Probing the Dusty Stellar Populations of the Local Volume Galaxies with JWST/MIRI

Olivia C. Jones1, Margaret Meixner1,2, Kay Justtanont3, and Alistair Glasse1

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218, USA
2 The Johns Hopkins University, Department of Physics and Astronomy, 366 Bloomberg Center, 3400 N. Charles Street, Baltimore, MD 21218, USA
3 Department of Earth & Space Sciences, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden

Abstract

The Mid-Infrared Instrument (MIRI) for the James Webb Space Telescope (JWST) will revolutionize our understanding of infrared stellar populations in the Local Volume. Using the rich Spitzer-IRS spectroscopic data set and spectral classifications from the Surveying the Agents of Galaxy Evolution (SAGE)–Spectroscopic survey of more than 1000 objects in the Magellanic Clouds, the Grid of Red Supergiant and Asymptotic Giant Branch Star Model (GRAMS), and the grid of YSO models by Robitaille et al., we calculate the expected flux densities and colors in the MIRI broadband filters for prominent infrared stellar populations. We use these fluxes to explore the JWST/MIRI colors and magnitudes for composite stellar population studies of Local Volume galaxies. MIRI color classification schemes are presented; these diagrams provide a powerful means of identifying young stellar objects, evolved stars, and extragalactic background galaxies in Local Volume galaxies with a high degree of confidence. Finally, we examine which filter combinations are best for selecting populations of sources based on their JWST colors.

Key words: galaxies: stellar content – infrared: stars – Local Group – Magellanic Clouds

Supporting material: machine-readable tables

1. Introduction

The James Webb Space Telescope (JWST) will revolutionize our knowledge of the stellar populations of galaxies out to and beyond the Virgo cluster. The large (6.5 m) aperture of JWST, combined with its subarcsecond spatial resolution and broad wavelength coverage (0.6–28.5 μm), will provide unprecedented opportunities to study the properties of resolved dusty stellar populations at moderate and large distances (∼4 Mpc). Notably, JWST will enable the accurate measurement of the star formation histories of nearby galaxies, determine the age of the oldest stellar populations, and characterize metal enrichment in a wide variety of environments.

Infrared observations of stellar populations are critical for studies of chemical enrichment, as both the early and late stages of a star’s life are enshrouded in dust and molecular gas. However, the ability to correctly interpret infrared observations (especially for galaxies at high-redshift) relies on accurate constraints of the stellar populations. Currently, resolved mid-infrared stellar population studies of galaxies with multiple populations are limited to nearby galaxies such as the Magellanic Clouds. With JWST this will be possible for well over a hundred galaxies within the Local Volume.

The dusty stellar populations of the Large and Small Magellanic Clouds (D = 50 and 60 kpc; Ngeow & Kanbur 2008; Szewczyk et al. 2009; Feast 2013), with metallicities of 0.5 and 0.2 Z⊙ (Russell & Dopita 1992), have been well characterized in the IR from 3.6 to 500 μm using the Spitzer and Herschel Space Telescopes (Meixner et al. 2006, 2013; Gordon et al. 2011). More than 10.5 million point sources were photometrically detected, along with key populations of sources throughout the Magellanic Clouds identified in the color-magnitude diagrams (CMDs). Furthermore, more than 1250 of these sources were observed with Spitzer’s Infrared Spectrograph (IRS), revealing the mineralogy and evolutionary status of these sources (Woods et al. 2011a; Ruffle et al. 2015; Jones et al. 2017). This large spectroscopic data set and corresponding point-source classification is an ideal empirical library of template spectrum, which we can use to predict the flux densities and magnitudes that we will detect with the JWST Mid-Infrared Instrument (MIRI; Rieke et al. 2015).

The Mid-Infrared Instrument (MIRI; Rieke et al. 2015) on board JWST will provide broadband imaging, coronography, and spectroscopy over the 5–28.5 μm wavelength range (Bouchet et al. 2015; Rieke et al. 2015; Wright et al. 2015). MIRI imaging will be a factor of 50 more sensitive than Spitzer’s IRAC and MIPS instruments, with a sevenfold improvement in resolution; the field-of-view for the MIRI imager (MIRIM) is 74″ × 113″, with a plate scale of 0.11 arcsec/pixel and a full-width half maximum of ~0.7″ (Bouchet et al. 2015). MIRIM provides continuous mid-IR wavelength coverage for broadband imaging in nine filters from 5.6 to 25.5 μm; these filters have been optimized for the detection of the most astronomically relevant molecular and dust species. For instance, the F1130W and F1000W filters are sensitive to PAHs and silicate dust, respectively.

The MIRI imager is significantly more sensitive than the Medium Resolution Spectrograph (MRS), with a larger field-of-view, which means that studies of stellar population on a galactic scale can be done in a reasonable time. The downside is that it is more difficult to correctly identify the nature of the observed object. In this paper we will evaluate potential photometric classifications with JWST/MIRI using the stellar populations of the Large Magellanic Cloud (LMC) as a template. In Section 2 we describe our method for calculating the MIRI synthetic photometry. Section 3 presents the results of these calculations and shows some illustrative MIRI color-magnitude diagrams for the stellar populations of the
Magellanic Clouds. Finally, in Section 4 we discuss how to apply this study to more distant galaxies.

2. Method

The nine JWST/MIRI broadband imaging filters will generate a wealth of photometric data for mid-IR stellar populations. In the following section we use the MIRI filter curves from Glasse et al. (2015) to develop color selection criteria that can isolate and differentiate IR stellar populations. This analysis will provide guidance for planning JWST observing programs and determining point-source classifications across a range of metallicities.

