Star Formation in the Large Magellanic Cloud: Young Stellar Objects Revealed by the Spitzer SAGE Survey

M. Sewilo (STScI), B. Whitney (SSI), R. Indebetouw (U. Virginia), T. P. Robitaille (U. St. Andrews), M. Meixner (STScI), and the SAGE Team

SAGE (Surveying the Agents of a Galaxy's Evolution) is a Legacy project on the *Spitzer* Space Telescope, which mapped a ~7° × 7° region of the LMC using the IRAC camera in the 3.6, 4.5, 5.8, and 8.0 μm filters and the MIPS camera in the 24, 70, and 160 μm filters. The survey was done over two epochs with total observing time of 291 hrs with IRAC and 217 hrs with MIPS. The details of the survey are described in Meixner et al. (2006). The SAGE project allows for the first time a global study of star formation in the LMC at high enough resolution to resolve individual cores and protostars at a range of mid-infrared wavelengths. We present a list of >1000 new candidate Young Stellar Objects (YSOs) in the LMC using the SAGE first epoch point source catalogs of IRAC and MIPS 24 μm that have been merged together with 2MASS JHKs (1.2, 1.6, and 2.2 μm).

Color-Magnitude Selection Criteria

YSOs are typically surrounded by dusty envelopes and disks. In their early stages of evolution, the envelopes are opaque and relatively cool, and absorb most of the central stellar radiation, re-emitting in the infrared at the temperature of the dust. As these sources evolve, the envelopes and disks disperse and emit less IR radiation. An ensemble of YSOs of different evolutionary stages and masses will span a large range in infrared colors. Robitaille et al. (2006) computed a grid of 20,000 2-D radiation transfer models intended to cover the full range of stellar masses and evolutionary stages of YSOs. Each model produces spectral energy distributions (SEDs) at 10 inclinations and 50 apertures. The models accurately compute scattered and thermal emission from dust in a physically plausible geometry, which consists of a stellar source that illuminates a dusty disk, envelope and bipolar cavity (Whitney et al. 2003a,b). We used the grid of models to estimate where YSOs at the distance of the LMC might lie in the color-magnitude space. The resulting distribution of model YSOs is shown in Figure 1.

The candidate YSOs were selected from the SAGE point source catalog from regions of color-magnitude space occupied predominantly by YSOs (as indicated by the models), and less so by other stellar populations. Figure 1 shows examples of regions in color-magnitude space we have selected, redward of the purple lines or inside purple boxes in some cases. We are selecting YSOs that are brighter than galaxies, redder than most evolved sources, and in some cases, fainter than extreme AGB sources. The models show, that this selection biases our YSO list towards younger evolutionary stages and intermediate to high mass. We expect that there remains some contamination in our list from evolved dusty stars and galaxies. The initial list of YSO candidates contained 3773 sources.

