Embedded Star Formation in the Magellanic Clouds: Results from the *Herschel* Key Project HERITAGE

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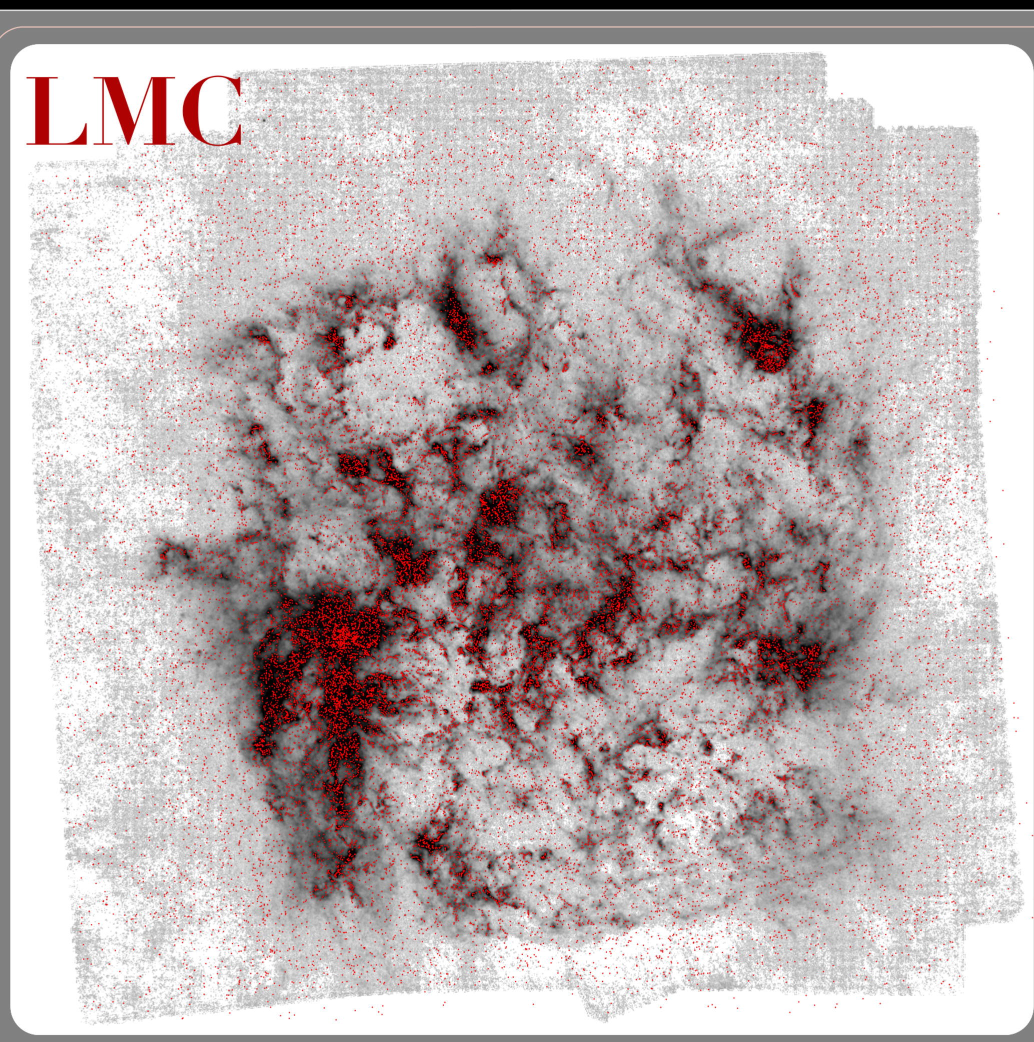
1 HERITAGE Survey of the Magellanic Clouds

The *Herschel* Inventory of the Agents of Galaxy Evolution (HERITAGE; Meixner et al. 2013) is a galaxy-wide survey of the Large and Small Magellanic Clouds (LMC & SMC, respectively). We mapped the Magellanic Clouds at 100, 160, 250, 350, and 500 μm with the Spectral and Photometric Imaging Receiver (SPIRE) and Photodetector Array Camera and Spectrometer (PACS) instruments onboard *Herschel* using the SPIRE/PACS parallel mode. The HERITAGE observations trace the life cycle of matter in the LMC and SMC using the far-IR emission from dust present in the ISM, warmed by deeply-embedded young stellar objects (YSOs), and created in and later ejected from the atmospheres of evolved stars.