2.1. Mid-infrared Spectroscopic Templates

2.1.1. Observational Data

In order to predict fluxes and colors through the MIRI filters, we have made use of Spitzer-IRS spectra (Houck et al. 2004), from the SAGE-Spec legacy survey of the LMC (Kemper et al. 2010). The IRS spectra cover a wavelength range from 5.3 to 38 μm with spectral resolutions, \( R = \lambda / \Delta \lambda \sim 60 - 600 \). The distance to the LMC is well known (see Ngeow & Kanbur 2008; Szewczyk et al. 2009; Feast 2013), the galaxy’s inclination angle is nearly face on (\( \sim 30^\circ \); van der Marel & Cioni 2001), and all the stellar populations are at essentially the same distance; thus the LMC Spitzer-IRS spectra can be used to predict fluxes and colors for any photometric filter within this range. As there is no spectral coverage by the Spitzer-IRS at \( \lambda < 5.3 \) μm, we cannot predict fluxes for the F560W filter. For all sources in the LMC, we adopt a distance modulus of 18.49 ± 0.05 (Pietrzyński et al. 2013).

More than 1000 point sources in the LMC have been observed with the Spitzer IRS and homogeneously reduced by the SAGE-Spec Spitzer legacy program (Kemper et al. 2010; Woods et al. 2011b), yielding a coherent spectral catalogue. The reduced Spitzer IRS data can be obtained from the NASA/IPAC Infrared Science Archive.\(^5\) These sources cover the range in luminosities and colors parameterized by IRAC, MIPS, and 2MASS magnitudes found in the SAGE-LMC photometric survey (Meixner et al. 2006). They have been classified in a uniform manner with respect to their base properties, according to their mid- and far-infrared spectral characteristics, SED shape, pulsation period, and bolometric magnitude, by Woods et al. (2011a), Ruffle et al. (2015), and Jones et al. (2017), using a classification flow chart (Figure 3 in Ruffle et al. 2015).

The point sources observed by the SAGE-Spec survey have been separated according to their evolutionary stage (young stellar objects, main-sequence star, asymptotic giant branch star, post-asymptotic giant branch, and planetary nebula), chemistry (oxygen or carbon rich), and by mass in the case of red supergiants. The Young Stellar Object (YSO) class has been further subdivided on the bases of their spectral features—

\(^5\) http://irsa.ipac.caltech.edu/data/SPITZER/SAGE

Herbig AeBe (HAeBe) stars. The spectral features of YSOs can be used as a proxy for the evolutionary stage: evolving from heavily embedded YSO-1s to compact H II regions.

A limited number of sources classified as YSO-3 may be confirmed as compact H II regions with JWST. This confusion arises because evolved YSOs and the (ultra)compact H II region have a continuum of similar properties, and the spatial resolution probed by the Spitzer-IRS in the LMC is at best \( \sim 1 \) pc (4″2). This makes it challenging to resolve compact H II regions and separate the contributions of the YSO from its environment. Readers interested in evolved YSOs should therefore consider both the YSO-3 and H II categories.

Several mid-IR spectroscopic studies of these spectral-classes have been published in the literature. Buchanan et al. (2006, 2009) obtained and classified the spectra of 123 of the 250 most luminous 8 μm sources in the LMC, while Kraemer et al. (2017) classify the bright mid-infrared population of the SMC. Objects specifically targeted were various intermediate to high-mass post-main-sequence stars or stars that are undergoing significant mass loss.

Evolved stars were the focus of several Spitzer-IRS programs (PID: 200, 1094, 3591, 3505, 3583, 50147, and 50167); their selection was predominantly based on near- and mid-IR color classification schemes (e.g., Egan et al. 2001 for GTO and cycle 1–3 programs or the SAGE evolved star photometric cuts by Blum et al. 2006, for later cycles), and in some instances includes variables identified in ground-based programs. The spectral properties of the carbon stars observed in the Magellanic Clouds were published by Sloan et al. (2016); the sample of O-rich AGB stars and RSGs was published by Jones et al. (2012). A large subset (145) of the dust-producing AGB and RSG spectroscopic sample has independently been characterized by Groenewegen et al. (2009).

Post-AGB stars and PNe were targeted by programs 103, 20443, 30788, 50092, and 50338, and their spectra were published by Stanghellini et al. (2007), Bernard-Salas et al. (2008, 2009), Volk et al. (2011), Gielen et al. (2011), Matsuura et al. (2014), and Sloan et al. (2014). The spectra of the PNe were obtained early on in the Spitzer mission; the majority of these sources had been previously observed with HST. Post-AGB stars were only explicitly targeted late on in Spitzer’s cryogenic mission. Candidate post-AGB stars were identified using a combination of flux limits and mid-IR colors to exclude YSOs and supergiants. The post-AGB candidates were then cross-matched with the literature to ensure a clean selection.

There are \( \sim 300 \) YSO and HII spectra observed in the LMC; these are predominantly from program 40650 (PI: Looney) and their spectra published by Seale et al. (2009). YSO spectroscopic targets were selected from the Gruendl & Chu (2009) catalogs of YSO candidates. These catalogs of high-mass YSOs in the LMC were produced using aperture photometry on the SAGE images.

The LMC spectroscopy available in the Spitzer archive is biased toward the science goals of the PI and the selection effects of the original programs. Spectroscopic studies performed in cycles 1–3 were skewed toward the brightest sources in the LMC, as target selection was limited by the Midcourse Space Experiment (MSX; Egan et al. 2001) sensitivity limits (7.5 mag at 8 μm) or was biased toward categories of objects known prior the launch of Spitzer. The reader is referred to Table 2 of Kemper et al. (2010) for a comprehensive...
description of all the Spitzer programs that have targeted objects in the LMC with the IRS.

