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The *Spitzer* Survey of the Large Magellanic Cloud: SAGE, A Review of Initial Results

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Abstract: We have performed a uniform and unbiased imaging survey of the Large Magellanic Cloud, using the IRAC and MIPS instruments on board the *Spitzer Space Telescope*. This *Spitzer* survey of the Large Magellanic Cloud is surveying the agents of a galaxy's evolution (SAGE), the interstellar medium and stars. The SAGE data are nonproprietary and the team has been creating catalogs and improved images for use by the astronomical community. This paper highlights some of the initial results being published by the SAGE team covering the topics of evolved stars and their mass-loss return to the ISM, young stellar objects and the properties of the ISM dust.

Keywords: Magellanic Clouds — ISM: dust — stars: circumstellar matter — stars: formation

1 Introduction

The interstellar medium (ISM) plays a central role in the evolution of galaxies as the birthsite of new stars and the repository of old stellar ejecta. The formation of new stars slowly consumes the ISM, locking it up for millions to billions of years. As these stars age, the winds from low-mass, asymptotic giant branch (AGB) stars and high-mass, red supergiants (RSGs), and supernova explosions inject nucleosynthetic products of stellar interiors into the ISM, slowly increasing its metallicity. This constant recycling and associated enrichment drives the evolution of a galaxy's baryonic matter and changes its emission characteristics. To understand this recycling, we have to study the physical processes of the ISM, the formation of new stars, and the injection of mass by evolved stars, and their relationships on a galaxy-wide scale.

Among the nearby galaxies, the Large Magellanic Cloud (LMC) is the best astrophysical laboratory for studies of the lifecycle of the ISM, because its proximity (50 kpc, Feast 1999) and its favorable viewing angle (35°, van der Marel & Cioni 2001) permits studies of the resolved stellar populations and ISM clouds. The ISM in the Milky Way (MW) is confused in infrared (IR) images due to crowding along the line of sight. In contrast, all LMC features are at approximately the same distance from the Sun, and there is typically only one cloud along a given line of sight, so their relative masses and luminosities are directly measurable. The LMC also offers a rare glimpse into the physical processes in an environment with spatially varying sub-solar metallicity ($Z \sim 0.3$–$0.5 Z_{\odot}$) that is similar to the mean metallicity of the ISM during the epoch of peak star formation in the Universe ($z \sim 1.5$, Madau et al. 1996; Pei et al. 1999). The dust-to-gas mass ratio has real spatial variations and is ~2–4 times lower

Figure 1 A three-colour image of the Large Magellanic Cloud based on *Spitzer*/SAGE data. The IRAC 3.6-μm image, shown in blue, reveals the old stellar population, red giants, and dusty evolved stars. The IRAC 8.0-μm shown in green traces the PAH emission which follows the neutral atomic gas distribution. The MIPS 24-μm shown in red traces the warm dust emission which peaks brightly at 24 μm. From a press release of the Spitzer Science Center (based on Meixner et al. 2006).

than the solar neighborhood (Gordon et al. 2003), resulting in substantially higher ambient ultraviolet (UV) fields than the solar neighborhood. The LMC is surveyed in depth and coverage revealing structures on all scales and a global asymmetry that varies with wavelength (Figure 1). The ISM gas that fuels star formation (Fukui et al. 1999;

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Table 1. SAGE survey characteristics (Meixner et al. 2006)

Characteristic	IRAC value	MIPS value
Nominal center point:		
RA (2000)	5 h 18 m 48 s	5 h 18 m 48 s
Dec (2000)	−68° 34′ 12″	−68° 34′ 12″
Survey area	7.1 × 7.1°	7.8 × 7.8°
λ (μm)	3.6, 4.5, 5.8 and 8	24, 70 and 160
Angular resolution at λ	1.7″, 1.7″, 1.9″ and 2″	5.8″, 17″ and 38″
Epoch 1 (2005)[a]	15–26 July	27 July–3 Aug
Epoch 2 (2005)	26 Oct–2 Nov	2–9 Nov
Source counts	∼4 million	∼60 000
	2MASS, *J*, *H*, *K* incl.	...
λ (μm)	3.6, 4.5, 5.8 and 8	24
Point-source sensitivity:		
5σ at λ (mJy)	0.044, 0.0071, 0.45, 0.25	0.5
5σ at λ (mag)	17, 16, 14, 13.5	10.4

[a]Epoch 1 catalog release, January 2007.