We here present the properties of roughly 35,000 and 8,000 far-IR point sources identified in the LMC and SMC HERITAGE images, respectively (See Figure 1, right). The brightest objects at *Herschel* wavelengths are the dustiest objects. Forming stars (i.e., YSOs) are surrounded by dusty envelopes of gas from which they accrete material, and radiation from the YSOs warms the surrounding medium, making them among the brightest objects at these wavelengths. Compact, dusty clumps of gas, even without an embedded source, can be warmed by the interstellar radiation field (ISRF) and appear as far-IR point sources. There is potentially a large population of background galaxies, whose ISM dust emits in the far-IR; (4) Finally, stars in an evolved stage of stellar evolution (e.g., planetary nebulae (PNe), Asymptotic Giant Branch stars (AGBs), and supernova remnants (SNRs)) produce dust that can emit in the far-IR.

We estimate approximately 10,000 and 5,000 background galaxies are in the HERITAGE LMC and SMC images, respectively (see below). The remaining sources are dusty, compact objects in the Clouds including YSOs, dust clumps, evolved stars, supernova remnants, and planetary nebulae. We here present the far-IR photometric properties of these populations across the *Herschel* wavebands.



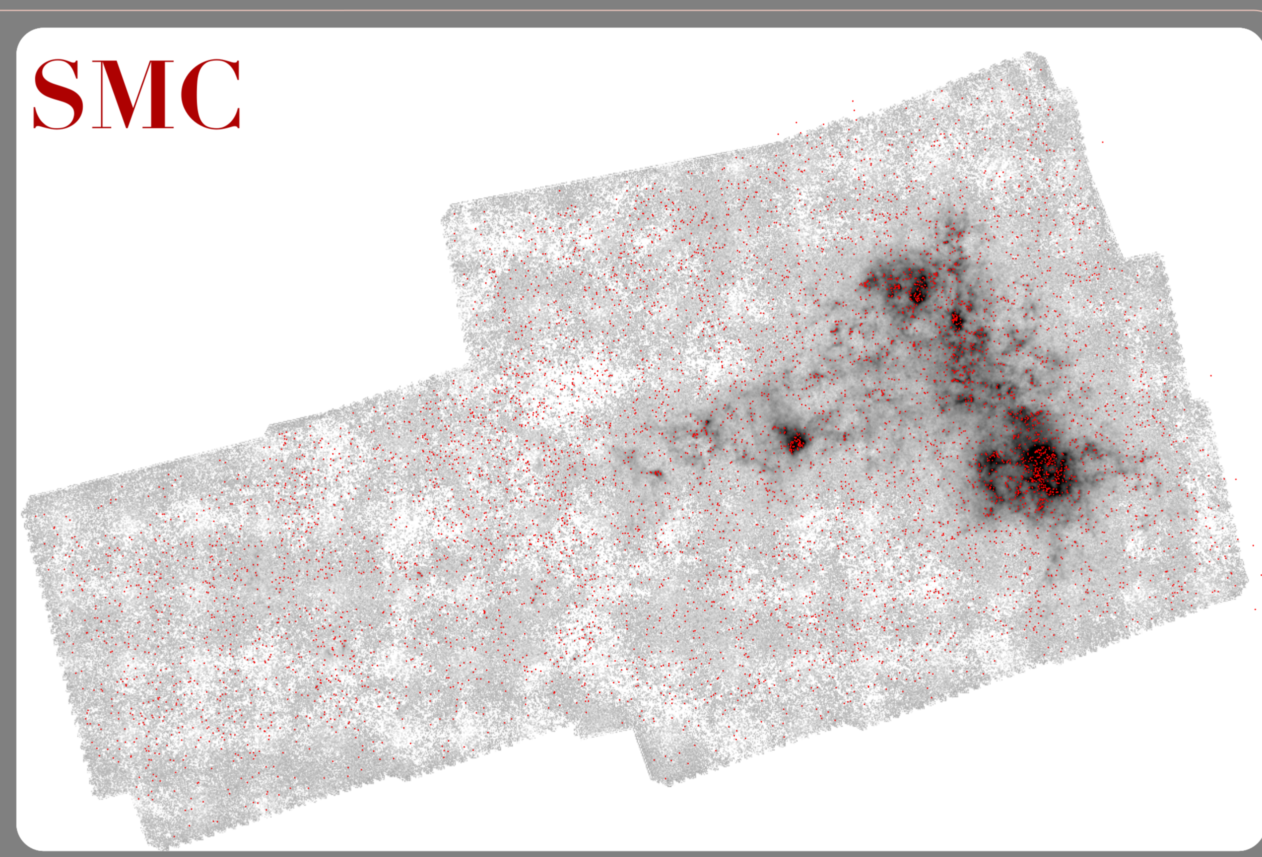


Figure 1: The Large and Small Magellanic Clouds (LMC & SMC) at 500 μm from *Herschel*. The SMC image includes part of the Magellanic Bridge, the large gaseous structure that extends to the east. The positions of all point sources identified in the HERITAGE images (100, 160, 250, 350, and 500 μm) are marked with red dots.