To eliminate biases in the LMC spectroscopic sample, the Spitzer SAGE-Spec program (PID: 40159) targeted unexplored and underrepresented region of IRAC/MIPS color-magnitude space for a range of object classes. Spectroscopic candidates were carefully selected to cover the full range in luminosities and color found in the SAGE data, while simultaneously sampling the key phases of stellar evolution. The sensitivity limit of the SAGE-Spec survey is [8.0] = 7.78 + 0.98 × (18.0) − [24]) and corresponds to a bolometric magnitude of $M_{bol} < -3.75$. It should also be noted that our spectral catalog is not very sensitive to low-mass sources, and in crowded star-forming regions some of the IRS sources may be small unresolved clusters (Ward et al. 2017), which would be resolved into multiple components with JWST.

The Spitzer-IRS spectra sample the complete range of object classes found in the infrared stellar populations of the Magellanic Clouds. Table 1 gives a summary of the spectral classification groups used by Woods et al. (2011a), Ruffle et al. (2015), and Jones et al. (2017). This spectral inventory can act as an empirical template for analyzing and interpreting future infrared data on stellar populations for more distant galaxies in both the local and high-redshift universe.

As a check on the flux calibration of the spectra, we compare the IRS spectra to the SAGE photometry at 8.0 and 24 μm. The absolute flux calibration of the SAGE photometry has a higher fidelity than the Spitzer IRS spectra and is accurate to 3% (Rieke et al. 2004; Reach et al. 2005; Engelbracht et al. 2007; Bohlin et al. 2011). Spectrophotometry for each source was synthesized from the Spitzer spectra at the effective central wavelength in each filter and checked against the observed IRAC and MIPS observations at 8 and 24 μm. About 17% of the spectral observations are offset from the Spitzer SAGE photometry by more than 10%. In some cases this is due to stellar variability, as both AGB stars and YSOs can show strong variations in brightness. To alleviate disparities in the flux, we exclude sources showing deviations that cannot be accounted for by pulsations. These sources are not included in Table 1. Any remaining systematic effects are minimal, since we are looking at a large population of stars.

In addition to stellar sources, we also incorporate into our sample Spitzer-IRS spectra for a broad range of galaxy morphologies, including ellipticals, spirals, merging galaxies, blue compact dwarfs, and luminous infrared galaxies. The galaxies in our sample are within $z < 0.05$, and their properties have been summarized by Brown et al. (2014). Low-resolution IRS spectra for these sources covering the 5.2–38 μm wavelength range were obtained from version seven of the Cornell Atlas of Spitzer IRS Sources (Lebouteiller et al. 2011), using the tapered column extraction that is optimized for extended sources. The inclusion of these galaxies (denoted as GAL) in our sample allows us to determine the level of confusion between the stellar population of the host galaxy and unresolved background contaminating point sources.

### Table 1

| Code | Object Type | Number |
|------|-------------|--------|
| C-AGB | Carbon-rich AGB stars | 145 |
| C-PAGB | Carbon-rich post-AGB stars | 19 |
| C-PN | Carbon-rich planetary nebulae | 13 |
| O-AGB | Oxygen-rich AGB stars | 73 |
| O-PAGB | Oxygen-rich post-AGB stars | 23 |
| O-PN | Oxygen-rich planetary nebulae | 27 |
| RSG | Red Supergiants | 74 |
| STAR | Stellar photospheres | 30 |
| YSO-1 | Embedded Young Stellar Objects | 53 |
| YSO-2 | Young Stellar Objects | 14 |
| YSO-3 | Evolved Young Stellar Objects | 77 |
| YSO-4 | HAeBe Young Stellar Objects | 21 |
| HII | H II regions | 134 |
| GAL | Galaxy | 136 |

2.1.2. Data from Radiative Transfer Models

To complement the observed Spitzer-IRS spectra, we have also obtained model data from the Grid of Red Supergiant and Asymptotic Giant Branch Star Models (GRAMS; Sargent et al. 2011; Srinivasan et al. 2011), and the grid of YSO models developed by Robitaille et al. (2006). These model grids have the advantage over observed sources in regard to lack of noise in the data and the fundamental knowledge about their stellar properties. This allows us to trace the evolution of a source using physical quantities in color-magnitude space. It also enables us to probe different mass regimes to what the Spitzer-IRS sample is sensitive to. However, the models suffer from some limitations; they do not account for molecular and complex dust emission from various species present in the spectra (e.g., the YSO models do not include contributions from PAH emission or atomic emission lines). They also do not include multiple stellar sources, which can influence the near- and mid-IR emission. As both the observed spectra and the models have their strengths and weaknesses, we use both methods to investigate MIRI colors.

The GRAMS models of carbon- and oxygen-rich AGB stars and RSGs sample a large range of stellar and spherical dust shell parameters relevant to evolved stars that are undergoing mass loss. The GRAMS models were produced using the 2DUST radiative transfer code (Ueta & Meixner 2003) and were constructed around model photospheres computed by Kučinskas et al. (2005) and Aringer et al. (2009) for the M and C stars, respectively. The oxygen-rich models were computed by Sargent et al. (2011) using oxygen-deficient silicate grains (i.e., silicates that have not reached their stochiometric proportions) from Ossenkopf et al. (1992), while the carbonaceous dust (Srinivasan et al. 2011) is composed of a mixture of 90% amorphous carbon (Zubko et al. 1996) and 10% silicon carbide (3C; Pégourie 1988). The GRAMS models do not distinguish O-rich AGB stars from RSGs. For both the carbon and oxygen-rich grids, we select models with a stellar effective temperature of $T_{eff} = 2100–4700$ K, a dust shell inner radius of $R_{in} = 3$, or 7 $R_{star}$ and log($g$) = −0.5. These parameters were chosen, as they are representative of the range of values expected for AGB stars, and together with mass loss they have greatest influence upon the model output.

