# A DEEP AND ULTRA-DEEP ISOCAM COSMOLOGICAL SURVEY THROUGH GRAVITATIONALLY LENSING CLUSTERS OF GALAXIES*

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## ABSTRACT

We present imaging results and source counts from an ISOCAM deep and ultra-deep cosmological survey through gravitationally lensing clusters of galaxies at 7 $\mu$m and 15 $\mu$m. A total area of about 53 sq.arcmin was covered in maps of three clusters. The lensing increases the sensitivity of the survey. A large number of luminous mid-infrared (MIR) sources were detected behind the lenses, and most could be unambiguously identified with visible counterparts. Thanks to the gravitational amplification, these results include the faintest MIR detections ever recorded, extending source counts to an unprecedented level. The source counts, corrected for cluster contamination and lensing distortion effects, show an excess by a factor of 10 with respect to the prediction of a no-evolution model, as we reported for A2390 alone in Altieri et al. (1999). These results support the A2390 result that the resolved 7 $\mu$m and 15 $\mu$m background radiation intensities are $(1.7\pm0.5)\times10^{-9}$ and $(3.3\pm1.3)\times10^{-9}$ W m$^{-2}$ sr$^{-1}$ respectively, integrating from 30 $\mu$Jy to 50 mJy.

Key words: ISO; infrared astronomy; gravitational lensing; galaxy clusters; number counts; morphology.

## 1. INTRODUCTION

Following the identification of the first cosmological gravitational lens by Young et al. (1980) the theoretical and observational exploitation of the lensing phenomenon developed rapidly. In 1987 luminous giant arcs were discovered in the fields of some galaxy clusters by Lynds and Petrosian (1986), and independently by Soucail et al. (1987), and these were soon recognised to be Einstein rings (Paczyński 1987). Since then observations of cluster-lenses have been extended to wavelengths other than the visible (e.g. Smail et al. (1993) for the NIR, and Smail et al. (1997) for the Sub-mm region). At the same time models describing the lensing have been refined (Kneib et al. 1996) to the point where source counts made through a cluster lens can be corrected to yield the counts which would be found in the absence of the lens.

We report key results of a deep-survey programme, initiated almost a decade ago as part of the "Central Programme" of the ISO mission, and which has extended the exploitation of the gravitational lensing phenomenon to the Mid-infrared (MIR) for the first time by using ISOCAM (Cesarsky et al. 1996) on ESA's ISO spacecraft (Kessler et al. 1996).

The programme achieved deep and ultra-deep (ISOCAM) imaging through a sample of gravitationally lensing clusters of galaxies, benefiting from the lensing to search for background objects to a depth not otherwise achievable. Lensing amplifies sources and, for a given apparent flux limit, suppresses confusion, due to the apparent surface area dilation. To the flux-limits of this sample, even rich foreground galaxy clusters are essentially transparent at 15 $\mu$m.

## 2. OBSERVATIONS, DATA-REDUCTION AND DATA-ANALYSIS

### 2.1. Observations

We observed the fields of the well-known gravitationally lensing galaxy clusters Abell 370, Abell 2218 and Abell 2390. A total area of about 53 sq.arcminutes was covered. Table 1 lists the observational parameters of the survey which used CAM's 6.7 $\mu$m (LW2) and 14.3 $\mu$m (LW3) filters. By employing the CAM 3 arcsec per-pixel field-of-view (PFOV) and raster

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step sizes which were multiples of 1/3 pixel, over many raster steps, we achieved a final mosaic pixel size of 1 arcsec. The diameter of the PSF central maximum is, in arcseconds, $0.84 \times \lambda(\mu m)$, and the FWHM is about half that. The final 1 arcsec pixel size improved source separation and allowed a better cross-identification with observations at other wavelengths. This strategy differs from many other CAM deep surveys which used the 6 arcsec per-pixel field-of-view. The $5\sigma$ sensitivity limits are given in Table 1 and depend on the lensing cluster in question. These limits refer to apparent source brightness **before** correction for the effects of lensing. For the clusters observed, the highest-magnification regions of the lenses give amplifications of 5 to 10 - so with this method we could in principle make $5\sigma$ detections in LW2 and LW3, of sources with intrinsic brigtnesses as low as $6\mu$Jy and $13\mu$Jy respectively, if any such faint background source falls in the regions of strongest lensing. Typical magnifications are about 2 over the central few square-arcmin of the clusters.