2 The HERITAGE Point Source Catalogs

The variable background emission present in the HERITAGE mosaics presents a challenging environment in which to attempt point-source photometry. Source extraction package Starfinder uses a smoothing algorithm to estimate the local background, and then iterates on the background as sources are found and extracted (Bertin and Arnouts, 1996). For a detailed description of the source extraction processes and the criteria used to establish catalogs , see Meixner et al. (2013).

The HERITAGE images are dominated by ISM emission, and the uncertainty of a point sources' flux measurements (Figure 2) and the completeness of the resulting catalogs (Figure 3) are highly dependent on the brightness and complexity of the ISM background from which the source is extracted. Parameters of the point source catalogs are below in the table (Table 6 in Meixner et al. 2013).

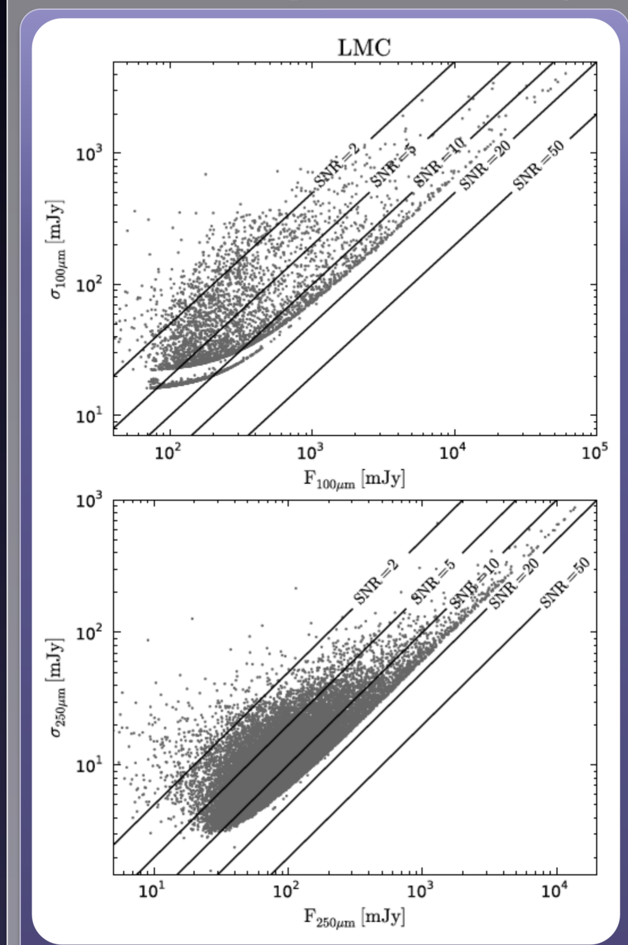


Figure 2: Point source flux uncertainty as a function of flux for LMC PACS 100 and SPIRE 250 μm sources. Lines of constant SNR are drawn to guide the eye. The bifurcation of the PACS uncertainty is caused by areas of high striping in the images.

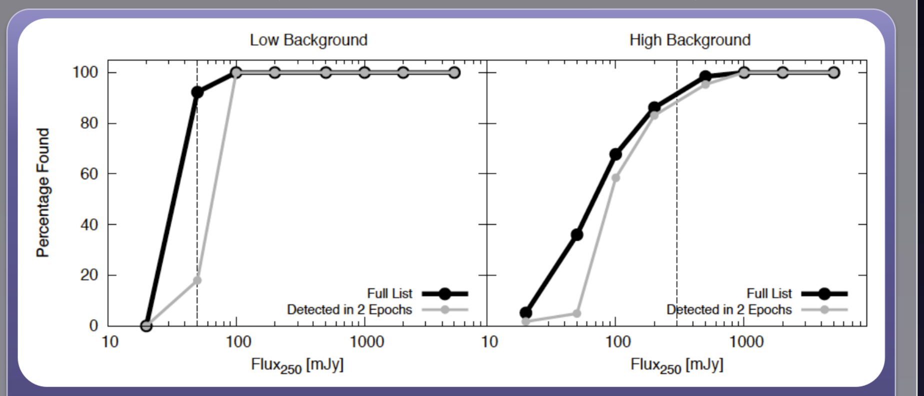


Figure 3: Completeness curves for SPIRE 250 μm created from the false source injection test, which show the percentage of false sources recovered as a function of flux. The left and right panels are for sources within a low (<10 MJy/sr) and high (> 10 MJy/sr) background, respectively. The vertical lines mark the Full List 90% completeness limit at each background level.