For the YSOs we use the precomputed 2D radiative transfer model grid developed by Robitaille et al. (2006). These models cover a range of stellar masses from 0.1 to 50 $M_\odot$ and assume a young central source (0.001–10 Myr) with a rotationally flattened infalling envelope, bipolar cavities, and a flared accretion disk. Each model SED is computed at 10 inclination
angles. The dust in the YSO models is represented by a mixture of astronomical silicates and graphite at solar abundances from the optical constants of Laor & Draine (1993). The grain size distribution varies with location in the disk and envelope. The models are divided into three stages, ranging from the early envelope infall to when the young star is dispersing its protoplanetary disk.

Stage I YSOs have substantial envelopes, and the central source accretes dust and gas at rates of $M_{env}/M_\star > 10^{-6} M_\odot$ yr$^{-1}$. Stage II YSOs have a dispersed protostellar envelope and optically thick disks $M_{env}/M_\star < 10^{-6} M_\odot$ yr$^{-1}$ and $M_{disk}/M_\star > 10^{-6}$. Finally, stage III YSOs have optically thin disks $M_{env}/M_\star < 10^{-6} M_\odot$ yr$^{-1}$ and $M_{disk}/M_\star < 10^{-6}$.

The Woods et al. (2011a) YSO-1 and YSO-2 objects are synonymous with the Stage I sources from the Robitaille et al. (2006) models, while the YSO-3 and YSO-4 class is the analogue of Stage II objects from the high and intermediate-mass regimes, respectively.

As the relative importance of the various parameters in the Robitaille et al. (2006) models are dependant on the given evolutionary stage, we do not limit a parameters range to focus on YSOs in three stellar mass regimes, 0.2, 2.0, and 20 $\pm 2.5\% M_\odot$, at a disk inclination of 48.5. These values are representative of the minimum YSO mass a program may detect in a reasonable integration time for the Milky Way, the Magellanic Clouds, and more distant local group galaxies.

2.2. Predicted MIRI Photometry

In order to calculate predicted MIRI broadband flux densities and colors for mid-IR stellar populations, we use the same convention outlined by earlier infrared space telescopes such as IRAS, ISO, Spitzer, and Wide-Field Infrared Survey Explorer (WISE); e.g., Beichman et al. 1988; Blommaert et al. 2003;Reach et al. 2005;Wright et al. 2010). Here photometry for the desired photometric band $f_\nu^{\text{MIRI}}(\lambda_{\text{eff}})$ is synthesized from a convolution of the template source spectra $F_\nu$ with the MIRI filter functions from Glasse et al. (2015).

The MIRI relative system response function $R_\nu$, defined as the fraction of detected electrons per photon crossing the focal plane of the MIRI Imager, were created by Glasse et al. (2015) from two independent measurements. The response function for the MIRI filters are in units of electrons per photon. This can be converted to a photon-counting response function $R$ in units of electrons per unit energy, by re-normalizing the product of $\lambda R_\nu$ (e.g., Bessell 2000).

Fluxes in the MIRI wavebands were calculated by integrating the Spitzer/model spectra ($F_\nu$) of each source over the MIRI spectral response according to the following equations:

$$ f_\nu^{\text{MIRI}}(\lambda_{\text{eff}}) = F_\nu(\lambda_{\text{eff}}) \times K, $$

where $\lambda_{\text{eff}}$ is the effective wavelength of the filter, $F_\nu(\lambda_{\text{eff}})$ is the flux density of the input Spitzer spectrum at $\lambda_{\text{eff}}$, and $f_\nu^{\text{MIRI}}(\lambda_{\text{eff}})$ is the monochromatic flux density that would be given if the source was observed by the MIRI imager. The dimensionless quantity $K$ is defined in terms of frequency units by

$$ K = \frac{\int (F_\nu/F_\nu_{\text{ref}})(\nu/\nu_{\text{eff}})^{-1} R_\nu d\nu}{\int (\nu/\nu_{\text{eff}})^{-2} R_\nu d\nu}, $$

where $F_\nu_{\text{ref}}$ is a reference spectrum; this is assumed to be a $\nu F_\nu = \text{constant}$ flux spectrum (see, e.g., Blommaert et al. 2003;Reach et al. 2005;Hora et al. 2008;Bohlin et al. 2011).

Alternatively, the flux can be calculated in terms of the photon weighted mean flux over the bandpass. This effective flux is defined in frequency units as

$$ F_\nu = \frac{\int F_\nu \nu^{-1} R_\nu d\nu}{\int \nu^{-1} R_\nu d\nu}. $$

This method is traditionally used by HST and optical telescopes; it does not involve the color corrections or effective wavelengths prevalent in flux calculations for IR space-based telescopes.

The choice of methodology between Equations (1) and (2), and (3) can return a flux for the MIRI filters ($f_\nu^{\text{MIRI}}$), which differs by a few percent (typically $< 3\%$). However, the divergence can be more severe if the shape of source spectrum significantly differs from that of the reference spectrum. By convention, the Jansky systems assumes a $\nu F_\nu = \text{constant}$ reference system.

When calculating uncertainties associated with the MIRI fluxes, we first consider the flux uncertainties of the observed Spitzer IRS sample and the absolute flux calibration errors. The formal uncertainties in the mean ($\sigma/\sqrt{N}$) and systematic uncertainties from the absolute flux calibration (Sloan et al. 2015); the presence of other sources in the slit; and pointing errors, which introduce discontinuities between the segments, need to be assessed. The flux uncertainties and calibration are described in detail by Woods et al. (2011b) and Lebouteiller et al. (2011), and are summarized in the Appendix.

To estimate the total uncertainty of a flux, we use the quadratic sum of these measured and systematic errors. For the GRAMS and YSO models, we assume a total uncertainty of 5%, to reflect the uncertainty in the stellar atmosphere models.

The final uncertainties in the MIRI fluxes were computed by propagating the uncertainties from the spectra and models.

