For extended sources and point sources off axis LWS beam exhibits fringing and in one direction the spectral fragments also do not show correct slopes. The lower panel shows an example where the data is from an LWS pointing of a bright extended source, and these optical effects appear in the data. Additionally, for this bright source, the effect of debiasing is not completely removed and in LW2 (centred at 120$\mu$m) a 'saggy' effect can be seen where the RSRF is no longer being correctly removed.

It is found that the agreement between the prime and parallel mode is generally good i.e. $<$20% overall, although they can differ by a factor of two in extreme cases. The best agreement is where uncertainties in dark current least affect the quality of the data. There are no systematic differences between prime and parallel mode, although detector SW1 can be more than a factor of two higher or lower than prime mode. This detector is often affected by transients and has a slow time constant leading to a strong variation of the flux level obtained.

## 6. COMPARISON WITH OTHER INSTRUMENTS

In addition to checking the internal calibration, comparisons were made with IRAS and ISOPHOT. For each of these other instruments the comparison made was difficult to interpret as the flux obtained for parallel observations is in a very narrow band (one grating resolution element) whereas the other instruments are observing in broad band.

This comparison allows a cross-check with other instruments, which cannot be done with internal checks, is to see if the beam shapes used for the conversion from $\mathrm{W\,cm^{-2}\,\mu m^{-1}}$ to $\mathrm{MJy\,sr^{-1}}$ are reasonable. Linear strips selected across LWS and IRAS maps to give a variation in brightness and structure have been compared. The agreement between the instruments at any point along an individual profile is generally within a few per cent.

## 7. DISCUSSION

The LWS parallel mode has successfully completed a partial sky survey utilising a part of the ISO telemetery which would not have otherwise been used, and it consists of a set of data for each LWS pointing when the instrument is not prime. A pipeline has been implemented which allows similar automated processing to the LWS prime mode data and which produces similar products. There are some differences to the parallel pipeline, mainly accounting for the downlinked ramp slopes in the first stage and for the non-availability of illuminator flashes for parallel and serendipity observations in the second stage.

There are three main uncertainties in the data. As with prime mode, when looking at faint sources, it is not possible to accurately determine the dark signal which can have a large spread of values. Hence when observing the background, the derived dark current subtracted from the data may be greater than the photocurrent measured from the source, leading to a negative flux.

The second aspect is the LWS fringing. Although the parallel mode fluxes follow the prime fluxes for fringed data (see Fig. 2), there is no way of determining from the parallel mode data alone whether a particular pointing contains fringed data. This can lead to a mismatch between detectors as the resolution element corresponding to the grating rest position can lie on a different part of the fringed data from one detector to another.

Finally, accurate glitch detection and removal is not possible because the detection of glitches on individual ramps can not be done due to only the slope being downlinked. This problem can be mitigated by the fact that there are often sufficient ramps at an individual pointing to allow statistical deglitching.

The parallel data are useful for investigating sparse maps of the ISM. This can be especially useful in the galactic centre region, areas of the galactic plane, and in the Rho Oph region. Although there is parallel data in the regions covered by deep extragalactic surveys such as Elias, LWS does not have sufficient sensitivity to provide any extra information.