Staveley-Smith et al. 2003; Kim et al. 2003), the stellar components that trace the history of star formation (Zaritsky et al. 2004; van Dyk et al. 1999; Nikolaev & Weinberg 2000) and the dust (Schwering 1989; Egan, van Dyk & Price 2001) have all been mapped at a variety of wavelengths. From the perspective of galaxy evolution, the LMC is uniquely suited to study how the agents of evolution, the ISM and stars, interact as a whole in a galaxy that has undergone tidal interactions with other galaxies, the MW and SMC (Zaritsky & Harris 2004; Bekki & Chiba 2005).

Spitzer IRAC and MIPS images provide key insights into this life cycle because the IR emission from dust grains is an effective tracer of the ISM, star formation, and stellar mass-loss. The SAGE team has conducted a uniform survey of the LMC (7 × 7°) in all the IRAC (3.5, 4.5, 5.8 and 8.0-μm) and MIPS (24, 70 and 160-μm) bands that has surveyed the agents of a galaxy's evolution, the ISM and stars. An overview of the whole project is described by Meixner et al. (2006). A summary of the principal characteristics of the survey are shown in Table 1. This survey builds upon previous IR surveys of the LMC such as IRAS (Schwering 1989), MSX (Egan et al. 2001), 2MASS (Nikolaev & Weinber 2000), and DENIS (Cioni et al. 2000). Three key science goals determined the coverage and depth of the survey. The detection of diffuse ISM with column densities $>1.2 \times 10^{21}$ H cm^{-2} permits detailed studies of dust processes in the ISM. SAGE's point source sensitivity enables a complete census of newly formed stars with masses $>3\,M_\odot$ that will determine the current star formation rate in the LMC. SAGE's detection of evolved stars with mass loss rates $>10^{-8}\,M_\odot\,yr^{-1}$ will quantify the rate at which evolved stars inject mass into the ISM of the LMC. In the sections below, I summarize some of the initial results to date coming from the SAGE project in three major areas: evolved stars, star formation and ISM.

2 *Spitzer*/SAGE View of the LMC

The three colour *Spitzer*/SAGE image of the LMC in Figure 1 shows at a glance the goals and gains of the SAGE project. The IRAC 3.6-μm component of the image traces the old stellar population, including the dusty evolved stars, and shows the bar which is very prominent in optical images. In contrast, the IRAC 8.0-μm component, which is dominated by the 7.7-μm C–C stretch of polycyclic aromatic hydrocarbon (PAH) emission commonly associated with warm neutral gas, traces the ISM gas, and appears much like the HI gas disk imaged by Kim et al. (2003). Punctuating the image in red, are the brightest peaks of the MIPS 24-μm image that traces the massive star formation regions, e.g. 30 Doradus, which is the brightest feature located on the left, middle portion of the image. These dusty components of the galaxy are the key transition points of baryonic matter. The ISM is the origin of baryonic matter. The sites of star formation is where the ISM is turned into stars. The dusty evolved stars are returning matter to the ISM.

3 Evolved Stars

Using colour–magnitude diagrams such as shown in Figure 2, Blum et al. (2006) identified the important evolved stars populations finding ∼18 000 oxygen-rich AGB stars, ∼7000 carbon rich AGB stars, ∼1200 extreme AGB stars, ∼1200 red supergiants. However, the dominant stellar population detected in the IRAC bands are red-giant stars, numbering ∼650 000. The next step after identifying these dusty evolved stars is to quantify their mass-loss return to the LMC. Srinivasan et al. (in preparation) are conducting an empirical study of the mass-loss return of the AGB stars using infrared excesses as a proxy for mass-loss rate. An AGB star is an evolved intermediate-mass star that looses mass in a dusty, molecule-rich wind. The dust emission from the stellar ejecta appears as an infrared excess