Lensing also causes a surface dilation effect over the area probed. This spatial dilation is stronger towards the core of the cluster and increases with source-plane redshift. These effects need to be corrected during analysis in order to compare results with *blank* sky counts (e.g. in the Hubble Deep field and Lockman Hole – Rowan-Robinson et al. 1997; Taniguchi et al. 1997; Aussel et al. 1998; Elbaz et al. 1998).

### 2.2. Data reduction and analysis

The reduction of ISO faint source data is extremely challenging and many work-years have been invested in developing effective and reliable techniques. The ultimate performance is particularly sensitive to the effectiveness with which the detector's global responsive transient and cosmic-ray-induced glitches can be removed from the data. Two substantially independent data reduction approaches were applied. These are described in detail in the ISOCAM Faint Source Report (Altieri et al. 1998 - available on the ISO www page). We particularly refer to Sections 3.3 and 3.4 of that document, and related sections. Key techniques employed to perform photometry and to extract source-lists and sensitivity limits are described in Section 5 of the report and also in Altieri et al. (1999).

Detailed lensing models of the three clusters used have been produced by Kneib et al. (1996) and (1999), and Bezecourt et al. (1999). By correcting for the lens magnification and surface dilation effects, contamination by cluster galaxies (mainly at $7\,\mu$m), and non-uniform sensitivity of our maps, we can derive number counts to compare with blank sky counts. The object density per flux bin was computed using magnification-dependant surface areas derived from the lensing models so dividing the maps into sets of sub-maps. The unreliable data at the boundaries of the maps were discarded.

## 3. RESULTS

In Section 2.1. the potential limiting sensitivity of this survey was described (6 and $13\,\mu$Jy at $5\sigma$ in LW2 and LW3 respectively). Achieving this potential is a matter of luck with respect to source distribution behind the lens. In practice, the faintest $15\,\mu$m source detected was intrinsically an $18\,\mu$Jy source amplified to $80\,\mu$Jy (a $6\sigma$ detection).

Fake-source simulations are described in Altieri et al. (1999), and show that our 80% completeness levels in LW3 (for which we report source counts here) before accounting for lensing are : 500, 250 and $100\mu$Jy for A370, A2218 and A2390, respectively. Our simulations for A370 and A2218 are still preliminary so their associated completeness levels may be adjusted slightly when the full analysis is finished. Lensing has a variable effect over the field so it is not possible to state a global completeness level after correction for lensing. Rather, we stopped counting at the 50% completeness flux level in the highest magnification bins we could use. This was an intrinsic $33\,\mu$Jy at $15\,\mu$m for A2390, corresponding to a $5\sigma$ threshold for counting a source.

### 3.1. Cluster images at $15\,\mu$m

Overlays onto visible images of ISOCAM LW3 ($15\,\mu$m) deep images through the three clusters can be found in figures 1, 2 and 3. (See also Barvainis et al. (1999) for additional ISO data on A2218.)

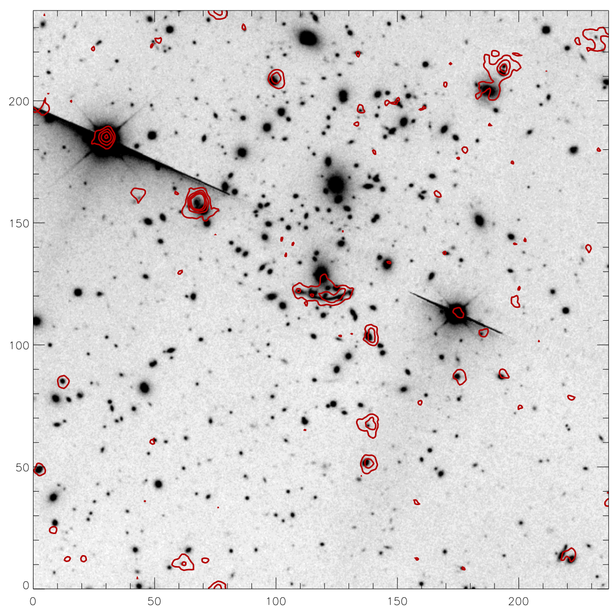


*Figure 1. Contours of an ISOCAM $15\,\mu$m image of Abell 370 over a deep CFHT I-band image. The giant arc is well detected by ISO, along with a number of other MIR sources in the field, some with quite faint optical counterparts. (All axes are arcseconds.)*

From these images we can remark that we generally do not see the optical arc(lets) at $15\,\mu$m. We see a Large Number of MIR sources, shown from spectroscopic, photometric or lensing redshifts to be behind the lens. These are, in effect, IR arc(let)s.

