Measuring the lifecycle of baryonic matter in the Large Magellanic Cloud with the *Spitzer* SAGE-LMC survey

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Abstract. The recycling of matter between the interstellar medium (ISM) and stars are key evolutionary drivers of a galaxy's baryonic matter. The Spitzer wavelengths provide a sensitive probe of circumstellar and interstellar dust and hence, allow us 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 the galaxy-wide scale of the LMC. Due to its proximity, favorable viewing angle, multi-wavelength information, and measured tidal interactions with the Small Magellanic Cloud (SMC), the LMC is uniquely suited for surveying the agents of a galaxy's evolution (SAGE), the ISM and stars. The SAGE-LMC project is measuring these key transition points in the life cycle of baryonic matter in the LMC. Here we present a connective view of the preliminary quantities estimated from SAGE-LMC for the total mass of the ISM, the galaxy wide star formation rate and the current stellar mass loss return. For context, we compare these numbers to the LMC's stellar mass.

Keywords. surveys, stars: AGB and post-AGB, circumstellar matter, stars: formation, stars: mass loss, dust, extinction, ISM: evolution, galaxies: evolution, galaxies: individual (LMC), Magellanic Clouds

1. The SAGE-LMC survey

We have performed a uniform and unbiased imaging survey of the Large Magellanic Cloud (LMC, $\sim 7° \times 7°$), using the IRAC (3.6, 4.5, 5.8 and 8 μm) and MIPS (24, 70, and 160 μm) instruments on board the Spitzer Space Telescope (*Spitzer*) in order to survey the agents of a galaxy's evolution (SAGE), through the interaction between the interstellar medium (ISM) and stars in the LMC. Three key science goals determined the

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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 $> 1 \times 10^{-8}$ M$_\odot$ yr^{-1} will quantify the rate at which evolved stars inject mass into the ISM of the LMC. The observing strategy includes two epochs in 2005, separated by three months, that both mitigate instrumental artifacts and constrain source variability. The science drivers, detailed observing strategy, data processing steps and preliminary results of the SAGE survey are described by Meixner *et al.* (2006).

The SAGE data are non-proprietary and point source lists are released to the community. The most recent release included an improved epoch 1 catalog, an epoch 2 catalog, of IRAC ($\sim$4 million point sources) and MIPS 24 ($\sim$ 40,000 point sources) photometry, and MIPS 24, 70 and 160 micron images (See poster contribution by Meixner and SAGE-LMC team). Further investigations have followed on the SAGE theme such as SAGE-SMC, a Small Magellanic Cloud survey with *Spitzer* led by Gordon (see poster contribution), SAGE-Spec, a *Spitzer* IRS spectroscopic survey of the LMC led by Marwick-Kemper, and HERITAGE, a HERschel Inventory of The Agents of Galaxy Evolution in the Magellanic Clouds led by Meixner (see poster contribution). To learn more about all of these SAGE related projects, visit http://sage.stsci.edu. In order to avoid confusion amongst this expansion of SAGE projects, we have retitled ours SAGE-LMC. Several presentations at this conference have been based on the SAGE-LMC data, the SAGE-LMC team contributions are noted throughout this article. In this contribution, we provide an overview of the mass inventory of the ISM, galaxy wide star formation rate, mass-loss rate return of the asymptotic giant branch (AGB) stars as derived from the SAGE-LMC project.

2. ISM mass

A global view of the ISM dust properties derived from the SAGE-LMC data is presented by Bernard *et al.* (2008) (see also poster contribution by Meixner *et al.*). Among the results is a derivation of the total mass of the ISM (see Table 1), which appears to be a factor of two larger than currently known from gas measurements of H I (21 cm; Kim *et al.* 2003) and of CO (Fukui *et al.* 1999). The MIPS 160 μm imaging provides us with the most sensitive measures of the total ISM mass in galaxies. Because the optical depth is quite low at 160μm, its emission is sensitive to all of the dust and, by inference the gas, in a galaxy independent of the physical conditions of the gas which can cause gas tracers to be only selective measures of the ISM column density.