In Figure 1 we present the Spitzer-IRS spectra of a representative subsample of evolved stars, YSOs, and galaxies, and the MIRI broadband flux densities these sources would have if they were observed with JWST. These sources are representative of their stellar class and can be characterized by their spectral appearance in the mid-IR.

2.3. Effective Wavelength

As noted earlier, the flux density of a source is evaluated at the effective wavelength of the filter. The optimal choice for the effective wavelength is the filter wavelength that is least sensitive to the spectral shape of the source (i.e., the weighted average wavelength), defined as

$$ \lambda_{\text{eff}} = \frac{\int \lambda R_\nu d\lambda}{\int \lambda^2 R_\nu d\lambda}. $$

This is related to the effective-frequency via $\nu_{\text{eff}} = c/\lambda_{\text{eff}}$. Table 2 gives the effective wavelengths calculated using the current spectral response curves ($R_\nu$) for the MIRI filters (Glasse et al. 2015).
2.4. Magnitudes

We estimate zero-magnitude flux densities for the MIRI bands to determine magnitudes of our template sources from their predicted flux densities. We define the magnitude system such that

\[ M_i = -2.5 \log_{10}(f_{\nu}^{\text{MIRI}}/f_{\nu,\text{zero}}). \]  

The zero-point magnitudes are estimated relative to an “ideal” Vega photospheric reference spectrum, and were determined by integrating a single-temperature Kurucz model spectrum of Vega (Cohen et al. 1992) over the MIRI bands, using the method outlined in Equations (1) and (2). This ideal Vega spectrum (shown in Figure 2) had a uniform effective temperature across the stellar surface and no infrared excess.

By using the Vega magnitude system, we eliminate the dependence on spectral shape. This follows the methodology outlined by Reach et al. (2005) to define the Spitzer/IRAC Magnitude System and should be comparable to other magnitudes relative to Vega in optical and infrared systems. Table 2 gives the resulting zero-magnitude flux densities for the MIRI channels. These zero points do not account for in-orbit telescope performance, and will need to be corrected once the total system throughput is verified post-launch.

### Table 2

| Filter | Calc. \( \lambda_{\text{eff}} \) \( \mu \text{m} \) | \( \Delta \lambda \) \( \mu \text{m} \) | Est. Zero Point Jy |
|--------|-----------------|----------------|------------------|
| F560W  | ...             | 1.2            | 116.60           |
| F770W  | 7.62            | 2.2            | 68.10            |
| F1000W | 9.94            | 2.0            | 40.71            |
| F1130W | 11.31           | 0.7            | 31.82            |
| F1280W | 12.79           | 2.4            | 24.76            |
| F1500W | 15.04           | 3.0            | 17.99            |
| F1800W | 17.96           | 3.0            | 12.46            |
| F2100W | 20.75           | 5.0            | 9.13             |
| F2550W | 25.32           | 4.0            | 6.18             |

Figure 1. *Spitzer*-IRS spectra of a young stellar object, a carbon-rich AGB star, an oxygen-rich AGB star, a planetary nebulae, and the rest-frame spectrum of a star-forming galaxy. The resulting fluxes from integrating the spectra over the MIRI bandpasses are shown in red. The thick black lines in the top panel show the wavelength coverage of the MIRI bandpasses.

Figure 2. An “ideal” Kurucz model spectrum of Vega, together with the relative spectra responses of the MIRI channels (in electrons per photon), normalized to unity. The red squares show the resulting zero-point fluxes.

### 3. Results

We derive MIRI synthetic photometry for more than 1000 *Spitzer*-IRS spectra with known object types. This photometry is analogous to the flux density (in Jansky) that would be obtained if a source was observed with the MIRI instrument. Table 3 presents the MIRI flux density calculated according to Equation (3). The source type and predicted MIRI magnitudes calculated according to Equation (5) are given in Table 4; all reported magnitudes are in the Vega System.

From this library of stellar classes, MIRI fluxes and magnitudes presented in Tables 3 and 4, it is straightforward to compute the expected fluxes and colors for the stellar populations of more distant galaxies. The flux listed in Table 3 scales with \( 1/(d/50)^2 \), where \( d \) is in kpc and the magnitudes can simply be adjusted to the required distance modulus from that of the LMC, \( M-m = 18.49 \pm 0.05 \text{ mag} \) (Pietrzyński et al. 2013).
The types of objects in our sample are representative of the IR stellar populations of Local Group galaxies and include both YSOs and evolved stars. One of the major contaminants of stellar populations studies is unresolved background galaxies. In order to explore the background galaxy population, we group all the spectra of individual galaxies into one class (GAL) and do not distinguish between galaxies based on their morphological type. It is important to note that the flux of the background galaxies should not be scaled with distance.

These results can be used to guide the choice of filter with which to observe specific object classes with JWST and to identify key populations in color-color and color-magnitude diagrams once JWST observations become available. The color is independent of distance.

### 3.1. MIRI Colors

We present example color-magnitude (CMD) and color-color diagrams (CCD) to aid the identification of the various IR stellar and extragalactic populations that will be observed with JWST. We estimate that the 3σ uncertainty in the color is up to ±0.6 mag. By employing different filter combinations, it is possible to isolate specific populations of objects with minimal confusion. Figures 3 and 4 show example MIRI CMD and CCDS constructed from Spitzer-IRS spectra with the regions occupied by various types of objects illustrated, while Figures 5 and 6 show the results from the evolved star and YSO models.

The CMDs and CCDS (Figures 3 and 4) from the spectral sample provide an accurate representation of the brightest IR population one may expect in a galaxy (including the variations due to various dust compositions). The model CMDs (Figures 5 and 6) enable us to assess low-mass sources and rare source classes that are not evident in the observed sample, and hence provide completeness. Here we describe the most favorable MIRI filters to identify specific populations of objects with minimal confusion.