Thanks to our high-resolution images we have been able to unambiguously identify 90% of sources with

*Table 1. Observational parameters and lensing clusters of galaxies used for the survey. On-chip integration time ($t_{int}$) was always 5.04 seconds and the 3 arcsec per-pixel field-of-view was used.*

| FIELD | FILTER † | Readouts per step | Raster steps X | Raster steps Y | dm arcsec | dn arcsec | area (sq.arcmin) | depth $5\sigma$ ($\mu$Jy) | No. of times repeated | Tot. time (sec.) |
|---|---|---|---|---|---|---|---|---|---|---|
| Abell 2390 | LW2 | 13 | 10 | 10 | 7 | 7 | 5.3 | 33 | 4 | 29300 |
| | LW3 | 13 | 10 | 10 | 7 | 7 | 5.3 | 67 | 4 | 29300 |
| Abell 2218 | LW2 | 14 | 12 | 12 | 16 | 16 | 16 | * | 2 | 22000 |
| | LW3 | 14 | 12 | 12 | 16 | 16 | 16 | 150 | 2 | 22000 |
| Abell 370 | LW2 | 10 | 14 | 14 | 22 | 22 | 31.3 | * | 2 | 22688 |
| | LW3 | 10 | 14 | 14 | 22 | 22 | 31.3 | 330 | 2 | 22688 |

(*) in Metcalfe et al. (1999). (†) LW2 and LW3 filters have reference wavelengths 6.7 and 14.3 $\mu$m, respectively.

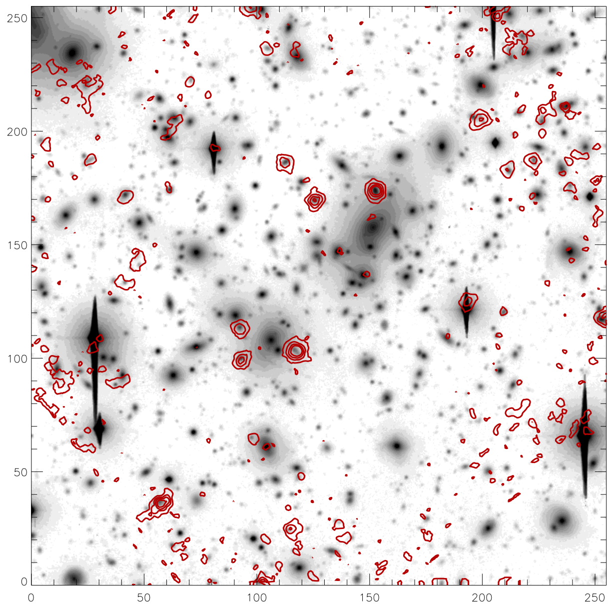

*Figure 2. Contours of the inner $4 \times 4$ square arcmin of an ISOCAM 15 $\mu$m image of Abell 2218 over a deep Palomar 5m I-band image (Smail, private communication). Note the strong ISO detection of the giant arc at (117,105), the several MIR sources corresponding to faint optical counterparts [e.g. (200,205), (45,140), (105,240)] and the fact that the IR "arclets" are generally not from the same population as the known visual arclets.*

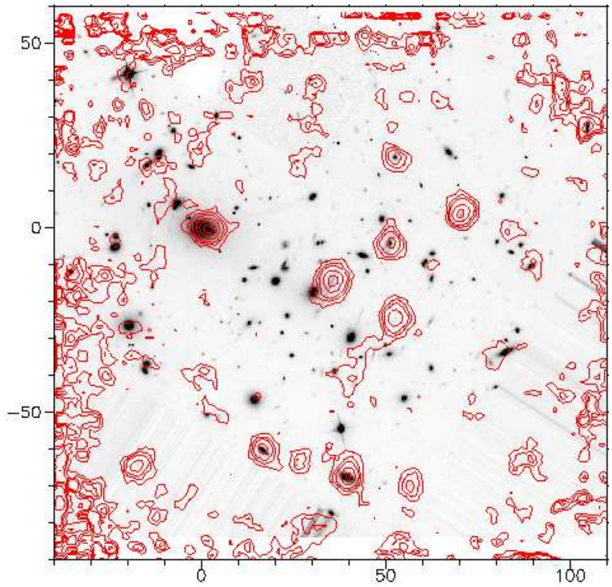

*Figure 3. Contours of an ISOCAM 15 $\mu$m image of Abell 2390 over an HST (F814W) I-band image. Note the ISO detection of part of the straight arc near the centre of the image (35,-15), and the two strong ISO detections (spectroscopic redshift unknown) at (53,-25) and (70,05). These objects have extremely red colours and very faint visual fluxes. Their colours, if interpreted as due to redshift, imply photometric redshifts greater than 3.*

(sometimes extremely faint) counterparts in deep NIR and visual (HST/WFPC2 and ground-based) images. Spatial resolution is good enough to allow recognition of IR correlations with the visual morphology of objects. (E.g. The ISO detection peak matches the bright visual knot in the straight arc (Pelló et al. 1991) near the centre of the A2390 map.)

