Stellar Populations with JWST: the Beginning and the End

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Abstract:

We discuss the recent progress on stellar populations provided by the influx of high sensitivity infrared photometry measurements using the Spitzer SAGE survey of the Large Magellanic Cloud as an example. We discuss the important role JWST will play in expanding such studies out to the local volume of galaxies (~10 Mpc) and its synergy with concurrent missions. In addition to observational capabilities, we will need theoretical tools to further this field in the next decade.

1. Introduction

Stars play an important role in the evolution of the Universe as beacons that we observe to chart distances, as the primary consumers of the interstellar gas in galaxies, as factories for producing all heavy elements, and as chronometers to tell us the age of a galaxy. The success that stellar studies have had so far in astronomy gives the illusion that it's a "solved problem." However, the very beginning and end of a star's life is enshrouded in dust and molecular gas making it a difficult to study with the traditional optical bands used in stellar population studies. Thus the stages of star formation and star death remain puzzles in the study of stars. Moreover, these are critical stages not only for the star but for its environment because they are the key transition points for baryonic matter transfer between the interstellar medium and the star. Our poor knowledge of these stages and how they fit into the realm of stellar populations and evolution causes problems for the interpretation of high red shift Universe galaxy spectra that can be interpreted either as a nearby galaxy with an old stellar population with a lot of asymptotic giant branch stars or as a very distant galaxy undergoing vigorous star formation. Indeed, we need to do more work in the nearby Universe on these beginning and ending stellar stages to establish a more solid foundation.

2. Spitzer SAGE Survey of the LMC, an example

This past decade ground based and space based facilities in the infrared have greatly improved the data on star formation and evolved stars field with high resolution imaging of nearby galaxies and the Milky Way. As an example of this work, Figure 1 shows the discovery space and results from the Spitzer Survey of the Large Magellanic Cloud (LMC): Surveying the Agents of a Galaxy's Evolution (SAGE; Meixner et al. 2006). For the first time, we have been able to push the study of stellar populations in the infrared to the fainter intermediate mass star stages of evolved and forming stars and even to stars without dust, main sequence O stars and red giant branch stars in a nearby galaxy. The Spitzer band photometry, which covered 3.6, 4.5, 5.8, 8 and 24 mircons, were combined with near-infrared photometry from 2MASS (J, H, Ks; Skrutskie et al. 2006) and optical photometry from the Magellanic Clouds Photometric Survey (MCPS; U, B,V, I; Zaritsky et al 2004) to construct complete spectral energy distributions for the analysis of the sources. The initial studies focused on trends found in the stellar populations identified in the color magnitude diagrams We note some of the initial results from this survey on a stellar populations approach to the beginning and end stages of stars.

