ISOPHOT 175 MICRON SURVEY IN THE LOCKMAN HOLE*

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ABSTRACT

An ISOPHOT 175 μm map covering approximately a $22' \times 22'$ area in the Lockman Hole is presented. The observations were made with the raster mapping AOT PHT22 and data were reduced with with the PIA (PHOT Interactive Analysis) package. The correlation between the HI column density and Galactic cirrus emission is used to predict 0.63 MJy sr^{-1}for the contribution to the 175 μm brightness from cirrus. The one σ ciruss confusion noise is estimated to be 0.2 - 3 mJy, which is by far smaller than the detection limit ($\sim$ 50 mJy) in this survey. Numerous point sources are found on the map, and the detection level is limited probably by galaxy confusion. The optical counterparts of bright 100 mJy sources are very faint or completely invisible on the Palomar Sky Survey I E-plate. Given R = 19 - 20 mag for the limiting magnitude, the color R - [175μm] rejects star forming spirals and starburst galaxies, and indicates that star forming dwarf galaxies like II ZW 40 and ultra-luminous IR galaxies like Arp 220 for the possible identification. The surface number density of 175 μm sources is compared with the models of galaxy counts.

Key words: galaxies: evolution, galaxies: infrared.

1. INTRODUCTION

ISOPHOT(PHT), the imaging photo-polarimeter (Lemke et al. 1996) on-board ISO (Infrared Space Observatory; Kessler et al. 1996) is equipped with the broad 175 μm band combined with a 2×2 stressed Ge:Ga detector array with an approximate linear pixel size of 92″. This band is well suited for finding distant star forming galaxies, because of the large, *negative* k-corrections:the 60 - 100 μm peak of dust emission from star forming galaxies is red-shifted into this 175 μm band with a 90 μm bandwidth. As part of Japan/UH cosmology program, a 175 μm survey was conducted in two $40' \times 40'$ fields in the Lockman Hole in order (1) to study the evolution of star forming galaxies and (2) to extract the cosmic far-infrared background emission in $40' \times 40'$ areas matching with the COBE beam. This article presents a 175 μm map of a $22' \times 22'$ area called LHNW4 which is one of four subfields in $40' \times 40'$ field LHNW.

2. LOCKMAN HOLE, CIRRUS CONFUSION NOISE, AND OBSERVATIONS

Lockman et al. (1986) have shown only < 0.1 % of the HI survey area, which covers $\delta \geq -40^o$, have N_{HI}(total HI column density) < 7×10^{19} cm^{-2}. These lowest column density all come from part of the sky centered on $\alpha = 10.7^h, \delta = 58^o$ or $l = 150^o$, $b = 53^o$. Our fields have N_{HI}=$5 \times 10^{19} cm^{-2}$. Assuming 1.25 MJy sr^{-1}at 175 μm per 10^{20} HI cm^{-2} (Boulanger, et al. 1996) implies B_{cirrus} = 0.63 MJy sr^{-1}for the cirrus emission or only 125 mJy per pixel (92″ × 92″). The models by Guatier et al. (1992) then predicts σ_{cirrus} = 0.2 mJy for one σ confusion noise. The ISO observations of cirrus (Lemke 1997) indicates σ_{cirrus} = 0.4 - 3 mJy when $\sigma_{cirrus} \propto \lambda^{2.5} B^{1.5}_{cirrus}$ is applied. These are more than 10 times smaller than the detection limit ($\sim$ 50 mJy) achieved in this survey. Indeed, the Lockman Hole is the *WINDOW* for far-infrared cosmologists.

The survey was conducted with ISOPHOT on ISO in May to June 1996 with the raster mapping AOT PHT22. The integration time per raster point is 16 sec, providing four integration ramps with 127 non-destructive readouts each. It took approximately 8,900 sec to complete

*Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) and with the participations of ISAS and NASA. The ISOPHOT data presented in this paper was reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium led by the Max Planck Institute for Astronomy (MPIA), Heidelberg.

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a $20' \times 20'$ area; note one field is made up with four $20' \times 20'$ sub-fields. The step sizes are a half pixel ($46''$) in the satellite Y-axis and a full pixel ($92''$) in the Z-axis. This means all the pixels looked at the same directions on the sky. Thus, the resultant maps should have virtually perfect flat-fielding, and be very robust against slow detector signal drift. Even in the Lockman Hole, 2% error in flat-fielding can cause 10 mJy fluctuation across the map, hampering detection of 50 mJy sources with S/N = 5. There are no such systematic errors recognized in the map.

3. ISO 175 μm MAP AND COMPARISON WITH IRAS 100 μm

Figures 1 and 2 compare the 175 μm map of sub-field LHNW4 with the IRAS 100 μm map. The pixel size is $23'' \times 23''$ on the ISO map, while $15'' \times 15''$ for IRAS. The IRAS map is a FRESCO (Full RESolution Survey COaddition) processed product supplied from IPAC. Signal to noise ratio per detector on the ISO map is about 100, where noise only includes the statistical error of data samples and signal includes zodiacal light contribution to the surface brightness. The surface brightness across the IRAS map ranges from -0.2 to 0.1 MJy $sr^{-1}$with the zodiacal contribution subtracted, and its standard deviations to each pixel is about 0.3. No IRAS point sources are cataloged in this field. On the ISO map, the extended brightness variation, the faint strip running from the lower left corner to the upper right seems to be common to the IRAS 100 μm map. Numerous faint spots should be point sources, but not caused by cirrus. The brightest spots are 100 mJy or brighter, and the detection limit is estimated to be around 50 mJy. The survey is quite likely to have reached the level of confusion by galaxies.