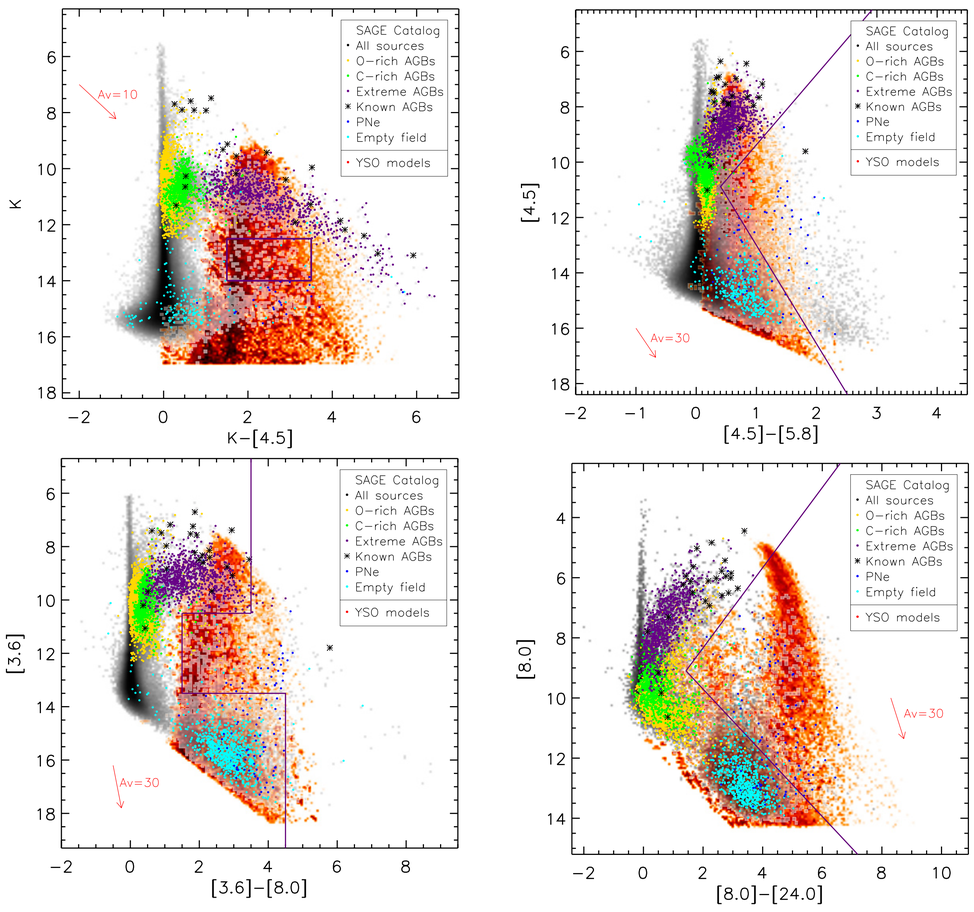


Figure 1. Subset of CMDs used to select the YSO candidates. The CMDs are displayed as Hess diagrams (2-D histograms where the number density is represented by the brightness of each pixel); the SAGE Catalog is shown in grey-scale and the YSO models in orange-tinted grey-scale. Overlayed are the known populations of sources, as described in the key.

To obtain a high-quality and reliable list, we performed several more checks and culls:

- We required that the 24 μm diffuse emission near each source be > 0.08 MJy/sr for the source to remain in the list.
- We increased our IRAC [5.8] and [8.0] errors by 10% and 30%, respectively, based on an empirical analysis of the rms variations of the flux measurements between observations
- We required that each source have at least three detections among the five IRAC and MIPS24 bands, each with the modified signal-to-noise (flux/error) > 10. => 1250 sources
- We fit stellar atmosphere models to all the sources and examined the fits. In cases where a stellar atmosphere could be fit if one of the data points were missing (except 24 μm), we removed the source from the list. We also fit YSO models to the remaining sources (Robitaille et al. 2007), and visually examined the SEDs, model fits, the image at each wavelength, and residual images produced by extracting the catalog flux from the mosaic images. In this way, we found some resolved galaxies, bad point source extractions, mismatched 2MASS and IRAC sources, and other such questionable results. => 1197 sources
- We searched for asteroids in the list by comparing to our second epoch data taken ~3 months after the first. All of the YSO candidates appear in both lists at the same locations, so are not asteroids.

Spatial Distribution

We correlated the list with known stellar populations and we did a SIMBAD search on all the sources. The sources identified as possible or probable non-YSOs total 186. This leaves 1013 probable YSO candidates in our final list.

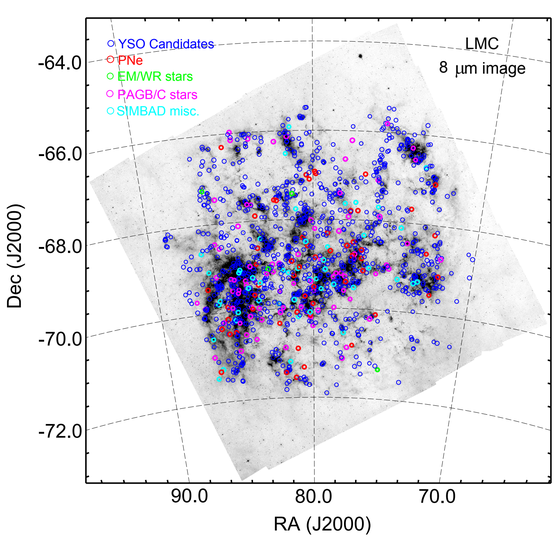


Figure 2. YSO candidates overlayed on a greyscale 8 μm image. The sources identified as other populations are also shown. The YSOs appear to be spatially correlated with the brighter 8 μm diffuse emission.