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# THE SCIENTIFIC POTENTIAL OF THE ISOPHOT SERENDIPITY SKY SURVEY

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## ABSTRACT

The telescope movement of the Infrared Space Observatory (ISO) was utilized for scientific observations in the far-infrared (FIR) using the ISOPHOT C200 stressed Ge:Ga array detector. While slewing from one target to the next, strip scanning measurements of the sky at 170 $\mu$m were collected, comprising the ISOPHOT 170 $\mu$m Serendipity Sky Survey. It is the first slew survey designed as an integral part of a space observatory mission, and the only survey to date covering a large area of the sky at a wavelength region beyond the IRAS 100 $\mu$m limit. During more than 12000 slews, FIR measurements with a total slew length of more than 150000 degrees within nearly 550 hours were collected, corresponding to a sky coverage of about 15%. The slew data cover a wide variety of source types from unresolved compact sources to extended structures of the galactic cirrus and the large scale diffuse galactic FIR emission. The slew data analysis has been focused on the detection of compact sources, particularly galaxies. The selection of known galaxies from the Serendipity Survey data requires a cross-correlation with galaxy entries in the NED and Simbad databases and a subsequent cross-check of optical images from the Digital Sky Survey. A large catalogue with 170 $\mu$m fluxes for $\approx$ 2000 galaxies is currently being compiled. The particularly interesting rare galaxies with very cold dust and very large dust masses further require additional FIR data from the IRAS survey as well as measured redshifts. A large fraction of the compact galactic structures are pre-stellar cores inside cold star forming regions. Early stages of medium and high mass star forming regions are identified by combining compact bright and cold Serendipity Survey sources with the near-infrared 2MASS and MSX surveys. This combination indicates large dust masses in conjunction with embedded young stars of early spectral types. In all the studied samples of different object classes the 170 $\mu$m flux provides the crucial data point for a complete characterization of the FIR spectral energy distributions and the derivation of total dust masses. Follow-up observations are underway to study selected objects in more detail.

Key words: Far Infrared Surveys, Data Analysis, Observatory Operations

## 1. INTRODUCTION

The far-infrared (FIR) wavelength region is crucial for the investigation of the cold dust content of normal, non-active galaxies with low or moderate star-formation rates such as the Milky Way. Dust exposed to the interstellar radiation field acquires temperatures in the range 15 - 30 K, and the spectral energy distribution (SED) peaks between 100 $\mu$m and 200 $\mu$m. The long wavelength detectors of ISOPHOT covered for the first time this wavelength region, and quite a number of studies of individual as well as small samples of galaxies have been carried out. These investigations confirmed the supposition that cold dust is ubiquitously found in these types of galaxies and their dust mass is higher by a factor 2 - 10 than that derived from the shorter wavelength IRAS data.

However, the collection of pointed ISOPHOT data of galaxies is still not large enough to provide a sufficient statistical sample to investigate the FIR properties of galaxies as function of e.g. Hubble type, and to provide the basis for selecting extraordinary objects such as galaxies with very cold dust or very large dust masses. By using the slewing time of ISO (Kessler et al. 1996) for scientific observations beyond the IRAS 100 $\mu$m wavelength limit, the ISOPHOT (Lemke et al. 1996) Serendipity slew survey (Bogun et al. 1996) avoided the problem of the prohibitively long observation time, which would have bee required for pointed photometric observations of a large galaxy sample.

Unlike the slew surveys from other space observatories, where the data taken between pointed observations have eventually been analyzed long after the end of the satellite's lifetime (Reynolds et al. 1999; Elvis et al. 1992), ISO was the first to include a slew survey as an integral part of its mission. The ISOPHOT team proposed to utilize the otherwise unused slewing time for scientific purposes (Lemke & Burgdorf 1992) already early in the mission preparation. Only the ISOPHOT detector with its fast read-out in conjunction with broad band filter had the prospect of delivering data serendipitously not only for bright extended FIR emitting material distributed on large scales in the Galaxy but particularly allowing the detection of a sufficiently large number of cold point or marginally extended sources for subsequent statistical analysis of source catalogues. The ISOPHOT Serendipity Survey successfully delivered data throughout the whole ISO mission (Stickel et al. 1999), and early scientific results were already obtained during the on-going mission (Bogun et al. 1996).