The optical counterparts of 100 mJy sources were searched on the PSS (Palomar Sky Survey) E plate. All of them are near the PSS detection limit or below. Given R = 19 - 20 mag for the detection limit, the color R - [175μm] rejects star forming spirals like M33 and starburst galaxies like M82. Figure 3 implies that the possible candidates are blue compact dwarf galaxies like II ZW 40 and ultra-luminous IR galaxies like Arp 220. It is noted that Arp 200 at z = 0.7 should be observed as 100 mJy sources at 175 μm.

4. ISOPHT 175 μm SOURCE COUNTS

The reader should keep in mind in the following discussions that the uncertainty of flux calibration is a factor of two in this work. The surface density for sources brighter than 100 mJy is $1.7 \pm 0.6 \times 10^5$ sr^{-1}. As seen in Figure 4, this agrees with the maximal model by Guiderdoni et al. (1997) with strongly evolving populations and the models by Franceschini et al. (1991) and Pearson and Rowan-Robinson (1996), both of which include moderately evolving populations. Notice that the large differences in counts among the models in the range of flux brighter than 1 Jy. This range should be covered by the ISOPHOT serendipity survey at the 175 μm band, the detection limit of which is around 1 Jy.

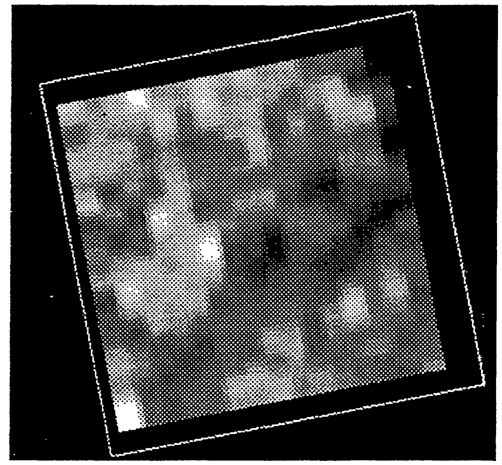

Figure 1. ISOPHOT 175 μm map of Lockman Hole sub-field LHNW4 which was taken with AOT PHT22. North is up and east to the left. The linear size of the map is 23.8' from side to side. The scale is $23'' \times 23''$ per pixel, while the 2×2 detector array has dimensions $184'' \times 184''$ and the step size in rastering is by $46''$ and $92''$ in the satellite axis directions. The map appears confused probably by galaxies and the detection limit is tentatively estimated to be $\sim$ 50 mJy. The surface brightness measured by COBE is 2.79 MJy sr^{-1} at 160μm (Reach 1996). Signal to noise ratio per pixel is about 100, where noise only includes the statistical error of data samples and the signal includes zodiacal light contribution to the surface brightness. The HI column density implies 0.63 MJy $sr^{-1}$for the contribution to the observed surface brightness from cirrus emission. The one σ cirrus confusion noise is estimated to be 0.2 - 3 mJy, which is more than 10 times smaller than the detection limit.

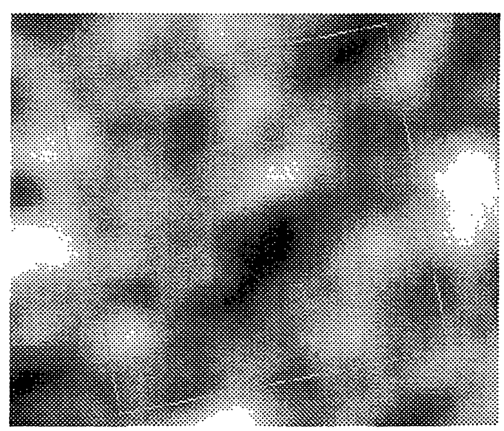

Figure 2. IRAS 100μm map with FRESCO (Full RESolution Survey COaddition) Processing provided by IPAC. The sub-field observed by ISO is enclosed by box. The surface brightness across the IRAS map ranges from -0.2 to 0.1 MJy sr^{-1} with zodiacal contribution subtracted, and its standard deviations to each pixel is about 0.3. No IRAS point sources are cataloged in this field. The extended brightness variation, the faint strip running from the lower left corner to the upper right seems to be common to the ISO 175 μm map.