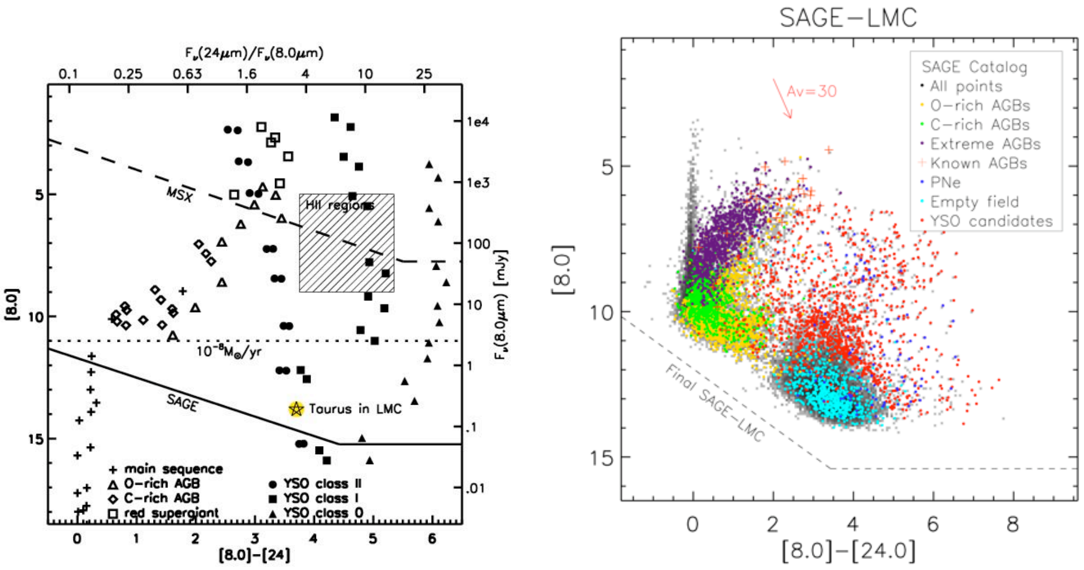

Figure 1: Left: The predicted discovery color-magnitude space of the infrared stellar populations in the LMC for the Spitzer SAGE survey. Right: Results from the SAGE epoch 1 point source catalog with candidate populations identified according to the legend. The symbol, [], denotes the brightness in Vega magnitudes at the wavelength enclosed in the brackets. For example, [8.0] means the Vega magnitude at 8.0 µm. The symbols identify populations of key sources throughout the LMC: YSOs (1-30 $M_\odot$), HII regions, Taurus-like clusters, O-rich and C-rich AGB stars, RSGs and main sequence O stars. Symbols, as noted in the legend, represent template/model photometry of Cohen (1993) and Whitney et al. (2004). SAGE's sensitivity limit (solid line) falls x1000 below the MSX limit (dashed line) and the lower limit to AGB mass loss, >10^{-8} $M_\odot$ yr^{-1} (dotted line). The (yellow) filled circle with a star represents a subregion of Taurus containing ~12 stars, placed at the distance of the LMC. From Meixner et al. (2006).

Using the SAGE-LMC catalog, we have been able to classify the candidate AGB star populations into three categories: ~17,500 probable oxygen-rich (O-rich) AGB stars, ~7000 carbon-rich (C-rich) AGB stars, and ~1200 extremely dusty (extreme) AGB stars based on color-magnitude diagram (CMD) selection (Figure 2; Blum et al. 2006). We have also estimated mass-loss rates based on infrared excesses to derive a preliminary total rate of mass return to ISM by AGB stars in the LMC (Srinivasan et al. 2009). Figure 2 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 ~7×10^{-3} Msun/yr. The C--rich AGB stars and O--rich AGB stars contribute ~1×10^{-3} Msun/yr and ~0.7×10^{-3} Msun/yr, respectively. The total mass-loss rate is > 8.7×10^{-3} Msun/yr. We set this as a lower limit, because the AGB stars are still candidates and need further analysis, particularly at the most luminous end. Photometric catalogs have been developed for both epochs of SAGE-LMC (separated by 3 months time), and a comparative analysis of the two epochs searching for infrared variability, which found ~2000 infrared variable stars out of ~3 million point sources, has been published by Vijh et al. (2009). Most of these infrared variable sources can be classified as asymptotic giant branch (AGB) stars, including ~350 probable O-rich AGB stars, ~ 430 probable C-rich AGB stars, and ~820 extreme AGB stars.

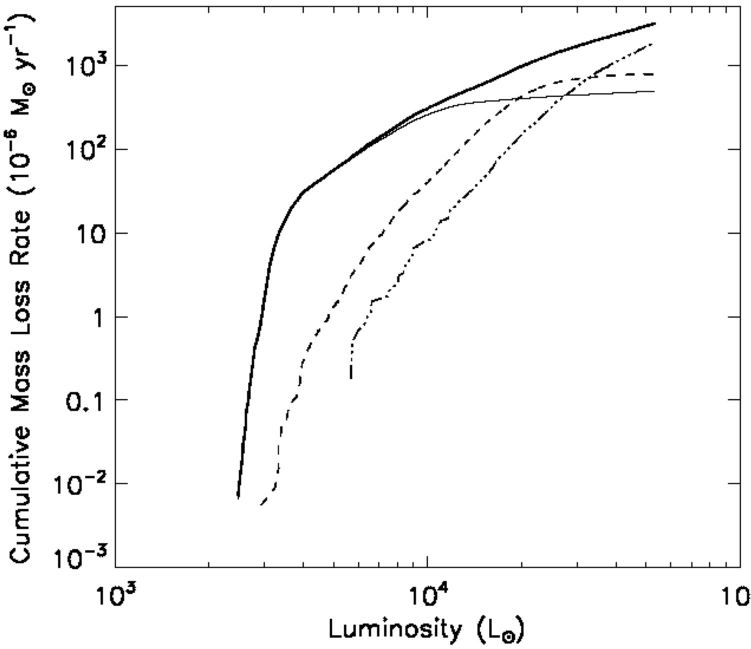

Figure 2: A preliminary cumulative mass-loss rate as a function of luminosity for the O--rich (thin solid line), C--rich (dashed line) and Extreme (dot-dashed line) AGB stars in our lists. The thick solid line is the total AGB mass-loss rate as a function of luminosity. From Srinivasan et al. (2009).

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 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 Msun/year. 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.

