Astro2020 Science White Paper

Infrared Stellar Populations: Probing the Beginning and the End

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☒Stars and Stellar Evolution ☒Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract: The very beginning and end of a star's life is enshrouded in dust and molecular gas making it difficult to study with the traditional optical bands used in stellar population studies. Thus, the early and late stages of star formation and star death remain puzzles. Results from Spitzer and Herschel on the Magellanic Clouds demonstrated the power of infrared stellar populations. We need to do similar studies of galaxies in the local volume and go fainter in the Magellanic Clouds. JWST will provide powerful insights. However, we will also need the far-infrared photometry to complete the spectral energy distributions, and wide field infrared photometry to get whole galaxies. The results will need better theoretical models to properly interpret.

Introduction

Stars play an important role in the evolution of the Universe. They are beacons that we observe to chart distances. They serve 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 difficult to study with the traditional optical bands used in stellar population studies. Thus the early and late stages of star formation and star death remain puzzles. 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, and back again through stellar feedback and death. Our poor knowledge of these stages and how they fit into the larger picture of stellar populations and evolution causes nagging and fundamental problems in the study of galaxy evolution. These problems are particularly acute for investigations of high redshift galaxies, where degeneracies in the interpretation of spectra can lead to wildly different conclusions about the star formation rates and histories of the earliest galaxies. **The key to solving these problems involves more detailed study of the beginning and endpoints of stellar evolution in nearby galaxies, particularly at wavelengths that can penetrate the dust that surrounds these important transitions in the life of a star.**

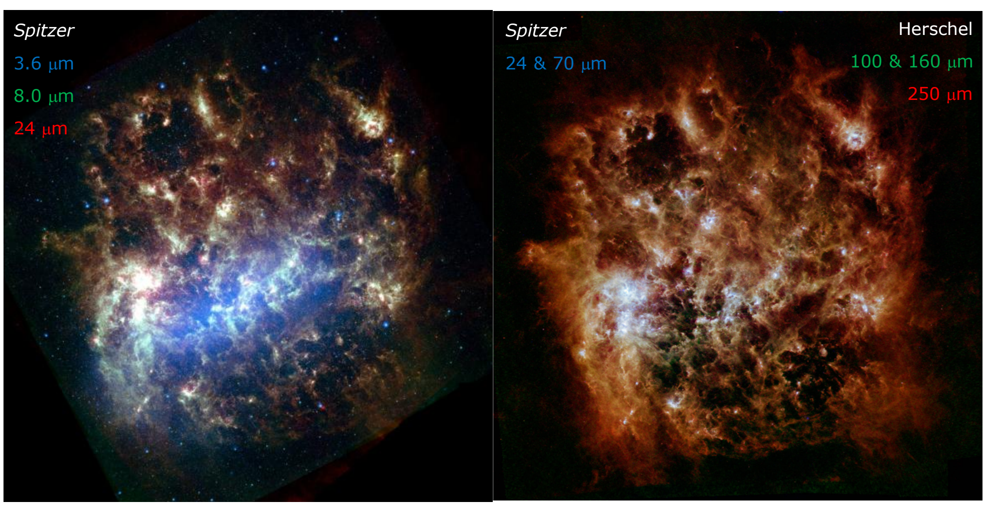

Figure 1: ***Left:*** The *Spitzer* Surveying the Agents of Galaxy Evolution image of the Large Magellanic Cloud (Meixner et al. 2006). The picture shows the places in the baryonic life cycle where dust plays its most important role: massive star formation regions (red-tinted, bright clouds at MIPS 24 μm); the interstellar medium (ISM, greenish clouds at IRAC 8 μm); and old stars (blue old stellar population at IRAC 3.6 μm and embedded old stars as red dots at MIPS 24 μm). ***Right:*** The Large Magellanic Cloud HERschel Inventory of The Agents of Galaxy Evolution (HERITAGE; Meixner et al. 2013) data combined with *Spitzer* SAGE. Red corresponds to SPIRE 250 μm, green to PACS 100 & 160 μm, and blue to MIPS 24 & 70 μm. While the ISM dominates this image, the most luminous young stellar objects and evolved stars appear as point sources.