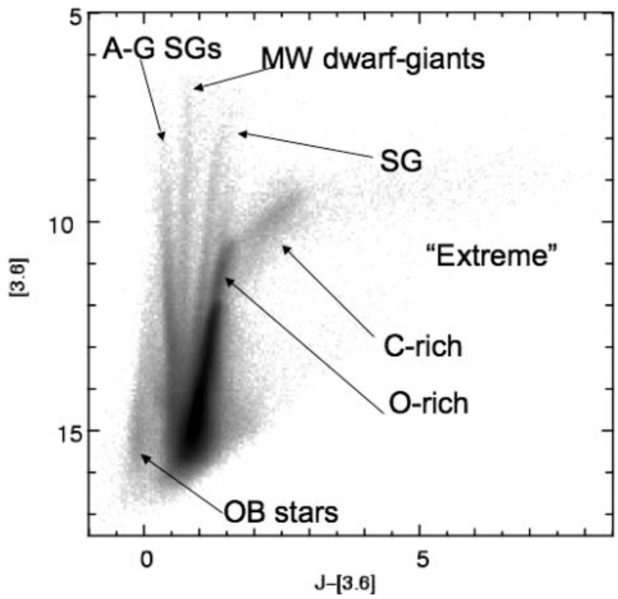

Figure 2 This IRAC 3.6 versus 2MASS *J*, IRAC 3.6-μm colour–magnitude diagram shows all the SAGE Epoch 1 catalog point sources in grey. The structures in the CMD represent populations identified by the arrows and labels (based on Blum et al. 2006).

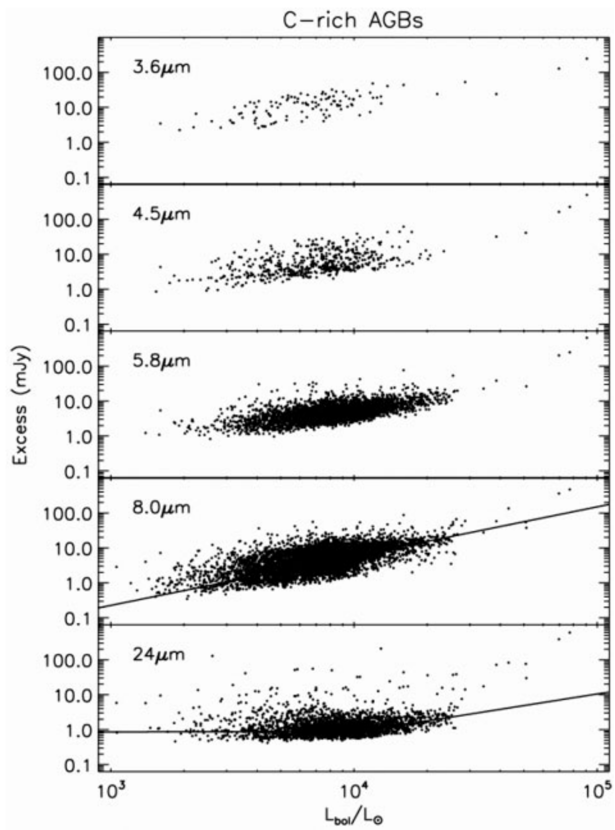

Figure 3 The infrared excess emission at IRAC and MIPS 24-μm bands above a typical stellar photosphere for these C-rich stars versus the bolometric luminosity of the stars. This infrared excess is related to the mass-loss rate from these stars (from Srinivasan et al. in prep.)

over the stellar photosphere emission. The more mass loss, the more dust emission and the greater the infrared excess. Srinivasan et al. find a trend of increasing infrared excess emission with increasing luminosity of the star for carbon-rich (C-rich), oxygen-rich (O-rich) and extreme AGB stars. Figure 3 shows the infrared excess measured for the C-rich AGB stars relative to their luminosity. The 8-μm excess versus luminosity has a power-law fit of 1.4. At 24 μm the lower luminosity C-rich AGB stars do not show a strong trend with luminosity, but a trend does appear when the stellar luminosity rises above $10^4\,L_\odot$ with a power-law fit of 1.10. As the dusty molecular envelope coasts away, the hot stellar core photodissociates and photoionizes the envelope which appears as a planetary nebula. Hora et al. (2008) used known lists of planetary nebulae in the LMC to extract SAGE photometry and find them scattered thinly at all luminosities in the right red cluster of sources in Figure 4.