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## 2. OBSERVATIONS AND SOURCE EXTRACTION

The Serendipity Survey data were taken with the ISOPHOT C200 detector (Lemke et al. 1996), a $2\times2$ pixel array of stressed Ge:Ga with a pixel size of $89\farcs4$, which was used in conjunction with the C_160 broad band filter (reference wavelength $170\,\mu$m, equivalent width $89\,\mu$m). The high dynamic range of sky brightness between the galactic plane and the galactic poles as well as the high slew speed of the telescope (max. $\approx 8'\,\mathrm{s}^{-1}$) required the fastest uncompressed read-out rate of the C200 camera with 1/8 s reset interval time, during which four detector read-outs took place. The extended lifetime of the ISO mission lasted 875 revolutions, during which more than 12000 slews totaling about 550 hours of observing time were gathered. The total slew length exceeds 150000°, resulting in a sky coverage of ≈ 15 %.

Long slews with a duration of at least 75 s were preceded by a responsivity measurement with the on-board Fine Calibration Source, which is used to convert the detector signals from the read-out ramps to surface brightnesses. For shorter slews the default calibration is used. This step is done within the ISOPHOT standard data processing software PIA[1] (Gabriel et al. 1997). The slew data consist of four datastreams, the surface brightnesses for each pixel as a function of sequential ramp number, together with additional data vectors containing detector positions, read-out time, processing flags, and the like.

Compact source candidates are searched for in the flux calibrated slews by using dedicated routines to determine the slew background, to coadd the four background subtracted datastreams and to find peaks therein, and to analyze the source candidates. The development of the processing routines as well as a much more detailed description of the slew data analysis can be found elsewhere (Stickel et al. 1998a; Stickel et al. 1999; Stickel et al. 2000a). Processing results such as coordinates, fluxes and associations in other databases are collected in a SQL database, while the processed slew data streams are kept as disk files for later inspection. A total of ≈ 325000 compact source candidates were extracted from the slews, the majority of which are due to galactic cirrus structures, either compact peaks with underlying extended and possibly irregular FIR emission, or relatively narrow elongated ridges crossed nearly perpendicular.

## 3. GALAXIES

The first list of $170\,\mu$m fluxes for 115 catalogued galaxies selected from the Serendipity Survey data (Stickel et al. 2000b; Stickel et al. 2001) was restricted to high quality crossings on a low FIR background, and used rather stringent selection criteria. Nevertheless, it was already the largest sample of galaxies with measured $170\,\mu$m fluxes and provided the first statistical distributions of dust color temperatures, dust masses, and gas-to-dust ratios.

To collect all galaxies among the Serendipity Survey compact source candidates, it is not sufficient to carry out a simple search for a galaxy association in the NED and Simbad databases within the positional uncertainties. Such an approach is bound to produce spurious associations with a large number of compact cirrus knots from the Milky Way, since the databases also include numerous faint galaxies with FIR fluxes far below the Serendipity Survey detection limit of ≈ 1 Jy. The overall ratio between compact cirrus structures and genuine point-like or slightly resolved sources is ≈ 10:1, indicating a quite severe cirrus confusion at $170\,\mu$m.

Therefore, a hierarchical search encompassing several steps is carried out to search for the Serendipity Survey sources with known galaxy associations. First, the position of each of the Serendipity Survey source candidates was queried in the NED and Simbad databases. If a galaxy was listed within $5'$, the slew data and the corresponding IRAS / ISSA $100\,\mu$m imaging data for Serendipity Survey source candidates were checked to remove spurious sources caused by unrecognized cosmic ray hits and bad detector pixels, and to separate cirrus structures from genuine point or slightly resolved sources. Since the extended cirrus structures often contain FIR emission on a wide range of angular scales, the limited angular resolution of the IRAS and ISOPHOT Serendipity Survey data do not always allow to determine whether the compact source candidate is actually a central cirrus core or a superposed galaxy. Therefore, for each of the unambiguous compact Serendipity Survey sources and also for questionable compact sources possibly due to cirrus, the R band images of the Digital Sky Survey were retrieved from the archive. Checking the DSS images is an effective method to get rid of cirrus structures mimicking compact FIR emission from galaxies, since bright FIR sources are expected to be associated with relatively nearby optically bright galaxies. The final list of galaxies is currently being compiled and comprises ≈ 2000 sources with compact Serendipity Survey counterparts. For a number of nearby galaxies with apparent diameters significantly greater than the ISOPHOT beam only lower limits for the $170\,\mu$m fluxes can be obtained. However, for the $170\,\mu$m number counts, they must nevertheless be included.