We found that at 7 $\mu$m about half the sources are cluster galaxies, the other half are lensed background sources. We infer that almost all 15 $\mu$m sources are lensed background galaxies because most sources for which we have spectroscopic redshifts are, while the photometric and lensing-inversion redshifts for the remaining sources are consistent with locations beyond the cluster. This indicates that, at 15 $\mu$m, the cluster-core becomes transparent, similar to the Sub-mm case (Smail et al. 1997).

Some ISO targets have extremely red optical and NIR colours. It appears that 15 $\mu$m imaging favours selection of star-forming galaxies and dusty AGNs that are not evident in UV/optical surveys.

### 3.2. Number counts and source properties

We have extracted 15 $\mu$m source counts for the three clusters taking only $5\sigma$ detections into account for statistical studies. The analysis performed for A370

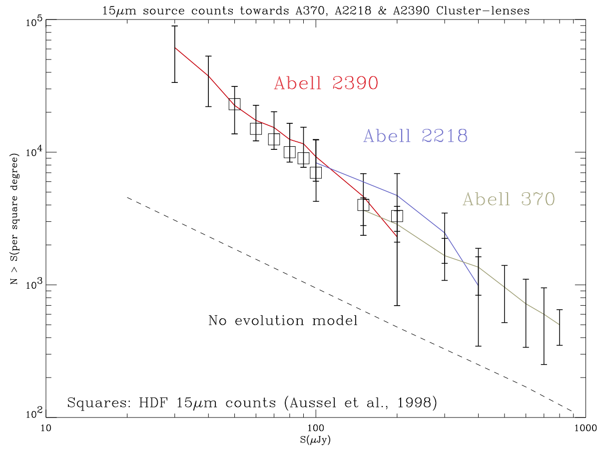


*Figure 4. ISO 15 μm source counts for three clusters. The slope from A2390 is -1.5 ± 0.3 and $N_{15}$(>30 μJy) = 13 ± 5 arcmin$^{-2}$ at 15 μm. Counts for A2390 are fully corrected for lensing. Counts for A370 and A2218 have only been roughly corrected. Planned final corrections are not expected to significantly alter the slope, but could move A370 and A2218 datapoints slightly along the curve towards lower flux.*

and A2218 is provisional, and is being refined. It is expected, however, that the final results will differ only in detail. We find a total of 71 sources within our survey area (see Table 1), with 30, 23 and 18 from A2390, A2218 and A370 respectively.

The 15 μm counts show a steadily increasing excess by a factor of order 10 over no-evolution models (see Figure 4, and Franceschini et al. 1994). These results confirm the Lockman hole result of Elbaz et al. (1998), and agree with the HDF counts of Aussel et al. (1998). There is no sign of flattening of the counts at the faintest levels. The slope stays close to -1.5 ± 0.3 down to the 30 μJy limit. These source densities favour extreme evolution models.

Integrating the number counts over our A2390 flux range (30 μJy to 200 μJy) and over other ISOCAM surveys (Elbaz et al. 1998) up to 50 mJy we find that the resolved background light is $(3.3\pm1.3)\times10^{-9}$ and $(1.7 \pm 0.5) \times 10^{-9}$ W m$^{-2}$sr$^{-1}$ at 15 μm and 7 μm, respectively. The 15μm lower limit is close to the upper limit from the gamma-CMBR photon-photon pair production (Stanev and Franceschini 1997).

## 4. CONCLUSIONS

The method of looking through gravitational lenses served to extend ISO coverage of background sources to the deepest levels, especially at 15 μm. The results suggest that abundant star formation occurs in very dusty environments at z∼1. Caution must be employed to take account of the effects of dust in inferring global star formation history from UV or optical luminosities of high-z galaxies. We will present a more complete description of these MIR observations, including 7 μm and 15 μm photometry. in a forthcoming paper (Metcalfe et al. 1999). A detailed study of the optical properties of the MIR galaxies may reveal the nature of the evolving or new population of luminous IR sources.

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