4 Star Formation

Star formation in the LMC has been focused mostly on the massive HII regions, such as 30 Doradus, in which star formation is already known to occur from previous work. The SAGE project provides an unbiased approach to finding young stellar objects (YSOs). Whitney et al. (2008) have discovered over 1000 new YSO candidates in the SAGE catalogs. The selection of these YSOs begins with colour cuts that are guided by the model calculations of Robitaille et al. (2006) and Whitney et al. (2004), but purposely avoids regions of confusion with the evolved star population and background galaxies (Figure 4). The candidate

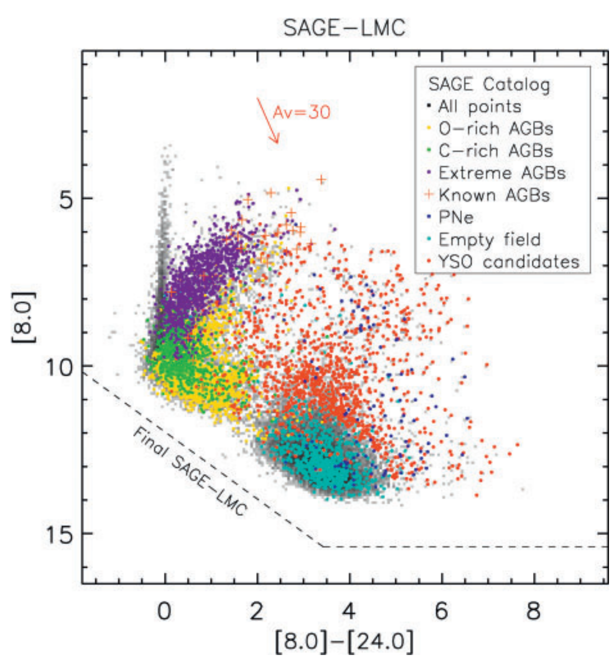

Figure 4 This IRAC 8 versus IRAC 8, MIPS 24-μm colour–magnitude diagram shows all the SAGE Epoch 1 catalog point sources in grey. Overplotted are SAGE sources classified by their infrared colours by various SAGE team members. The dashed line shows the final expected sensitivity limit when both epochs will be combined.

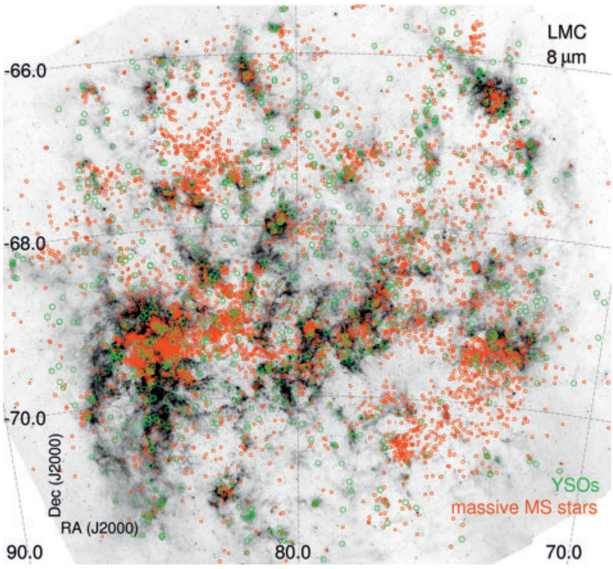

Figure 5 The distribution of YSOs (large green circles) and of massive main sequence stars (small red circles) overlaid on the 8-μm IRAC emission of the LMC (from Whitney et al. 2008).