#### 3.1.1. Main-sequence Stars

Stars with a stellar photosphere but no additional dust or gas features have MIRI colors that fall around zero. The majority of main-sequence and sub-giant stars fall within this class and can only be distinguished on the basis of their short wavelength colors. In MIRI CCDS stars tend to cluster in the upper left side of the diagram (e.g., Figure 4, panel A).

In some instances, main-sequence OB stars can illuminate and heat patches of dense interstellar medium (ISM) surrounding the star (Adams et al. 2013; Sheets et al. 2013). Stars of this nature have colors typical of stellar photospheres at (λ < 8 μm) but show a strong infrared excess at longer wavelengths (λ > 20 μm) indicative of warm dust associated with cirrus hotspots.

#### 3.1.2. Evolved Stars

Evolved stars occupy a wide range of MIRI color space. Their precise location depends on both the abundance and the chemistry of the dust in their circumstellar envelope. Evolved stars have either oxygen-rich or carbon-rich circumstellar envelopes, depending on the C/O ratio in their atmosphere. When C/O < 1, the CO molecule ties up the carbon, resulting in oxygen-rich molecules and dust grains. Conversely, when C/O > 1, all the oxygen is locked up in CO, resulting in carbon-rich molecules and dust. The [F1130W] band centered on the prominent 11.3 μm PAH feature and the peak of the silicon carbide (SiC) feature is a powerful diagnostic tool for separating evolved carbon-rich sources from oxygen-rich sources.
Figure 3. Example JWST/MIRI CMDs for more than 700 point sources in the LMC. The sources are classified by evolutionary stages (e.g., YSOs, asymptotic giant branch, post-asymptotic giant branch, and planetary nebula) and by chemistry (oxygen or carbon rich). Each colored symbol shows a different population of sources, as indicated in the legend; see Table 1 for the class definitions. For clarity, the YSO-1 and YSO-2 subcategories are grouped together as YSO. These colors effectively differentiate evolved stars from YSOs and separate carbon stars from oxygen-rich stars: this is critical for dust-production rate estimates and dust evolution models.
sources. The SiC feature at $\sim 11.3 \mu m$ weakens with increasing metallicity; thus this filter may not be as an effective discriminant in metal-rich environments. Carbon-rich post-AGB stars and PNe may show a combination of SiC and PAHs; for these objects, the $[F1130W]$ band is a powerful diagnostic.

3.1.3. Oxygen-rich AGB Stars

Stars on the early AGB are characterized by a slight IR excess, molecular absorption features, and photometric variability. They do not show any prominent dust features and have MIRI colors slightly to the red of main-sequence stars. Around oxygen-rich stars, the fundamental vibrational mode of SiO causes a slight absorption feature in the spectrum at $\sim 8 \mu m$, which will affect the $[F770W]$ channel.

Simple metal oxides are the first dust species to form in low-density winds, with amorphous silicates becoming increasing prominent as the star evolves. In O-rich stars with weak dust emission, a broad, low-contrast alumina ($Al_2O_3$) feature that peaks at $\sim 11 \mu m$ is often found to co-exist with amorphous silicates. Therefore it may be possible to trace changes in O-rich dust evolution using the four MIRI bands that cover the 10 $\mu m$ region.

Amorphous silicates are the dominant dust component in oxygen-rich AGB stars, RSGs, and post-AGB stars, with broad features at 10 and 20 $\mu m$. These features show considerable variation in shape, width, and the peak wavelength as the star evolves (e.g., Cami et al. 1998; Sloan & Price 1998; Speck et al. 2000; Jones et al. 2014). This can cause a spread in the MIRI colors. Oxygen-rich AGB stars are best identified using the $[F1000W]$, $[F1280W]$, $[F1500W]$, and $[F2100W]$ filters (e.g., Figure 3, panels B, E, and F).

Figure 5 shows the evolutionary tracks from the oxygen-rich and carbon-rich GRAMS models. At low dust mass-loss rates, the O-rich GRAMS models form a narrow sequence in the $[F1000W]$ versus $[F1000W]$–$[F1500W]$ CMD. This reaches the highest magnitudes at the bluest colors. As the infrared excess increases the colors of the O-AGB, stars start to diverge. They become redder and have fainter magnitudes. A similar dispersion in the mid-IR color is not seen in the carbon stars with the onset of mass loss; instead C-AGB stars tend to occupy a distinctive wedge of less than 0.5 mag in IR color space.
The colors and evolutionary tracks of the AGB stars from the GRAMS models shows good agreement with the JWST/MIRI colors derived from IRS observation (cf. Figure 3(B)). The major difference between the two results is the density of O-AGB sources with [F1000W]−[F1500W] > 1; this is a consequence of the sampling in the models. The GRAMS models have not been weighted by an initial mass function; thus this region of color space is overpopulated for a given stellar population.

O-AGB stars and C-AGB stars show the cleanest separation from each other in the [F1500W]−[F2100W] color. In this diagram the GRAMS O-AGB stars have a higher source density at [F1500W]−[F2100W] ~1.2, where the evolutionary tracks turn back on themselves; this is due to the source becoming optically thick, and hence the silicate emission features changing to absorption features.

In some cases if the O-AGB star is undergoing an intense superwind and the dust shell is optically thick, the 10 µm silicate feature may be in absorption or self-absorption. These objects are rare, especially in low metallicity environments (Sloan et al. 2008; Jones et al. 2012, 2014), and thus may blend in with other objects (e.g., YSOs in color space). For certain color combinations, such as the [F1500W]−[F2100W] color, an O-AGB star may have progressively redder colors until the source becomes optically thick. At this point, the color now becomes bluer as mass loss increases, and the star traverses back on itself in color space. This effect is seen in the left panel of Figure 5.