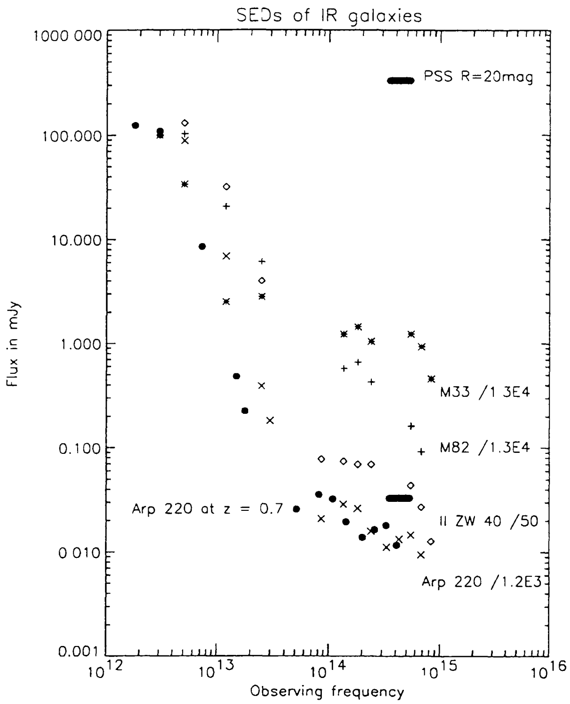

Figure 3. UBV to 100 μm spectral of typical star forming galaxies, namely, M33 representative of star forming spirals, M82 of starburst galaxies, II ZW 40 of star forming dwarf galaxies, and Arp 200 of ultra-luminous IR galaxies. The spectra are normalized to 100 mJy at 100 μm by dividing the observed fluxes by 1.3×10^4 for M33,1.3×10^4 for M82, 50 for II ZW 40, and 1.2×10^3 for Arp 220. In addition, the expected spectrum when Arp 220 is placed at z = 0.7 is shown. Given the limiting magnitude of R = 19 - 20 mag for the Palomar Sky Survey I E plates, the faintness of the optical counterparts of 175 μm sources indicates that star forming dwarfs and ultra-luminous IR galaxies are possible identification with the 175 μm 100 mJy sources.

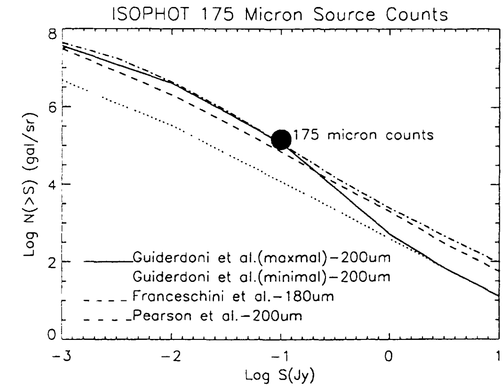

Figure 4. ISOPHOT 175 μm source counts compared with the galaxy counts models which were developed mainly based on the IRAS 60 μm galaxy counts. The reader should be reminded that the uncertainty of flux calibration is a factor of 2. The maximal and minimal models for 200 μm galaxy counts are from Guiderdoni et at. (1997). For the minimal model, the passive evolution of star forming galaxies is assumed with the Schmidt law (SFR $\propto$ (total gas content)/(star forming time scale). The maximal model adds to the minimal model the starbusrt (L_{IR}=13$L_\odot M_\odot^{-1}$) and ultraluminous starburst (L_{IR}=52$L_\odot M_\odot^{-1}$) modes. All star formation occurs in the ultra-luminous starburst mode at $z > 2$. The IRAS 60 μm galaxy counts fit to the both models. The model by Franceschini et al. (1994) for 180 μm galaxy counts consists of non-evolving spiral and elliptical galaxies and evolving AGNs and starburst galaxies in the form of pure luminosity evolution $L(z)=L(0)e^{\kappa\tau(z)}$ where $\tau(z)$ is the look-back time. κ is 2.5 for AGNs and 3.2 for starburst galaxies. The model for 200 μm galaxy counts by Pearson & Rowan-Robinson consists of non-evolving spirals and elliptical components mixed with an evolving population of starbursts, AGN, and hyper-luminous galaxy components. Pure luminosity evolution in the form $L(z)=L(0)(1+z)^{3.1}$ is used for the evolving population. Notice the large differences in source counts among the models in the range of flux greater than 1 Jy. This range should be covered by the ISOPHOT serendipity survey.

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REFERENCES

Boulanger,B., Abergel,A., Bernard, J.-P., Burton, W.B., Désert, F.-X., Hartmann, D., Lagache, G., & Puget, J.-L. 1996, A&A, 312, 256.

Franceschini, A., Toffolatti, L., Mazzei, P., Danese, L., & Zotti, G.De 1991, A&AS, 89, 285.

Gautier III, T.N., Boulanger, F., Pérault, M., & Puget, J.L. 1992, AJ, 103, 1313.

Guiderdoni, B., Hivon, E., Bouchet, F.R., & Maffei, B. 1997, preprint.

Kessler, M. et al. 1996, A&A, 315, L27.

Lemke, D. et al. 1996,A&A , 315, L64.

Lemke, D. 1997, *Taking ISO to The Limits*, The proceedings of a workshop held at ISO Science Operations Centre, Febuary 3 & 4, 1997.

Lockman, F.J., Jahoda, K., & McCammon, D., 1986, ApJ, 302, 432.

Pearson, C., & Rowan-Robinson, M., 1996, MNRAS, 283, 174.

Reach, W.T. 1996, private communication.