Table 6: Parameters of Extracted Point Source Catalogs

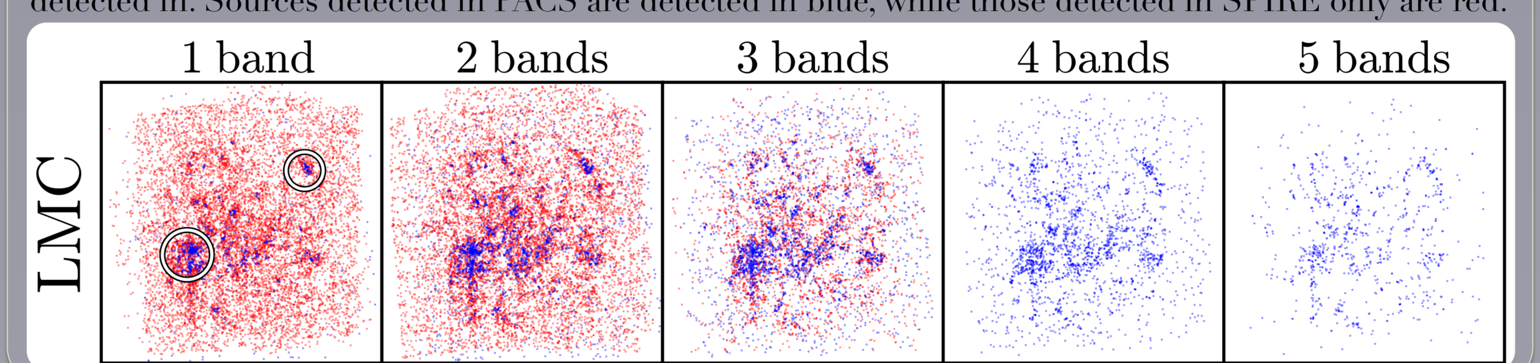
Parameter	PACS λ (μm) 100	160	SPIRE λ (μm) 250	350	500
LMC					
Total Number in extracted List	8686	27136	48082	38482	12224
Number in Catalog	4164	9324	25445	22082	7355
FWHM of extracted source (″)	8.6	12.6	18.3	26.7	40.5
SMC					
Total Number in extracted List	1353	5810	11923	11669	2335
Number in Catalog	898	1590	5465	5313	1069
FWHM of extracted source (″)	8.8	12.6	18.3	26.7	39.7
90% Completness limits from Simulated Source tests					
low background (MJy/sr)	≤15	≤25	≤10	≤5	≤2.5
low background 90% completeness limit (mJy)	450	150	50	50	90
high background (MJy/sr)	>15	>25	>10	>5	>2.5
high background 90% completeness limit (mJy)	450	400	300	400	400

The HERITAGE catalogs can be downloaded from the *Herschel* Science Center: http://herschel.esac.esa.int/

3 The HERITAGE Band-Merged Catalogs

To identify astronomical objects that are detected in multiple HERITAGE images, we positionally cross-matched the five HERITAGE Catalogs (P100, P160, S250, S350, and S500) with each other. We adopt a matching distance of 0.7×$FWHM_{max}$, where $FWHM_{max}$ is the largest of the two matching Catalog's FWHMs. We identify 7,503 and 35,322 unique far-IR objects in the SMC and LMC, respectively.

Figure 4: The positions of sources in the LMC as a function of the number of bands the sources are detected in. Sources detected in PACS are detected in blue, while those detected in SPIRE only are red.



4 Classification: YSOs, Galaxies, AGBs, PNe, and SNRs

Matches to previously-classified objects:

We have matched the HERITAGE band-merged catalogs to those available in the literature of the most likely constituents – YSOs, dust clumps, background galaxies, PNe, SNRs, and other evolved stellar types (e.g., AGBs). We use a matching distance of 0.7×FWHM, where FWHM is the FWHM of the shortest-wavelength HERITAGE image the source is identified in. The table below documents the numbers and types of sources matches were found for.

	LMC	SMC
YSOs	1424	645
Evolved Stars	1051[a]	183[a]
Galaxies	1355	149[b]
PNe	79	12
SNR	2	0

a – most are likely mismatches to SPIRE-only sources.
b – previous studies restricted their search to behind the body of the SMC, and hence we find no matches in the outskirts of the SMC or in the Bridge.