Bernard *et al.* (2008) created an infrared excess image (Fig. 1) that is derived as follows. The dust optical depth map at 160 μm is scaled to a total gas column density map by multiplying it by a gas-to-dust mass ratio determined from the lowest optical depth regions of the map. The ISM mass listed in Table 1 is integrated over the total area of this map. From this total gas column density map, we subtract the gas column density maps derived from the H I and CO maps. The result is the infrared excess map shown in Fig. 1. If the H I and CO maps had detected all of the ISM mass, as measured by the MIPS 160 μm map, then Fig. 1 would be blank. However, it is not blank and instead appears very similar in distribution to the H I image. This infrared excess map may be tracing the location of H$_2$ gas mass not detected by CO, or cold H I not detected by the 21 cm line emission. On the other extreme, it may be tracing (rather large) variations in the dust-to-gas mass ratio, although Bernard *et al.* (2008) tend to think the dust extinction
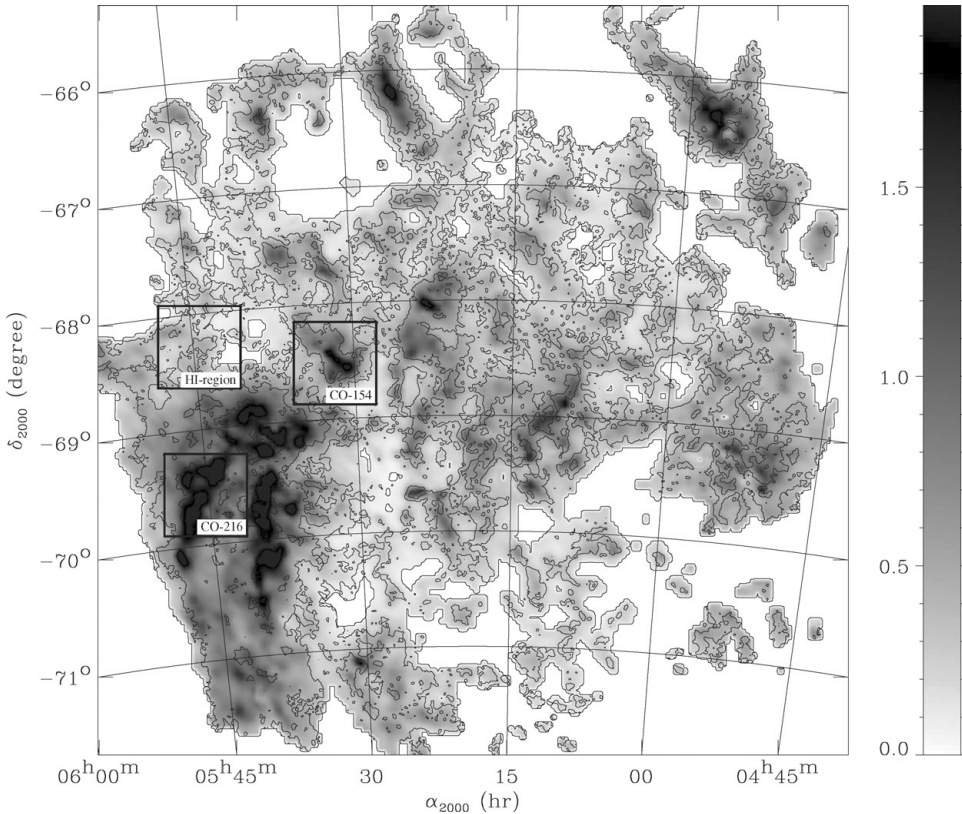
Figure 1. Map of N_H^X in units of 10^{22} H/cm^2. White regions were removed based on their high relative errors. The contours show the distribution of the H I emission of Kim *et al.* (2003). From Bernard *et al.* (2008).

maps do not support this interpretation. Additional ISM results based on the SAGE-LMC data are presented in these proceedings by Marble *et al.* (variations in Aromatic features in the ISM).