A severe limitation could be the fact that even for optical brightnesses of 16 mag or brighter, not all galaxies are catalogued and listed in databases. Among the compact Serendipity Survey source candidates, it is likely that there are more as yet uncatalogued galaxies to be found. An example for that is a FIR source found in the North Ecliptic Pole region during the first small statistical assessment of the Serendipity Survey and identified as an apparently interacting galaxy pair not appearing in any of the databases (Stickel et al. 1998b).

Of particular interest is the existence of a significant very cold dust component in the temperature range 10 - 15 K, much colder than the typical interstellar cirrus with a temperature of ≈ 17 K detected in e.g. the Milky Way and M31. Prime candidates for an additional very cold dust component are galaxies showing a cold SED already in the FIR, as indicated by

[1] The ISOPHOT data presented in this paper were reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium. The ISOPHOT Consortium is led by the Max-Planck-Institute für Astronomie, Heidelberg.

large 170 $\mu$m / 100 $\mu$m flux ratios. If present, a very cold dust component should show up as a significant excess of the sub-mm fluxes above the extrapolation of the SED from the longest wavelength of the IRAS (100 $\mu$m) and the ISOPHOT Serendipity Survey (170 $\mu$m). A small sample of 15 cold galaxies from the Serendipity Survey were selected for a follow-up study of their FIR - sub-mm spectral energy distributions with the bolometer array SCUBA at the JCMT. All galaxies have an optical diameter smaller than $2'$, corresponding to a redshift greater than 2200 km/s, so that the galaxies are completely covered by the SCUBA field of view in jiggle-mapping mode. For all sources, 450 $\mu$m as well as 850 $\mu$m photometry was obtained. Remarkably, the SEDs containing the four fluxes at 100 $\mu$m, 170 $\mu$m, 450 $\mu$m, and 850 $\mu$m of all observed sources can quite well be represented with the combination of only two modified black-bodies with an emissivity frequency exponent of 2. The average temperature of the colder component in the observed galaxies is 18 K $\pm$ 2 K and agrees well with initial estimates from the combined IRAS 100 $\mu$m and ISOPHOT Serendipity 170 $\mu$m photometry. This temperature is similar to that found for our Milky Way and other non-active galaxies. Particularly, no indication was found for a significant excess of the sub-mm fluxes above the fluxes imposed by the dust component with an average dust temperature of 18 K.

The typical dust mass of spiral galaxies of $\approx 10^{7.5}\,\mathrm{M}_{\odot}$, with a relatively sharp drop-off towards higher dust masses (Stickel et al. 2000b). A potentially very interesting class of objects are galaxies with very large masses of cold dust in the temperature range 15 - 25 K. Such objects would appear as ultraluminous FIR emitters ($\gtrsim 10^{12}\,\mathrm{L}_{\odot}$), but nevertheless would have a cold FIR SED, similar to what is found for normal local non-active spiral galaxies. As a result of the Malmquist bias, such objects should show up in flux limited samples just above the detection limit with redshifts much higher than the majority of sources. Indeed, one such source (z $\approx$ 0.2) has now been found, where the combined IRAS – ISOPHOT data together with 1.3 mm follow-up measurements give a dust temperature of 21 K and a total FIR luminosity of $2\times10^{12}\,\mathrm{L}_{\odot}$ (Krause et al. 2002a).