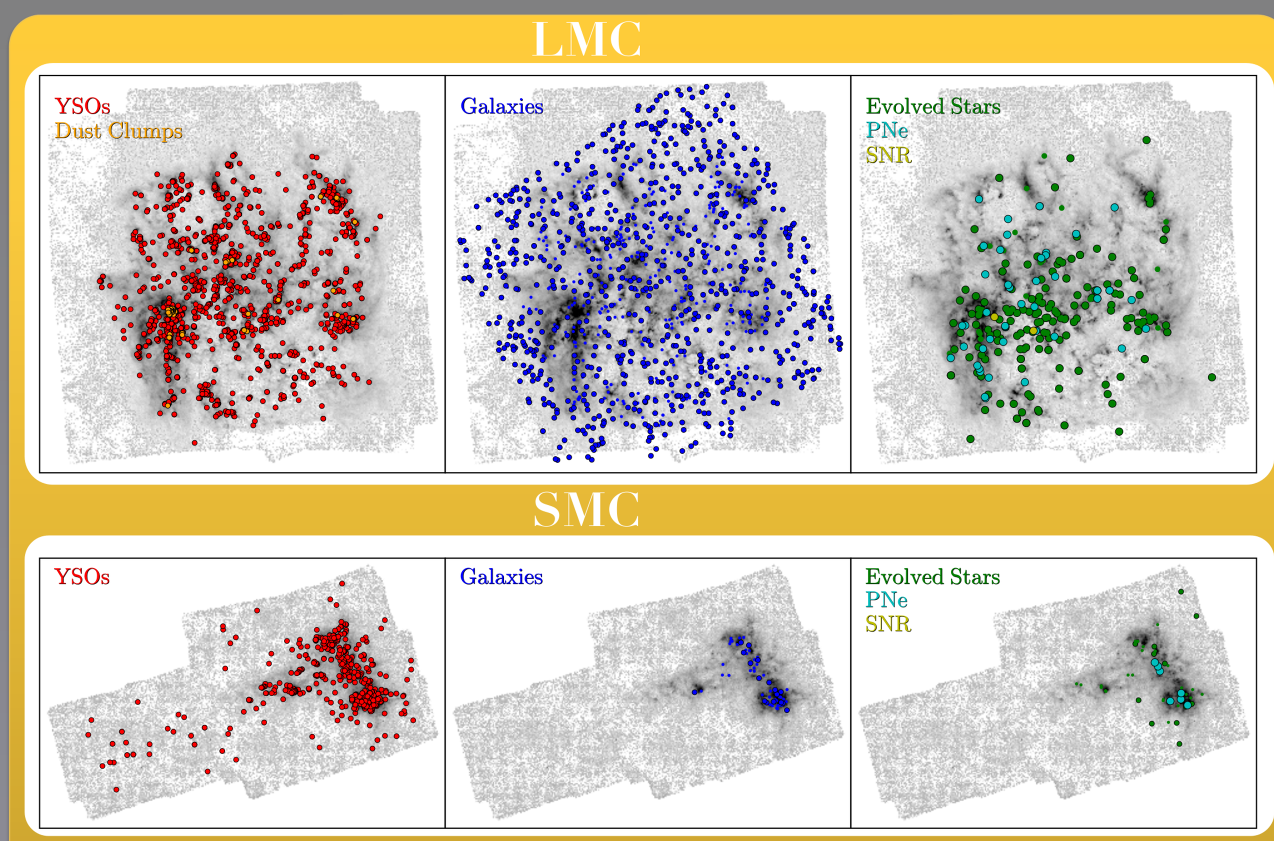


Figure 5: Positions of previously-classified objects that have coincident far-IR point sources.

Identifying background Galaxies:

There is potentially a large population of background galaxies in the HERITAGE images whose ISM dust emits in the far-IR. Identifying these sources presents a challenging problem, as their photometric colors are identical to those of other dusty objects (particularly YSOs). However, the YSOs are embedded in dusty ISM structures, often causing the sources to be marginally extended spatially (i.e., not strictly point-like). Conversely, background galaxies are unresolved at SPIRE wavelengths and appear point-like in the HERITAGE images (with the rare exception of very close neighbors). In Figure 6, we show the distribution of sources in the LMC, color- and size-coded by the FWHM of the source. Note that point-like sources dominate in the outskirts of the galaxy, where background galaxies are expected to be prevalent. Point-like sources in low background are selected to be the most likely candidates for background galaxies (Figure 7); at higher backgrounds, the completeness level is insecure.