3. Star formation rate

An overview of the Star Formation as seen with the SAGE-LMC survey is presented by Whitney *et al.* (2008). The discovery of ∼1000 new candidate young stellar objects (YSOs) and our preliminary characterization of them, described in this proceedings by Indebetouw, demarks a major step forward in our understanding of star formation processes in the LMC. However, the list is just a first attempt and collects mainly the dustiest, and most massive sources. One of the properties determined from the model fits to the YSOs is the mass. Figure 2 shows the mass distribution of the published YSO candidates which reside over the whole LMC. Whitney *et al.* (2008) fitted a Kroupa (2001) initial mass function to the part of the mass distribution in which they had the most confidence, the more massive star end. They derive a star formation rate of 0.1 M$_\odot$ yr^{-1} (see Table 1). This bottoms up approach to star formation rate provides a comparable value to that measured from the Hα and far-infrared continuum emission. However, this measurement is almost certainly a lower limit, because not all of the YSOs have been found. Indeed, the poster contribution by Smith *et al.* in these proceedings shows the new
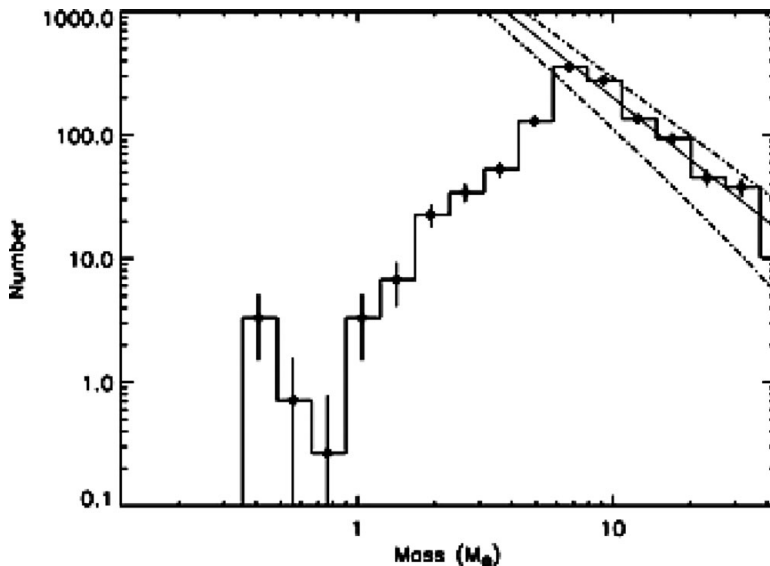
Figure 2. Histograms of stellar mass for the well-fit high-probability YSO candidates from Whitney *et al.* (2008). The dashed line in the left panel is the (Kroupa 2001) initial mass function.

mosaicked photometry catalogs from SAGE-LMC, and reveals 5 times more additional YSO candidates using the same color cut criteria as Whitney *et al.* (2008), and 30 times more additional YSO candidates if we include the fainter magnitudes in the cut for the Henize 206 and N 11 star formation regions.