## 4. GALACTIC SOURCES

The coldest interstellar clouds and cloud cores within star-forming regions are searched for by a combination of the Serendipity slew data and the surface brightnesses extracted from the IRAS / ISSA 100 $\mu$m and 60 $\mu$m maps along the slew path. The Serendipity slew data are smoothed to match the resolution of the IRAS - extracted data streams, and the 170 $\mu$m / 100 $\mu$m ratio along the slews is inspected for peaks indicating cold compact structures. A color parameter related to the dust color temperature of the sources is derived by finding the slope of a straight line of the 170 $\mu$m vs. 100 $\mu$m brightness diagram. A comparison of this 170 $\mu$m / 100 $\mu$m color temperature of the dust with the kinetic temperature of the gas in a sample of 14 ammonia cores showed a statistical correlation between the two temperatures (Hotzel 2001). This is remarkable, as it not expected that gas and dust are directly thermally coupled.

The search for pre-stellar cores is based on the assumption that cold cores, as identified by a large 170 $\mu$m / 100 $\mu$m color parameter, are the favourable hosts for very cold condensations. The cores are being found as sub-mm and mm sources without an associated IRAS point source. A survey aimed at finding pre-stellar objects outside previously studied regions has been started, where in the first step, the cold cores are mapped in molecular high density tracers, such as $C^{18}O$, $N_2H^+$ or $NH_3$. Then, the densest parts of the cores from the molecular line study are observed in mm/sub-mm continuum to trace the emission from the dust. Case studies of cold cores with molecular line data and mm data support the assumption that cold cores from the Serendipity Survey are closely linked with pre-stellar cores (Hotzel et al. 2001).

The low temperatures for the coldest cores found are confirmed by high $H_2$ gas densities and low gas kinetic temperatures. Furthermore, the 170 $\mu$m surface brightness is correlated with optical extinction data over a much larger range than the 100 $\mu$m brightness, indicating that the 170 $\mu$m surface brightness is a very good tracer of dust column density. The initial study of the Chamaeleon (Tóth et al. 2000) is being extended to cover the whole sky (Fig. 1), which will allow statistical studies of the cold cores and their correlation with other observational data.

The NIR emission of already formed stars together with the strong FIR emission of a large dust mass still surrounding them is used to detect early stages of medium and high mass star forming regions. A subset of cold compact Serendipity Survey sources with 170 $\mu$m / 100 $\mu$m flux ratio greater than 2 was cross-correlated with source catalogues from the near-IR 2MASS sky survey and the mid-IR MSX satellite mission. The high 170 $\mu$m / 100 $\mu$m flux ratio indicates a large amount of cold dust, while the required NIR sources separate the sites with on-going star formation from cold interstellar cirrus structures. A large sample of $\approx$ 200 candidates has been collected, for which kinematic distances will be estimated from recent CO line emission data. Sub-mm follow-up observations of three sources have already been obtained. Remarkably, the brightest sub-mm sources are in no case coincident with NIR sources, as expected for the less evolved objects in these regions. One of the investigated sources contains a young bright Herbig B2 star with $\approx 6\,M_{\odot}$ and estimated age of the less than 40000 y, while in adjacent region the dust is still very cold with a temperature of $\approx$ 12 K (Krause et al. 2002b).

## 5. SOLAR SYSTEM OBJECTS

Planets and asteroids are of particular importance for the Serendipity Survey as primary FIR calibrators, since they increase the available sample of dedicated calibrators and extend the compact source calibration to the highest fluxes.