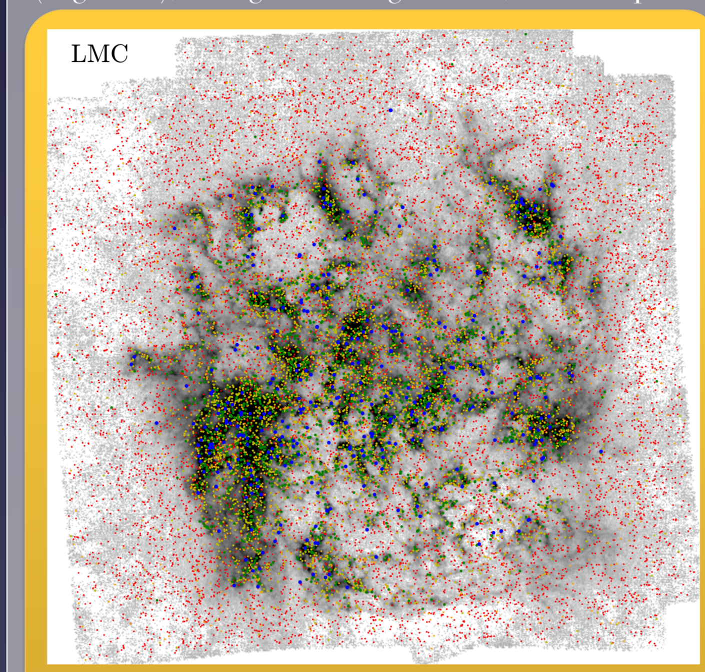


Figure 6: Positions of sources in the LMC on the SPIRE 500 μm image. Sources are color-coded from smallest to largest SPIRE 250 FWHM as follows: red, orange, yellow, green, blue.

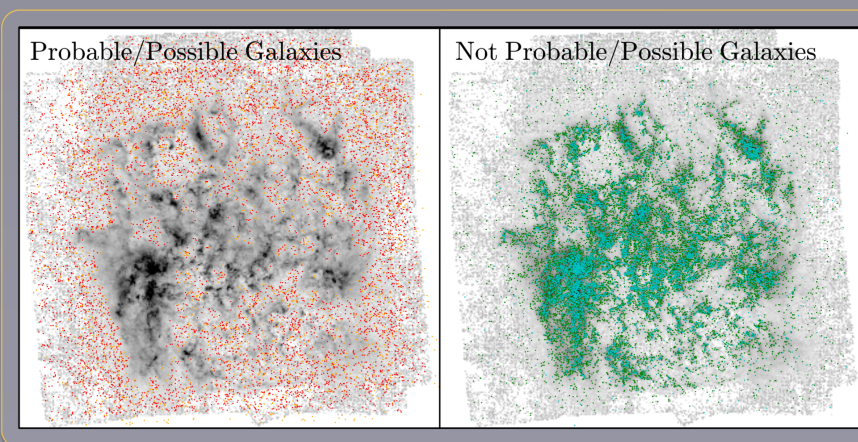


Figure 7: Positions of HERITAGE sources in the LMC determined to be probable or possible galaxies (left) and those that are not (right). Probable/possible galaxies reside in the outskirts of the galaxy where the background emission is low, allowing faint sources to be detected.

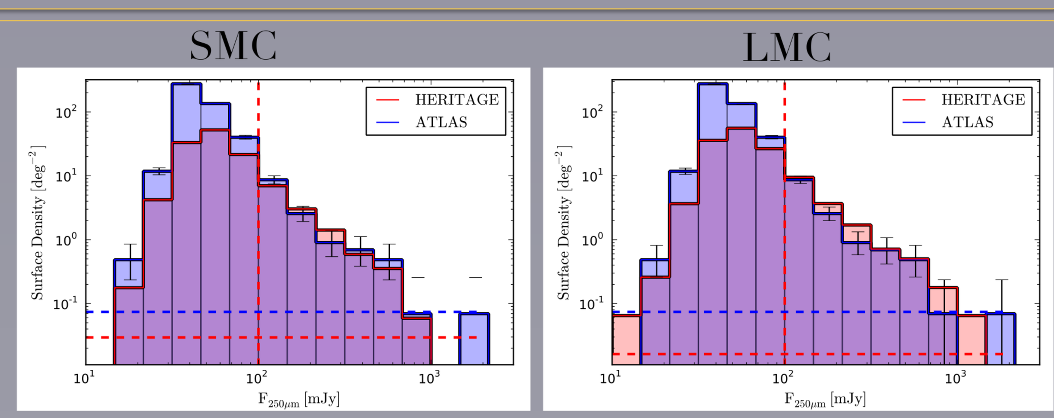


Figure 8: Comparison of the flux distribution for the HERITAGE probable/possible galaxies and that predicted by the ATLAS survey.