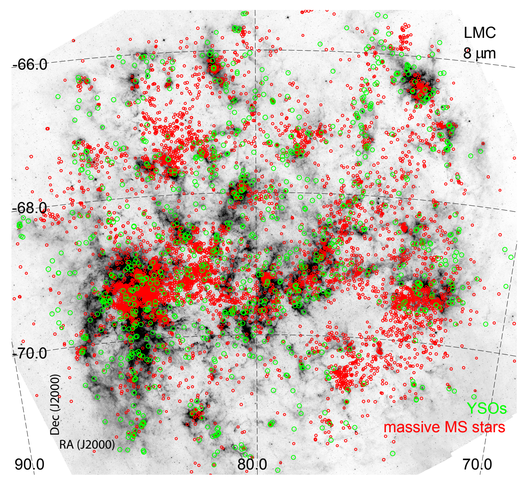


Figure 3. Comparison of the distribution of YSOs with the location of massive young main sequence stars (< 5-10 Myr, M > 10 $M_\odot$). The massive MS stars tend to cluster inside the bubbles and the YSOs lie in the shells formed by the bubbles. This is consistent with both triggering in the compressed shells formed by the previous generation of massive stars, as well as the stochastic self-propagating star formation scenario due to differential rotation of the galaxy.

Comparison to Gas Tracers

The YSO candidates are spatially correlated with both the neutral and molecular gas, with a preference for the molecular gas (yellow and red in Fig. 4). The correlation coefficients between the spatial density of YSOs and the CO and H I column densities are 0.82±0.03 and 0.73±0.05, for the CO and H I maps, respectively.

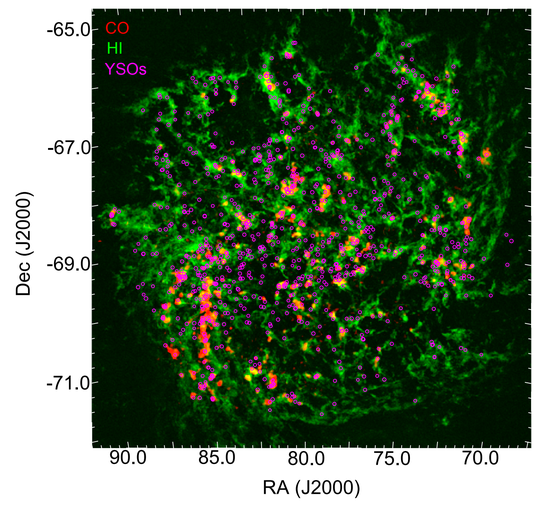


Figure 4. YSOs overlayed on 2-color image of H I and CO gas.

Another measure of gas-YSO correlation:

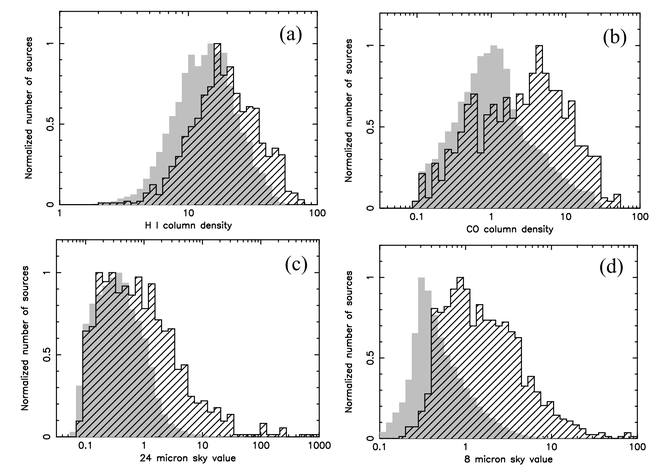


Figure 5. Distribution of YSO candidates (hashed) and of the entire SAGE catalog (grey) as a function of (a) H I and (b) CO column densities (in units of 10^{20} cm^{-2}) and as a function of (c) [24.0] intensity and (d) [8.0] intensity (in MJy/sr).