Only by a hierarchical preselection of possible targets (Müller et al. 2002), it was possible to identify the solar system objects among the large number of compact Serendipity Survey source

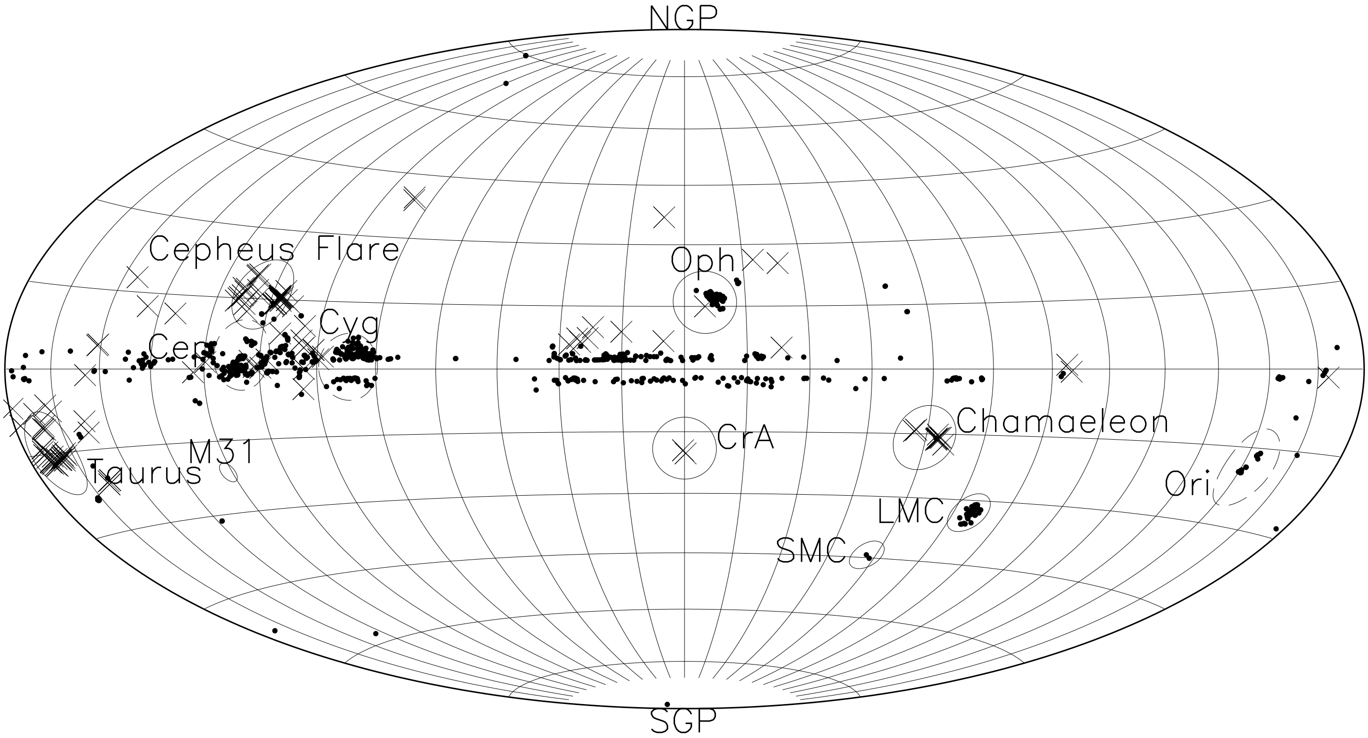


*Figure 1. The overall distribution of the coldest cores (crosses) with color temperatures below 12 K across the Milky Way. For comparison, warmer cores are indicated by filled dots. The largest cluster of very cold cores is found in the Taurus and Cepheus Flare region, both of which are associated with large molecular cloud complexes (Hotzel 2001).*

candidates. A complete cross-check of all $\approx$ 69000 known solar system objects against the $\approx 4 \times 10^6$ individual pointings of all $\approx$ 12000 slews would have required the prohibitively large number of $\approx 3 \times 10^{11}$ N-body ephemeris calculations. With limits on the expected flux and distances to the slews, the number of required two- and N- body ephemeris calculations was reduced to a tractable number. Eventually, only $\approx$ 90 slews had to be checked for the presence of sources near the predicted positions. Among those solar system objects, for which detailed models are available to derive the 170 $\mu$m flux, two planets (Neptune, Uranus) and four asteroids were unambiguously detected in the Serendipity Survey (Müller et al. 2002). Neptune was crossed eight times with an excellent flux agreement between repeated crossings. The two planets extend the calibration baseline to $\approx$ 700 Jy. There is a considerable overlap in the flux density between the asteroids and the serendipity calibration galaxies observed with the photometric mapping method. The good overall agreement in the derived scale factors is an independent and direct cross-check of the two different calibration methods (Fig. 2).