3.1.4. Oxygen-rich Post-AGB Stars

Depending on the binary fraction of the star or the inclination angle of the disk, the SED of post-AGB stars can be either single peaked or double peaked (e.g., Ueta & Meixner 2003; van Aarle et al. 2011). In post-AGB stars with a double-peaked SED; one peak is due to stellar emission from the hot central star and the other due to an outward moving circumstellar dust shell (van Winckel 2003). As post-AGB stars age, the detached, expanding dust shell cools and becomes fainter in the [F560W] and [F770W] bands, which are sensitive to warm dust (e.g., Min et al. 2013).

O-PAGB stars form a diagonal branch in the [F1000W]−[F1500W] versus [F1000W] CMD, as seen in Figure 3(B), where they occupy the less-dense region between C-rich AGB stars and YSOs. As they transition from the AGB region to the PN region of color space, O-rich PAGB stars can have similar mid-IR properties to evolved YSOs. To conclusively identify O-PAGB stars, a long color-baseline is required. The two colors should cover the hot stellar emission (with the NIRCam filters) and the second should be sensitive to the oxygen-rich dust.

Post-AGB stars with a binary companion can have a high crystalline silicate fraction and large dust grains indicative of a circumbinary dusty disc (Gielen et al. 2011). These post-AGB stars have a significant near-IR excess that is superimposed on top of the stellar emission in the SED, rather than as double peak (de Ruyter et al. 2006). In cases where the SED is single peaked, O-rich post-AGB stars may be indistinguishable (in the MIRI filters) from their less evolved AGB counterparts. These “disc” sources would be classified as AGB stars with a large dust excess by Woods et al. (2011a).

3.1.5. Red Supergiants

Red supergiants (RSGs) have very similar dust characteristics to O-AGB stars and are almost indistinguishable in color space. Due to their higher mass (8–25 M☉), RSGs are in general more luminous than AGB stars, and may fall on a sequence that extends to brighter magnitudes than the AGB population; however, care needs to be taken, as this region is also inhabited by foreground stars.

Previous color classification schemes for separating RSG from O-AGB stars rely on near-IR photometry (e.g., Boyer et al. 2011). RSG stars (with little to no dust) are slightly bluer than the O-AGB stars in the J − Ks versus Ks and J − [3.6] CMDs, due to their warmer effective temperatures. As RSG
stars become enshrouded by dust, their $J - K_s$ color grows redder, and it becomes impossible to separate dusty AGB from RSG using the current set of photometric bands.

Figure 3 panel B shows that in the mid-IR, RSGs are discernible by their [F1000W]–[F1500W] colors. In this CMD, O-rich AGB stars form a left-leaning vertical sequence, which is slightly to the blue of a near-vertical sequence at [F1000W]–[F1500W] $\sim 0.2$ and extends to bright magnitudes, formed of RSGs. Finally, slightly to the red of this RSG track is a right-leaning vertical sequence composed of C-AGB stars; all three sequences merge at lower luminosities where the photosphere dominates the colors in systems.

3.1.6. Carbon-rich Stars

In carbon-rich AGB stars, molecular absorption bands due to acetylene ($C_2H_2$) and numerous other carbon chain molecules form. Carbon-rich molecules produce strong absorption features in the 4–8.5 and 13–14 $\mu$m wavelength intervals (Matsuura et al. 2006), and the strength of these bands increases at low metallicity, which may affect the [F560W], [F770W], and [F1280W] MIRI bands in metal-poor carbon stars. At solar metallicity, HCN may also be an important opacity source in carbon stars up to $T_{\text{eff}} \sim 2800$ K (Eriksson et al. 1984; Aoki et al. 1999; Harris et al. 2002), affecting the [F560W] and [F1500W] MIRI fluxes.

Amorphous carbon and graphite are the dominant dust species in carbon stars (see Groenewegen et al. 2009; Sloan et al. 2016, and references therein). They produce a dust-dominated continuum in the mid-IR. However, they do not have a clear spectroscopic signature. Instead, dust features due to silicon carbide (SiC) at 11.3 $\mu$m and the broad 26–30 $\mu$m feature, which is often attributed to MgS dust (Goebel & Moseley 1985; Hony et al. 2002), are the characteristic features of carbon-rich sources.

C-AGB stars are easily separated from all other types of objects using MIRI fluxes. The [F1500W]–[F2100W] color (Figure 3(F)) is especially good for this, as it separates carbon- and oxygen-rich evolved stars, and evolved stars from YSOs. Colors in the $\lambda = 10–20$ $\mu$m region enable us to separate these evolved stars, as both carbon-rich and oxygen-rich AGB stars have prominent dust features in this region due to silicon carbide (SiC) and amorphous silicates, respectively.

3.1.7. Carbon-rich Post-AGB Stars

Carbon-rich post-AGB stars have UV and optically excited PAH features, triangular SiC features at 11.3 $\mu$m, and a prominent feature at 30 $\mu$m, possibly due to MgS (Sloan et al. 2007; Smolders et al. 2010; Matsuura et al. 2014), although alternate carriers have been suggested (Zhang et al. 2009), and in some instances an “unidentified” 21 $\mu$m emission feature that is unique to this class of stars (Kwok et al. 1989; Hirvinen et al. 2009). The strongest observed PAH features occur at wavelengths of 5.7, 6.2, 7.7, 8.6, and 11.3 $\mu$m.

C-PAGB stars occupy the relatively isolated region of color space between AGB stars and YSOs; thus they can be identified in the MIRI color-color space using a wide variety of colors (see Figure 4, panel C). By using a combination of filters, pollution of the color-selected C-PAGB stars by YSOs and extremely red carbon stars is limited.