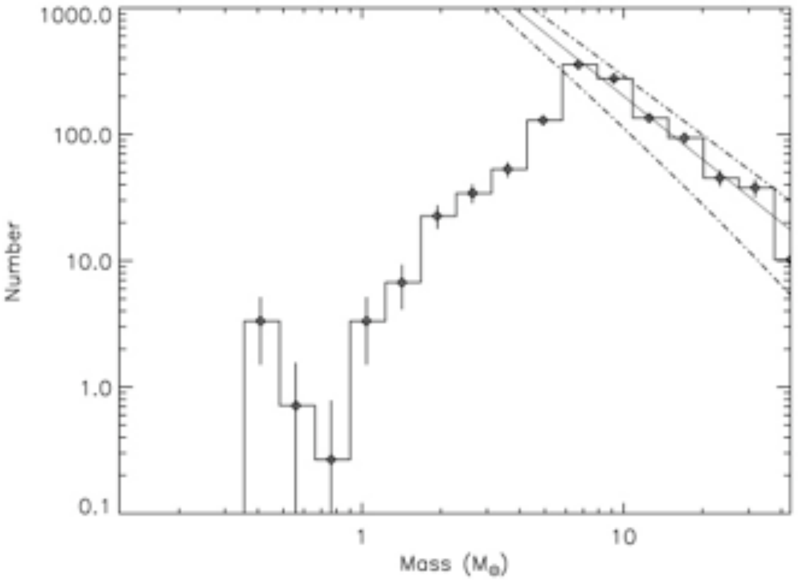

Figure 3: Histograms of stellar mass for the well-fit high-probability YSO candidates from Whitney et al. (2008). The dashed line is the (Kroupa 2001) initial mass function.

3. Capabilities needed for future progress

These nearby galaxy and Milky Way studies of stars in the infrared with Spitzer will provide both very useful catalogs for studies with future observatories, but will also provide calibrated relations for analyzing and interpreting the infrared data on stellar populations anticipated in this coming decade. In order to progress further in this area, we need improved observing capability and also improved theoretical tools for stellar populations. JWST will provide the improved angular resolution and sensitivity to not only allow us to study fainter sources in the Magellanic Clouds, but also push studies like SAGE out to more distant galaxies in the local volume of galaxies (~10 Mpc). Figure 4 illustrates the gains we could make with the anticipated sensitivity for the Mid-InfraRed Instrument (MIRI) on JWST in the nearby universe. These JWST wavelengths will be complemented by the HST photometry on nearby galaxies for these stellar populations. Ground based and space based (JWST/NIRCam) near-infrared photometry will be necessary to get complete spectral coverage. Higher angular resolution imaging at wavelengths longer than 24 microns are really needed to properly study the young stellar objects (YSOs). Facilities such as Herschel and SOFIA will provide necessary improvement for sources in the Milky Way. However, new facilities, yet to be designed or built will be needed for nearby galaxies. Temporal coverage of these objects at all wavelengths will also be necessary in order to understand the dynamic processes that shape these stages of stellar evolution.

Theoretical progress will be needed to tie in the YSOs and evolved stars properly into the stellar evolutionary tracks. The new data will test theories for the late stages of stellar evolution which are dominated by poorly understood mass loss processes and for star formation which are dominated by accretion processes. There will need to be iterative adjustments to evolutionary tracks based on comparison of these new data to predictions from the evolutionary tracks. The overall result will be improved understanding of these important stages of stellar evolution as well as improved stellar population synthesis models that may be applied to high red shift galaxies.

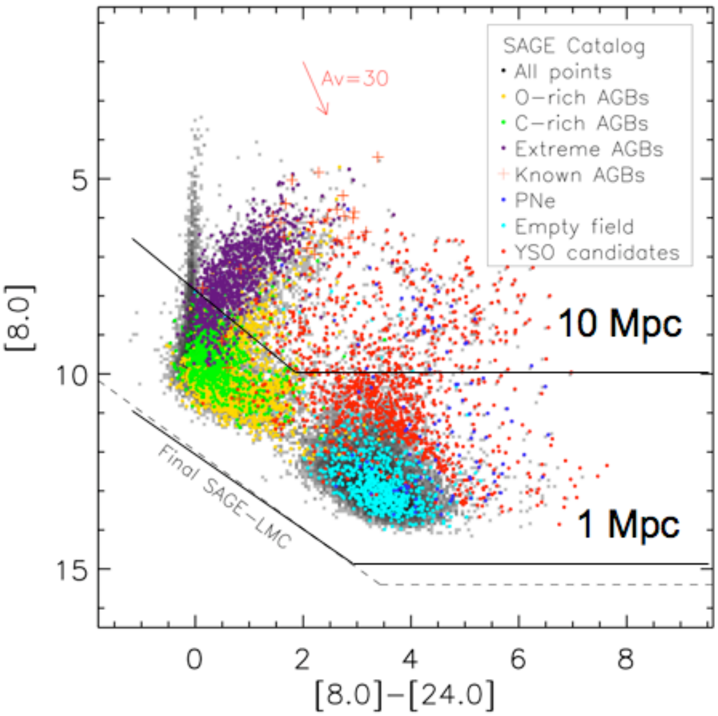

Figure 4: This figure roughly shows the types of infrared populations detectable in galaxies located at distances of 1 and 10 Mpc, i.e. the local volume of galaxies, assuming the same amount of exposure time with the Mid-InfraRed Instrument on JWST as was used by Spitzer IRAC and MIPS in a SAGE survey pointing (~50 seconds).

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