Stellar populations revealed in the infrared, current knowlege:

Understanding these stellar beginning and endpoints requires observations from the infrared (>1 μm) out to the submillimeter (<1 mm) to constrain their spectral energy distributions and probe the energetics of their circumstellar environments through spectral line observations. Complete catalogs of these sources offer powerful statistical samples to address fundamental questions. For example, the space based facilities, *Spitzer* and Herschel, have obtained resolved observations of young stellar objects and evolved stars and supernovae remnants in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) for the first time (Fig. 1; Meixner et. 2006, Meixner et al. 2013; Gordon et al. 2011).

Star Formation: Analysis of the point source photometry from these surveys led to the discovery of tens of thousands of massive young stellar objects (YSOs) whereas only 20 in the LMC and 1 in the SMC were known before the launch of Spitzer and Herschel (> 8 M⊙, e.g., Whitney et al. 2008; Gruendl & Chu 2009; Sewilo et al. 2013; Seale et al. 2014; Fig. 2). The most luminous YSO, H72.97-69.39, detected with Herschel in the Large Magellanic Cloud may in fact be a forming super star cluster (Ochsendorf et al. 2017a). The mass/luminosity function of these YSOs that are fitted by an initial mass function provide a robust star formation rate measurement on the 0.5 Myr timescale (Carlson et al. 2011). Spatial distributions of the YSOs reveal that massive star formation is correlated with the presence of young massive star clusters and is not at the peak of molecular cloud column densities but on the borders closest to the young massive star clusters indicating a propagation of star formation between generations (Ochsendorf et al. 2016). Moreover, contrary to theoretical predictions, the star formation efficiency is not correlated with the mass of the molecular cloud because the star formation occurs in only part of the cloud (Ochsendorf et al. 2017b). The most massive molecular clouds, as revealed by ALMA, tend to be populated by the YSOs and there is a ~500 M⊙kpc^{-2} threshold for massive star formation in N159 region of the LMC (Nayak et al. 2018).

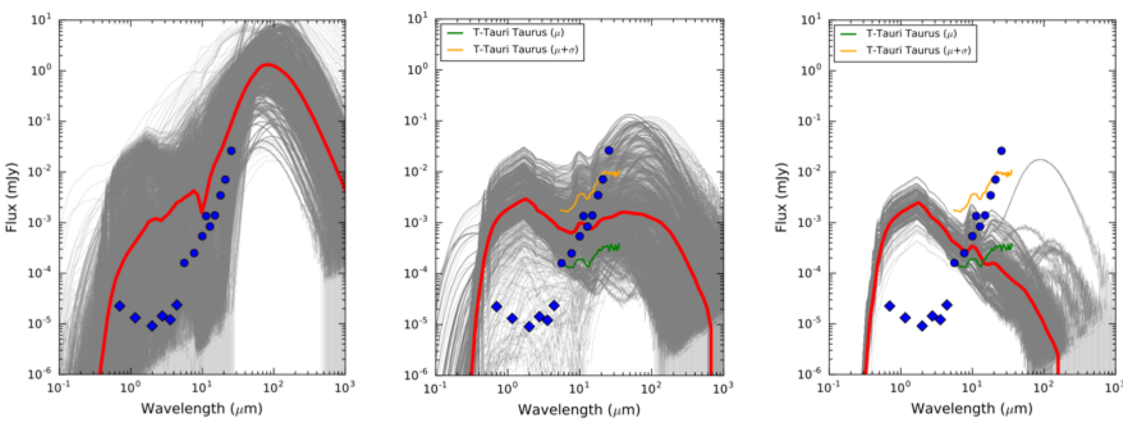

Figure 2: Spectral energy distribution (SED models of Stage 1, 2 and 3 of 1 M⊙ YSO models from Robitaille (2017) at different inclinations. The red line shows the median expectation. ***Photometry from 1 to 500 μm is essential for identification and determination of luminosity and mass of YSOs.*** JWST will be sensitive enough to measure these SEDs as shown by the blue diamonds, that mark the 10 sigma sensitivity limits in 3 minutes of integration in JWST NIRCam and MIRI filters, for YSOs in the SMC. After JWST, a mission sensitive to far-infrared wavelengths (>30 μm) will be needed to complete these SEDs.