YSO candidates are statistically associated with greater amounts of gas than generic point sources in the LMC. As expected, there is a stronger association with dense CO gas than H I gas.

SAGE catalog is associated with low values of 8 μm sky and with a range of 24 μm sky values. The SAGE catalog consists mostly of stars detected in the 3.6 and 4.5 μm bands. As Figure 3 shows, the massive stars are located preferentially inside the 8 μm shells and H II regions. The 24 μm diffuse emission is bright in the shells but also bright inside the H II regions where massive stars are found. Thus, the massive stars are spatially anti-correlated with 8 μm emission and associated with 24 μm emission in H II regions, whereas the YSOs are associated with high 8 μm emission. This is another way of showing the visual result from Figure 3 that star formation takes place in the shells created by the previous generation of high-mass star formation (the massive stars inside the shells).

Physical Properties of the YSOs

We fit YSO models to the SEDs using a large grid of radiation transfer models (Robitaille et al. 2006, 2007) and estimate stellar masses, envelope infall rates, disk masses and luminosities of the well-fit YSOs (χ^2 per data point < 2). To improve the parameter estimates, we required the sources have a 24 μm data point (helps constrain the longwave shape of the SED and therefore the luminosity of the sources) and at least 2 IRAC data points ==> 922 sources ==> 520 are well-fit. Note that a poor-fit does not necessarily indicate that a source is not a YSO; the poorly-fit sources are usually due to one bad data point, mismatch between 2MASS and Spitzer due to variability, multiple sources in the beam, or inadequacies in the models

--- We have 255 Stage I (young embedded) sources, 234 Stage II (optically thick disk) sources, and 31 Stage III (optically thin disk) sources.
--- The estimated summed mass and luminosity of the YSOs is ~4800 $M_\odot$ and ~$4 \cdot 10^6$ $L_\odot$, respectively.
--- Three most massive YSOs have masses ~37 ± 10 $M_\odot$ All are assigned evolutionary stage I and are therefore young, with envelope infall rates ranging from ~10^{-4} −10^{-3} $M_\odot$/yr. The best-fit luminosities for these sources are all > 10^5 $L_\odot$.

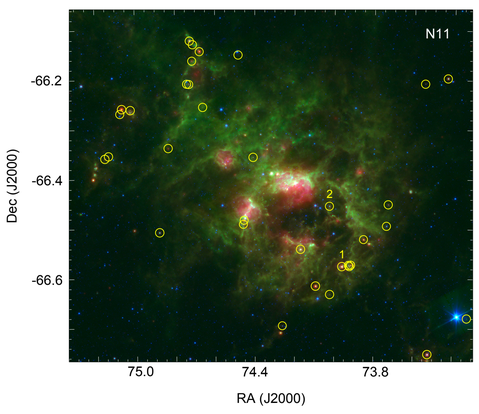


Figure 7. The 3-color (24 μm: red, 8 μm: green, 4.5 μm: blue) image of the N11 region with the YSOs overlayed.