4. Mass-loss rate return from AGB stars

The identification of the evolved star populations for the whole SAGE-LMC catalogs has been presented by Blum *et al.* (2006) who suggests there may be two types of oxygen-rich (O-rich) AGB stars. Srinivasan *et al.* (2008, also poster contribution in these proceeding), confirms these two types of O-rich AGB stars and also investigates the properties of carbon-rich (C-rich) and extreme AGB stars, in particular, the excess infrared emission in the IRAC and MIPS 24 μm bands. The infrared excess measured in these stars is an excess above the expected photospheric emission in these bands, as known from scaled model atmosphere profiles. The excess is due to the dusty, molecular rich mass loss experienced by AGB stars. The larger the excess, the larger the mass-loss rate the AGB star is experiencing. Srinivasan *et al.* found a positive, strong correlation between the measured excess at 8 μm of ~ 40 evolved stars for which mass-loss rates were derived from radiative transfer model fits of ISO data by van Loon *et al.* (1999). They made fits to these relations for the three classes of AGB stars under consideration: O-rich, C-rich and Extreme. Applying this relation to the entire sample of AGB stars, they estimate a mass-loss rate for each candidate AGB star in the sample. Figure 3 shows the cumulative mass-loss rate for the entire populations of AGB stars. The extreme AGB stars are the major contributors to the mass-loss rate, at $\sim 7 \times 10^{-3}$ M$_\odot$ yr^{-1}. The C-rich AGB stars and O-rich AGB stars contribute $\sim 1 \times 10^{-3}$ and 0.7×10^{-3} M$_\odot$ yr^{-1}, respectively. The total mass-loss rate is $> 8.7 \times 10^{-3}$ M$_\odot$ yr^{-1} (see Table 1). We set this as a lower limit, because the AGB stars are still candidates and need further analysis, particularly at the most luminous end. Additional evolved star results based on
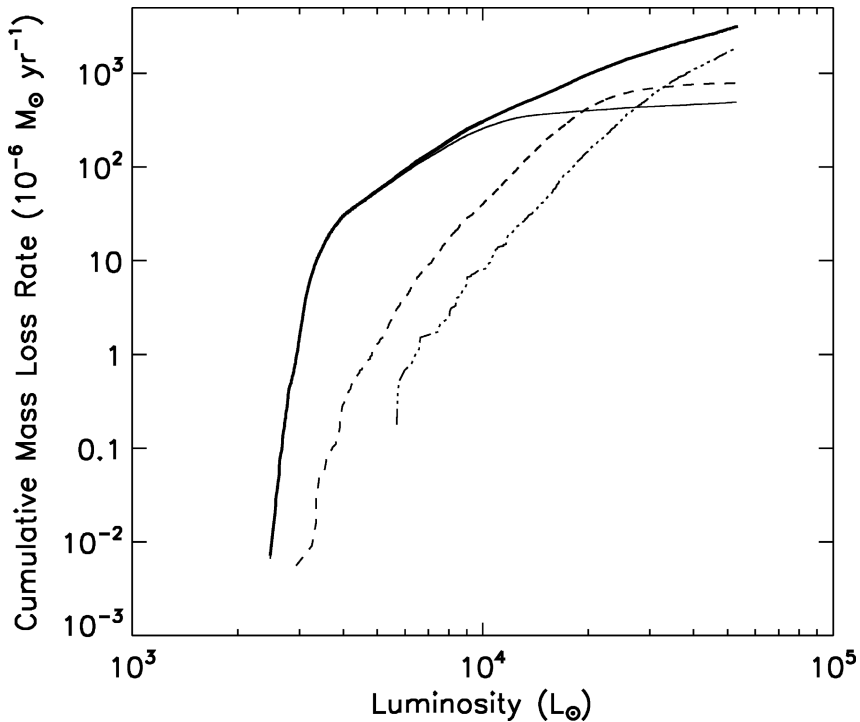
Figure 3. A preliminary cumulative mass-loss rate as a function of luminosity for the O–rich (thin solid line), C–rich (dashed line) and Extreme (dot-dashed line) AGB stars in our lists. The thick solid line is the total AGB mass-loss rate as a function of luminosity. From Srinivasan *et al.* (2008).

Table 1. SAGE-LMC Inventory of the Baryonic Mass Life Cycle

Item	Value	Reference
Stellar Mass	3×10^9 $M_\odot$	van der Marel *et al.* (2002)
ISM Mass	10^9 $M_\odot$	Bernard *et al.* (2008)
Star Formation Rate	> 0.1 $M_\odot$ yr^{-1}	Whitney *et al.* (2008)
AGB Mass Loss Return	$> 8.7 \times 10^{-3}$ $M_\odot$ yr^{-1}	Srinivasan *et al.* (2008)

the SAGE-LMC data are presented in these proceedings by Vijh *et al.* (infrared variables discovered comparing epoch 1 and 2 data), Meixner *et al.* (comparison of SAGE and MACHO data on AGB stars), Srinivasan *et al.* (near-IR spectroscopic followup), Ueta *et al.* (post-AGB stars), and Cohen *et al.* (planetary nebulae).

5. Inventory of Baryonic Mass Flow in the LMC

The mass inventory of these three components, ISM, star formation and AGB mass loss, is presented in Table 1. Our new measurement of the ISM mass makes it about one third that of the stellar mass. The formation of new stars appears to be consuming the ISM at a faster rate than the AGB stars are replenishing it. However, both of these rates are preliminary and most likely lower limits to the actual rates. Moreover, they represent a current snap shot in the lifetime of the LMC and we would need to incorporate the the star formation and evolution history to fully interpret. As we work to improve this

inventory of baryonic matter, we will add the contributions of planetary nebulae, red supergiants, luminous blue variables, supernova (remnants), and infall and outflow caused by tidal interactions with nearby gas and the SMC. The SAGE-LMC and SAGE-SMC projects will be able to provide a means to calibrate such measurements from infrared observations and act as a proving ground for procedures in making such inventories in nearby galaxies. Such calibrations will be important for missions like *JWST*, which will be able to extend such studies to nearby galaxies.

Acknowledgement

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