Stellar Demise: Intermediate mass stars (0.8 M⊙<M<8 M⊙) experience massive dusty winds during the asymptotic giant branch (AGB) that enrich the interstellar medium (ISM) with dust. For both the LMC and SMC, a complete census of the tens of thousands of dusty AGB and red supergiant (RSG, M>8 M⊙) stars for the first time using infrared color-magnitude diagrams (Blum et al. 2006; Srinivasan et al. 2009; Boyer et al. 2011; Fig. 3). By measuring the dust production rates, we were able to put these stars in the context of the full-galaxy dust budget, the first measurement of this kind (Riebel et al. 2012; Boyer et al. 2012; Srinivasan et al. 2016). The dustiest LMC and SMC sources have the highest dust production rate and were detectable in the far-infrared bands of Herschel (Jones et al. 2015). Similar studies with Spitzer in nearby dwarf galaxies demonstrated that dust from carbon-rich AGB stars may not have a strong dependence on metallicity (Boyer et al. 2014 a&b, 2017).

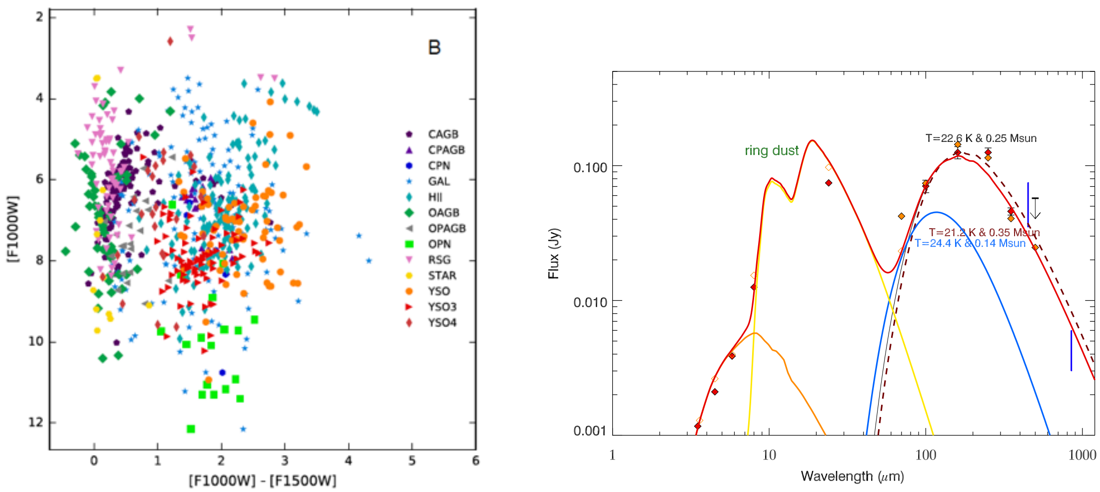

Figure 3: Infrared photometry can be used for source selection in color magnitude diagrams (left) or SED fit analysis to derive physical quantities (right). Simulated color magnitude diagram for the MIRI imager filters showing the types of objects that will be detectable in nearby galaxies (left, Jones et al. 2017). SN 1987A's SED revealed a cold, massive (~0.4-0.8 $M_{\odot}$, Matsuura et al. 2015) when the far-infrared photometry (>70 μm) from Herschel was added.

Massive stars ($M>8\ M_{\odot}$) end their life in an explosive supernova (SN) event that expels the metal rich-ejecta into their surrounding medium. The expanding and cooling ejecta is an astronomical factory for the production of molecules and dust. Theoretical models suggest the early and rapid formation of molecules (CO, SiO2, MgO) and dust (silica, and alumina) in their ejecta (e.g. Sarangi & Cherchneff 2015). Line and continuum infrared observations of young SNe and evolved SNR have provided important information on the elemental, chemical, and dust content of their ejecta, and tests of these models (e.g. Sandstrom et al. 2009; Rho et al. 2018; Barlow et al. 2010; Dwek & Arendt2015). For example, SN1987A was detected in the Herschel data and its far-infrared emission interpreted to arise from 0.4-0.8 $M_{\odot}$ of dust associated with the explosive ejecta (Fig. 3, Matsuura et al. 2011, 2015), a result with important implications for understanding dust formation in supernovae and its contribution to the dust budget of galaxies.