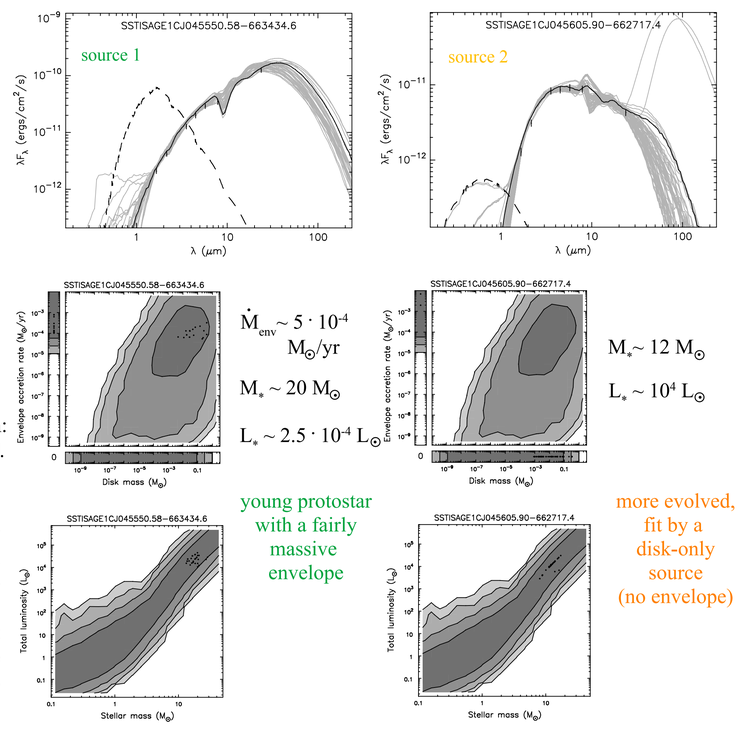


Figure 8. Example YSO fitter results on sources 1 and 2 in N11. *Top*: the grey lines show all the models with χ^2 per data point between the minimum value, cpd_{min}, and cpd_{min} + 1. The dashed line shows the input stellar atmosphere file extincted by the fitted foreground value.

The *middle and bottom panels* show different model parameters for the same set of model fits as the top panel. The contoured greyscale shows how the parameters of the entire model grid are distributed.

What sources are we missing?

YSO candidates were chosen from the SAGE point source catalog based on their infrared colors and magnitudes. The current list is incomplete on both the low- and high-mass ends.

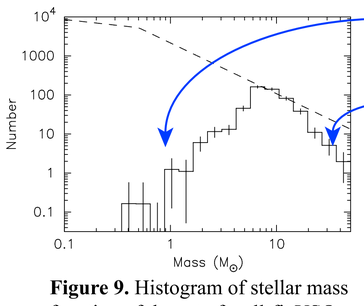
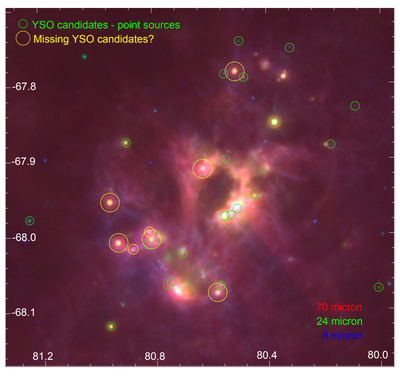


Figure 9. Histogram of stellar mass function of the set of well-fit YSO candidates. The dashed line is the IMF (Kroupa 2001).

- Low-mass sources are missing due to our selection criteria avoiding the low luminosity background galaxies.
- High-mass sources are missing from the SAGE point source catalog since they illuminate large regions and are extended at IRAC wavelengths (often these are the most massive sources). The fall-off may also be caused by faster evolution expected for the high-mass protostars and thus shorter YSO lifetimes.
- Since we based our criteria on the wavelength range from 1 to 24 μm, we are not sensitive to the very youngest sources which may be detected only at longer MIPS wavelengths.
- Our list may also be incomplete due to bright backgrounds.



The follow-up program to search for the YSO candidates extended at IRAC wavelengths has been initiated. We will improve our catalog by adding massive YSOs that we missed. We are expecting to find several hundred of these sources in the SAGE survey area. **Figure 10** (right) shows example of sources identified as possible massive YSOs (yellow circles): they are bright at 70 μm and extended at IRAC. We will do photometry on the initial list of visually selected sources and do a similar analysis as for point sources.

References: Meixner, M., and the SAGE Team 2006, AJ, 132, 2268
Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K., Denzmore, P. 2006, ApJS, 167, 256
Robitaille, T. P., Whitney, B. A., Indebetouw, R., Wood, K. 2007, ApJS, 169, 328
Sewilo, M., Whitney, B. A., M., Indebetouw, R., Robitaille, T., Meixner, M., and the SAGE Team 2007, AJ, in prep
Whitney, B. A., Wood, K., Bjorkman, J. E., Cohen, M. 2003a, ApJ, 598, 1079
Whitney, B. A., Wood, K., Bjorkman, J. E., Wolff, M. J. 2003b, ApJ, 591, 1049
Whitney, B. A., Sewilo, M., Indebetouw, R., Robitaille, T., Meixner, M., and the SAGE Team 2007, AJ, submitted