We compare the flux distribution of HERITAGE sources suspected to be galaxies behind the LMC and SMC to the flux distribution of galaxies in the ATLAS *Herschel* Science Demonstration Phase catalog (Rigby et al. 2010), which imaged a roughly 4°×4° area of the sky (Figure 8). We find good agreement between the two distributions, with the ATLAS prediction matching to within 2-sigma the HERITAGE observations at each flux bin.

5 The Embedded YSO Population

YSOs are bright at Herschel wavelengths because they are surrounded by dusty gas that is warmed by the embedded source. However, clumps of dust can also be warmed by the interstellar radiation field (ISRF). Dust around YSOs and dust warmed by the ISRF can be indistinguishable photometrically in the far-IR (Figure 9).

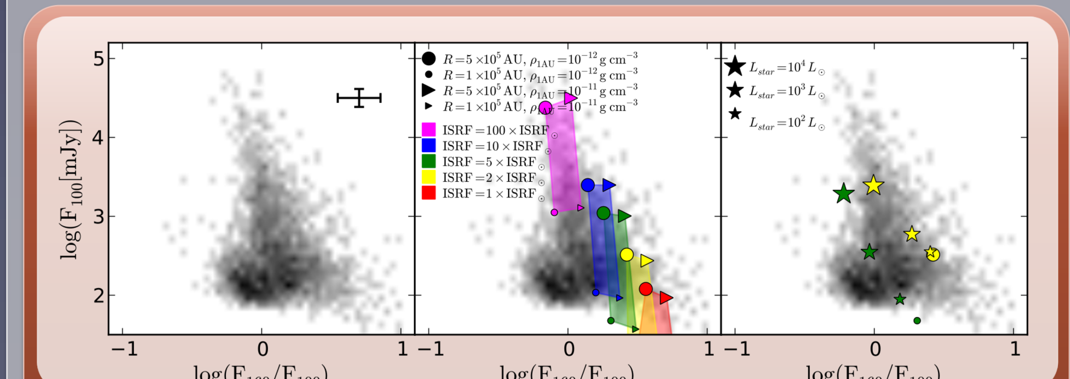


Figure 9: *Herschel* PACS color-magnitude diagram. The Hess diagram is of HERITAGE sources. The shaded regions in the center panel are for a starless dust clump illuminated by an external ISRF of varying strengths. The right panel shows dust warmed by an embedded source. Note that with sufficient incident radiation, a starless clump can imitate in color a YSO at these wavelengths.

Mid-IR photometry can help to distinguish starless clumps from true YSOs – clumps with an embedded source will be sufficiently warmed by the central star to be bright at *Spitzer* wavelengths. Matching the HERITAGE catalog to the MIPS 24 μm SAGE catalog (Meixner et al. 2006; Gordon et al. 2011), we identify the sources most likely to be YSOs.

The table below documents the number of sources identified in the HERITAGE data as being candidate YSOs (with a 24 micron detection) and dust clumps (without).

	LMC	SMC
YSO candidate	**4,680** (1,018)	**1,120** (400)
Dust clump candidate	**20,284** (221; 1%)	**1,009** (54; 5%)

The number in bold is the total number identified. The number in parentheses is the number/percentage of those that were previously identified as YSOs by *Spitzer*.

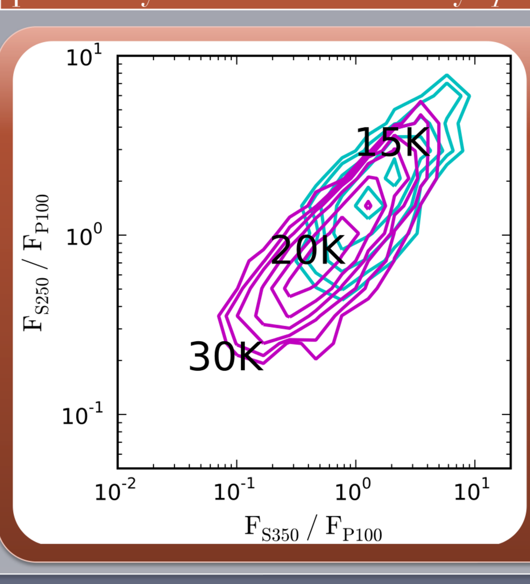


Figure 10: *Herschel* color-color diagram of non-galaxies in the LMC HERITAGE images. Sources with a 24 micron detection are shown in magenta contours, while those without are shown in cyan. Positions for several temperatures of greybodies are also marked.