Remaining outstanding questions:

The LMC and SMC offer two galaxy environments for the analysis of infrared stellar populations. **We need to do similar studies of galaxies in the local volume.** ***How does galactic environment affect the process of star formation and dust production by dying stars?*** Both of

these processes are short lived stages of a star's life. The infrared stellar population anaylsis offers a "snapshot" in time. Its critical to gather statistics for a variety of galaxies in order to determine how the star formation and stellar death phases are associated with the star formation histories of galaxies and the properties of the ISM.
More sensitive observations of the LMC and SMC will probe the lower mass YSOs that are currently missing from the catalogs and address the question: ***Are there substantial differences in the star formation process at lower metallicity? Does the initial mass function change with metallicity?*** These larger galaxy samples will also provide examples of especially extreme star formation objects such as super star clusters. ***How are super star clusters formed?***

By associating the stellar dust production with star formation histories, we can calculate the total dust contributed by a star of a given mass over its life addressing the following questions: (1) ***How rapidly is dust formed in galaxies?*** (2) ***What fraction of a galaxies dust is contributed by AGB and RSG dust winds? By SNe?*** (3) ***What is the dust composition in SN ejecta?***; (4) ***What fraction of the newly-formed SN dust is destroyed by the reverse shock?***

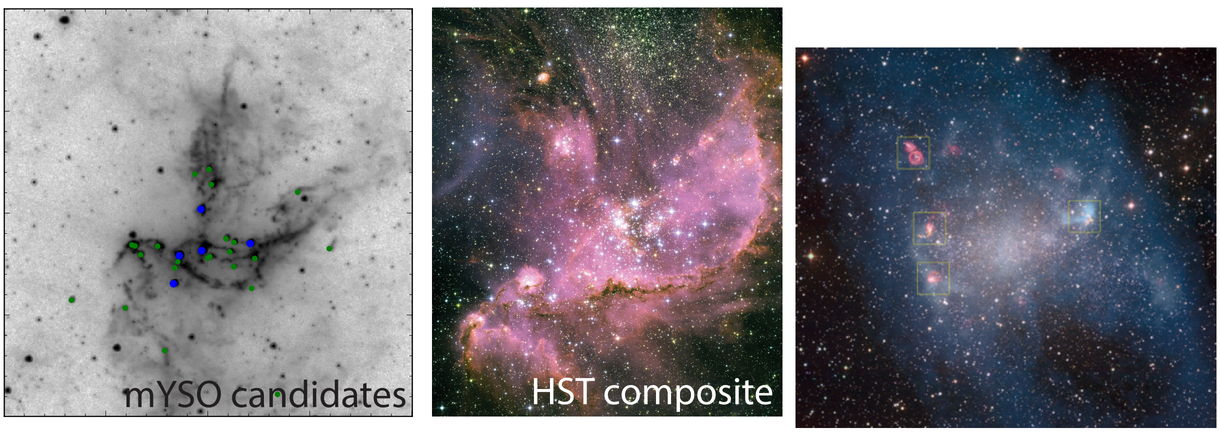

Figure 4: SMC-NGC 346 is a massive star formation region will be a guaranteed time observation (GTO) JWST . ***Left:*** The location of known Spitzer/Herschel massive YSO candidates overlaid on the SAGE 8 μm image (Gordon et al. 2011). ***Middle:*** The HST image of the young massive cluster in which pre-main sequence stars reside (Nota et al. 2006). Missing from this picture are the lower mass embedded YSOs that require more sensitive infrared (e.g. JWST) and far-infrared photometry to detect. ***Right:*** NGC 6822, will be a JWST GTO target for infrared stellar populations analysis and would benefit from a far-infared photometry survey of its stellar population (Schruba et al. 2017; the boxes denote both the location of extreme star formation activity and the location of ALMA observations).

Required Observations:

JWST Contributions: 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, $\leq$ 10 Mpc, in the local volume of galaxies. For example, JWST will obtain infrared images with the same angular resolution as that of HST and enable studies of star formation in the Magellanic Clouds similar to the Spitzer studies of Milky Way star formation regions. In particular, we can investigate specific star formation regions, like NGC 346 (Figure 4), and extend the census of young stellar objects to $1 M_{\odot}$ at near- to mid-IR wavelengths of their spectral energy distribution (Figure 2). By extending to these fainter young stellar objects, we expect to increase the number of sources from 10's found with Spitzer and Herschel to 1000's with JWST.

In nearby galaxies such as NGC 6822 (Fig. 4), we can get a complete census of the infrared stellar populations with JWST NIRCam and MIRI (Fig. 3). As in the SAGE project, such studies will reveal the evolved dusty stars and the young stellar objects. With the large statistical sample from these imaging studies, we can estimate the dust mass return to these galaxies and the current star formation rate.