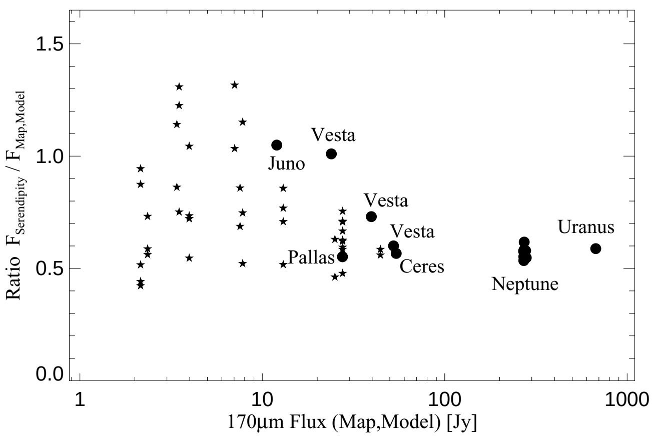


*Figure 2. Distribution of ratios of the Serendipity Survey fluxes and photometric fluxes from mapping observations of galaxies (asterisks) and theoretical models of solar system objects (filled circles) vs. photometric fluxes. The ratio of fainter solar system objects confirm the values found from mapping observations. The bright solar system objects extend the Serendipity calibration out to $\approx$ 700 Jy, with an excellent reproducibility, as shown by the repeated measurements of Neptune.*

## 6. CONCLUSIONS

The ISOPHOT Serendipity Survey slew data encompass a wide variety of astrophysical sources within the Galaxy and extragalactic systems, and its analysis is pursued in various directions. The selection of galaxies and the preparation of a large catalogue containing 170 $\mu$m for $\approx$ 2000 galaxies is a primary goal, allowing for the first time a detailed study of their FIR properties such as dust temperatures, dust mass, and gas-to-dust ratios depending on their Hubble type. A large sample is also needed for the selection of rare and unusual types of galaxies. The investigation of galactic sources include regions of medium and high mass star forming regions and the search for the coldest cores across the galaxy. In addition, 170 $\mu$m fluxes for classes of objects rarely observed with ISOPHOT at the longest FIR wavelengths are collected by cross-correlating catalogues of these objects with the compact source candidates from the ISOPHOT Serendipity Survey.

In all these cases, the new 170 $\mu$m flux measurement is crucial in determining the overall FIR SED and deriving the total dust mass including cold components not directly measured by the shorter wavelength IRAS 60 $\mu$m and 100 $\mu$m data. Readily accessible supplementary information from databases and surveys allow the selection of samples large enough for statistical studies and a prerequisite to find rare or extraordinary objects with unusual properties. To obtain similar large samples of various object types would have required a prohibitively large fraction of the available dedicated observing time of the ISO observatory mission. For genuine compact sources unrelated to the interstellar medium of the Milky Way, this multi-wavelengths approach is the only way to separate the sources of interest from cirrus structures appearing on the slews with similar size.

The raw Serendipity slew data are accessible via the general ISO data archive interface. The calibration and extraction of astrophysically relevant information from the slews, however, requires in depth knowledge of the ISOPHOT C200 detector and the ISOPHOT data processing, as well dedicated routines adapted to the slew data. The results from the Serendipity Survey data analysis will therefore be made available as catalogues of various object classes, and eventually be incorporated into and available from databases such as Simbad and NED. Specific projects which might want to utilize already processed Serendipity data should contact the first author at the ISOPHOT Data Centre in Heidelberg.

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