In Figure 10, we show the far-IR color – indicative of dust temperature – of HERITAGE YSOs and dust clump candidates in the LMC. Cooler sources are located to the upper right, and warmer to the lower left. Sources with a 24 μm detection have warmer dust temperatures than those without, indicating the presence of an embedded source that is heating its surroundings.

The Herschel PSF FWHM is 2–10 pc, so the very cool dust temperatures implied by Figure 10 are unrealistic. The increasing FWHM with increasing wavelength causes more material to be included in the beam at longer wavelengths, thus causing artificially reddening.

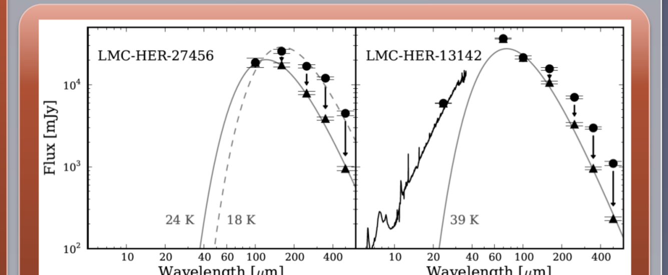


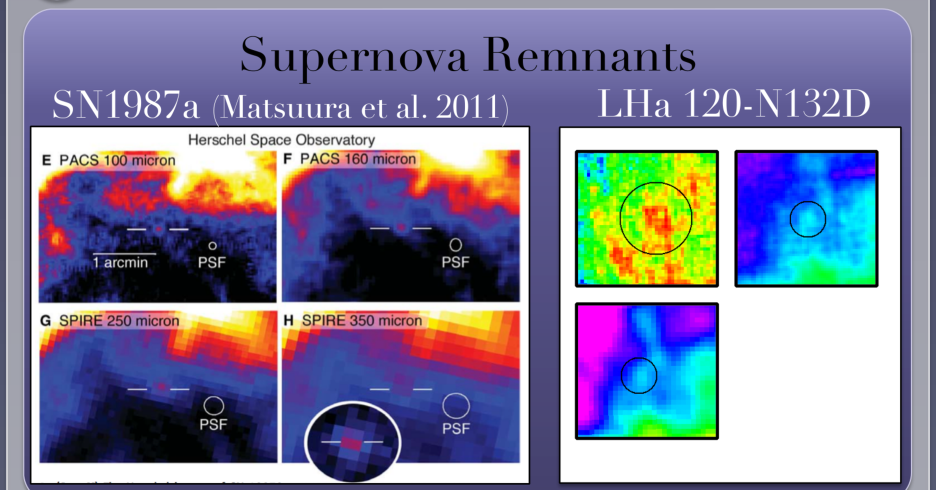
Figure 11: Greybody fits to two sources: one with a 24 μm detection (right) and one without (left).

6 Other (non-YSO) Sources

Supernova Remnants

SN1987a (Matsuura et al. 2011)

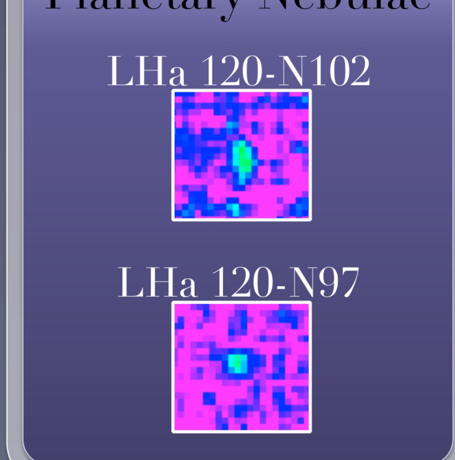
LHa 120-N132D



Planetary Nebulae

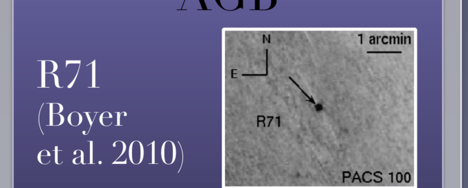
LHa 120-N102

LHa 120-N97



AGB

R71 (Boyer et al. 2010)



References:
Boyer et al. 2010
Gordon et al. 2011
Matsuura et al. 2011
Meixner et al. 2006
Meixner et al. 2013 (submitted)
Rigby et al. 2010
Whitney et al. 2013 (submitted)