Far-infrared photometry: We will need photometry at the far-infrared wavelengths (25 to 600 µm) in order to complete the spectral energy distributions identified by JWST. Moreover, followup to Herschel discoveries, e.g. SN 1987A's dust, and the proto-super star cluster, H72.97-69.39, can be best carried out with a more sensitive far-infrared space observatory. The sensitivity would need to be a factor of >10 improvement over Herschel and angular resolution gain of ~2 such as could be provided by the *Origins* Space Telescope.

Wide field near-infrared imaging and photometry: To study the population over entire galaxies and their circum-galactic regions, we will need the wide field imaging capability in the near-infrared, such as could be provided by a WFIRST mission.

Theoretical tools:

In addition to longer wavelength observations, we also require improved theoretical tools for stellar populations. Theoretical progress is 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 in never-before tested environments, 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.

Summary: We anticipate good progress with JWST on the studies of star formation and stellar demise. However, we will need longer wavelength photometry (e.g. Origins Space Telescope), wide field photometry of whole galaxies (WFIRST) and parallel progress on theory of stellar evolution.

References:

Barlow, M.J., Krause, O., Swinyard, B.M. et al. 2010, A&A, 518, 138

Blum, R.D., Mould, J.R., Olsen, K.A. et al. 2006, AJ, 132, 2034

Boyer, M. L., Srinivasan, S., van Loon, J. T., et al. 2011, AJ, 142, 103 SMC AGB

Boyer, M. L., Srinivasan, S., Riebel, D., et al. 2012, ApJ, 748, 40

Boyer, M., L., McQuinn, K.B., Barmby, P.,et al. 2014a, ApJS, 216, 10

Boyer, M., L., McQuinn, K.B., Barmby, P., et al. 2014b, ApJS, 800, 51

Boyer, M., McQuinn, K.B.W., Groenewegen, M.A.T., et al., 2017, ApJ, 851, 152

Carlson, L. R., Sewiło, M., Meixner, M., et al. 2011,ApJ, 730, 78

Dwek, E., Arendt, R.G., 2015, ApJ, 810, 75

Gordon, K. D., Meixner, M., Meade, M. R., et al. 2011, AJ, 142, 102

Gruendl, R. A., & Chu, Y.-H. 2009, ApJS, 184, 172

Jones, O.C., Meixner, M., Sargent, B. et al. 2015, ApJ, 811, 145

Jones, O.C., Meixner, M., Justtanont, K., Glasse, A., 2017, ApJ, 841, 15

Matsuura, M., Dwek, E., Meixner, M., et al. 2011, Science, 333, 1258

Matsuura, M., Dwek, E., Barlow, M.J., et al. 2015, ApJ, 800, 50

Meixner, M., Gordon, K. D., Indebetouw, R., et al. 2006, AJ, 132, 2268

Meixner, M., Panuzzo, P., Roman-Duval, J. et al. 2013, AJ, 146, 62

Nayak, O., Meixner, M., Fukui, Y., et al. 2018, ApJ, 854, 154

Nota, A., Sirianni, M., Sabbi, E., et al. 2006, ApJ, 640, L29

Ochsendorf, B. B., Meixner, M., Chastenet, J., et al. 2016, ApJ, 832, 43

Ochsendorf, B. B., Zinnecker, H., Nayak, et al. 2017a, Nature Astronomy, 1, 784.

Ochsendorf, B.B., Meixner,M., Roman-Duval, J., Rahman, M., Evans, N. 2017b, ApJ, 841, 109

Riebel, D., Srinivasan, S., Sargent, B., & Meixner, M. 2012, ApJ, 753, 71

Rho, J., Gomez, H.L., Boogert, A., et al. 2018, MNRAS, 479, 5101

Robitaille, T.P., 2017, A&A, 600, 11

Sandstrom, K., Bollato, A., Stanimirovic, S., et al. 2009, ApJ, 696, 2138

Sarangi, A., Cherchneff, I., 2015, A&A, 575, 95

Schruba, A., Leroy, A.K., Kruijssen, J.M.D. et al. 2017, ApJ, 835, 278

Seale, J., Meixner, M., Sewilo, M., Babler, B., et al. 2014, AJ, 148, 124

Sewiło, M., Carlson, L. R., Seale, J. P., Meixner, M et al. 2013, ApJ, 778, 15

Srinivasan, S., Meixner, M., Leitherer, C., et al. 2009, AJ, 137, 4810

Srinivasan, S., Boyer, M., Kemper, F., Meixner, M. et al. 2016, MNRAS, 457, 2814

Whitney, B.A., Sewilo, M., Indebetouw, R. et al. 2008, AJ, 136, 18