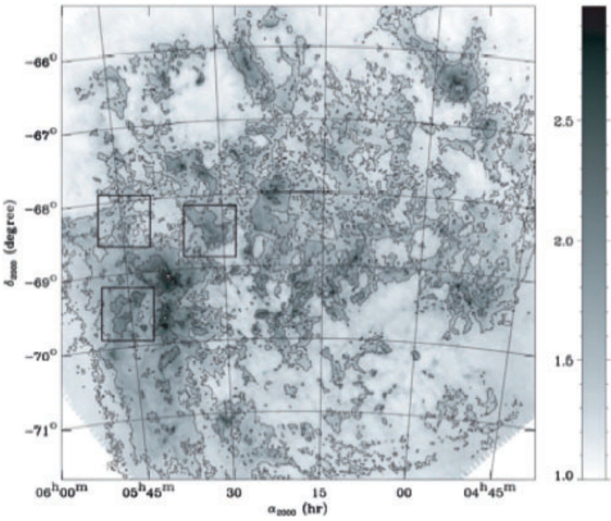

Figure 6 The distribution of HI gas, shown in contours (Kim et al. 2003), compared with MIPS 160-μm emission (greyscale) of the LMC with (from Bernard et al. 2008). The square boxes outline regions analyzed in more detail by Bernard et al. (2008) to derive dust-to-gas mass ratios.

YSOs are further culled by retaining only those sources near significant ISM emission, represented by 24-μm flux. The candidates are then modeled using the model grid of Robitaille et al. (2006). These models provided further screening of the list by removing sources that were poorly fit, e.g. extreme AGB stars. Finally, a cross check with SIMBAD sources was performed to check the list and objects with similar colours such as planetary nebulae, and Wolf-Rayet stars were identified and removed. The modeling also suggests that our selection technique was biased towards the more massive YSOs. These new YSO candidates are found on the redward edge of the evolved star population and extend to the redward clump of sources on the right of Figure 4. Most of the new YSO candidates tend to be luminous and massive because the lower mass YSO candidates are confused with background galaxies which reside in large numbers in the faint red clump of point sources in Figure 4. The locations of the new YSO candidates are illustrated in Figure 5. The distribution of YSOs lies in the filaments of the HI gas clouds traces by the 8 μm. These YSOs appear to surround the vast populations of massive young stars as well, perhaps suggesting a progression or propagation of star formation into the gas clouds.

5 ISM

Bernard et al. (2008) have been analyzing the extended IRAC and MIPS emission from the ISM in the LMC and comparing it to the gas distribution of neutral atomic and molecular hydrogen as traced by the HI 21 cm emission and CO rotational transitions. Figure 6 shows the MIPS 160-μm emission, which traces the large dust grain emission, is well correlated with the HI 21 cm line emission map of Kim et al. (2003) indicating that the gas and dust components of the ISM are well mixed. Empirical analysis of the data reveals that the ISM dust emission has a typical temperature of ∼20 K. The average dust-to-gas mass ratio was derived by Bernard et al. (2008) for three separate regions (outlined in square boxes in Figure 6) and found to be ∼6 times less in the LMC than the Milky Way. One can scale the HI gas emission to make a simulated far-IR emission, via some assumptions including the dust-to-gas ratio, then subtract this from the far-IR MIPS images to determine a far-IR excess map. The far-IR excess can typically identify molecular clouds, where the HI gas emission has decreased. However, in the case of the LMC the far-IR excess correlates better with the HI gas, suggesting that a lot of the HI gas is optically thick or cold.

6 SAGE Data

The preliminary SAGE catalog of Epoch 1 photometry, prepared by the SAGE team and released to the public on 3 January 2007, contains over 4 million IRAC sources, band-merged with 2MASS photometry and over 60 000 MIPS 24-μm sources (Table 1). Preliminary estimates indicate that foreground Milky Way stars and background galaxies may comprise as much as 18% and 12%, respectively, of these catalogs. Further deliveries are forthcoming in 2007–2008[1].

7 Conclusions

The *Spitzer*/SAGE survey of the LMC has been successful at revealing the three main components central to galaxy evolution: the evolved stars, star formation and the ISM. The evolved stars have been identified and their infrared excess appears to increase with increasing luminosity of the star. Over 1000 new YSOs have been discovered in the

[1] To learn more about the SAGE project visit our website, `http://sage.stsci.edu/`

SAGE point source catalog. The dust-to-gas mass ratio is lower in the LMC than in the Milky Way and the infrared dust emission appears to be well correlated with the H I gas.

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