3.1.8. Planetary Nebulae

Planetary nebulae are emission line sources that can have a dust continuum that peaks in the mid-IR between $\lambda \sim 20–40$ $\mu$m; they may also have dust features due to either silicate or carbonaceous material (i.e., SiC or MgS). All the PNe in our sample have a thermal IR continuum that rises toward longer wavelengths. However, the strength of the dust continuum compared with the emission lines varies considerably (Stanghellini et al. 2007). In addition to forbidden line emission from collisionally excited atomic species, most carbon-rich PNe (C-PN) have PAH emission lines in their spectra, with features at 6.2, 7.7, and 11.2 $\mu$m typical (Bernard-Salas et al. 2009). PAH emission is often used as a discriminant between C-PN and O-PN, as not all objects show solid state features.
Oxygen-rich PNe have spectral energy distributions that rapidly rise toward the far-IR. There is some overlap in color with massive YSOs and background galaxies; however, the O-PNe tend to be fainter than the vast majority of YSOs. Both the [F1130W]–[F1800W] and the [F1130W]–[F1500W] colors (see Figures 3(D) and (G)) provide a clean separation between O-PN, YSOs, and other emission line sources. The CMDs for both colors are almost identical; however, the [F1130W]–[F1800W] color has a slightly larger spread due to the longer baseline, and is thus preferred.

Due to their atomic emission lines, PAH features, and rising dust continuum, carbon-rich PNe have colors that are more or less indistinguishable from the bulk of the YSO population. It is difficult to separate PNe and YSOs using only one or two color combinations; however, multiple CCD composed of four different MIRI bands may help in their identification (cf. Figure 4(D)).

### 3.1.9. Young Stellar Objects: YSOs

As YSOs evolve, their envelopes become hotter and less dense. Thus YSOs of different evolutionary stages span a range in IR colors. We illustrate this by comparing two independent YSO classification schemes: one from observed spectra (Woods et al. 2011a) and one from models (Robitaille et al. 2006). The spectral data provide the most accurate information for massive ($M > 8 M_\odot$) YSOs, while the Robitaille et al. (2006) models provide the complete range of YSO masses down to 0.2 $M_\odot$. Both these schemes portray an evolutionary sequence (1–3) from least to most evolved.

In the mid-IR, YSOs are characterized by a superposition of ice, PAH, and oxygen-rich dust features on a very red cold dust continuum. As discussed in Section 2.1.1, we have divided the YSO spectra into four groups to reflect changes in their IR properties as they evolve toward the main sequence. The YSO spectral groups 1–3 represent an evolutionary sequence for massive YSOs: from deeply embedded sources in the early stages of formation, to stars surrounded by a dusty envelope that is being progressively dispersed. The majority of these sources would be classed as Stage I or Stage II YSOs on the color-color diagram of Robitaille et al. (2006).

YSOs are prominent in all the MIRI bands. They occupy the reddest regions of color space and are clearly separated from the evolved stars. Embedded protostellar objects (YSO-1) have the reddest colors, due to their dense cool envelopes. In principal, as you go to bluer colors, the YSO appears more evolved. However, clear subdivisions between the YSO 1–3 categories is not possible, as YSOs inhabit regions with complex backgrounds. Evolved intermediate-mass YSOs (YSO-4) have a flat or declining spectrum with silicate emission; they occupy a slightly different region of color space compared with the YSO 1–3 classes. This region of color space is relatively sparse, typically populated by sources with dusty disks.

The best way to isolate YSOs in color space is to select two MIRI filters (e.g., [F770W]–[F2500W] or [F1000W]–[F2100W]; Figure 3, panels A and C; and Figure 4, panel C), with a wide baseline in wavelength that has $\lambda > 12 \mu m$. This mitigates contamination from AGB stars, which unlike YSOs, only have moderate amounts of cold dust (Jones et al. 2015b). Consequently, the YSOs have a rising SED at $\lambda > 20 \mu m$, whereas AGB stars and post-AGB stars generally have a falling spectra after $20 \mu m$.

Figure 6 shows model sequences for YSOs, with a stellar mass of 0.2, 2.0, and 20 ±2.5% $M_\odot$ at a disk inclination of 48°. These models sample a variety of the SEDs in the Robitaille et al. (2006) model grid for low-, intermediate-, and high-mass stars. We identify in the MIRI CMDs and CCDs the models that correspond to each of the three evolutionary stages: Stage I, II, and III, defined by Robitaille et al. (2006). At earlier stages, the disk geometry and the inclination has a significant effect on the SED, since this alters the optical depth along the line of sight, although globally the inclination angle is not as important, as it averages out over the stellar population. Stage I sources have the reddest colors and correspond to the youngest embedded YSOs; here the envelope dominates the mid-IR flux. As a source of a given mass evolves, the envelope and disk disperse; the YSO becomes brighter with bluer colors due to the lower-extinction. An evolutionary sequence is seen in the color distribution, with Stage III, II, and I sources moving from lower left to upper right. Figure 6 shows that the evolutionary stages of YSOs are best separated with a long baseline, with one color $\geq 18 \mu m$. This long baseline also provides the greatest separation between YSOs and non-YSOs.

It can be clearly seen in Figure 6 that the YSO models have a large spread in luminosity; this corresponds to the initial mass

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**Table 5**

| Filter | Magnitude |
|--------|-----------|
| F560W  | 22.15     |
| F770W  | 21.09     |
| F1000W | 19.69     |
| F1130W | 18.43     |
| F1280W | 18.67     |
| F1500W | 17.78     |
| F1800W | 16.39     |
| F2100W | 15.27     |
| F2550W | 13.43     |

Estimated from the Zero Points Given in Table 2
of the YSO. In principal, if you have a nearby field-of-view with little contamination, you could cleanly separate the stages and potentially detect YSOs with sub-solar masses. This would require substantial integrations times, even for the Magellanic Clouds.

3.1.10. H II Regions

Compact H II regions form around young hot stars and are typically embedded in giant molecular clouds. They have a steeply rising infrared continuum and can be differentiated from PNe using the long-wavelength shape of the SED. Furthermore, H II regions are typically brighter than PNe and occupy the upper-right region of the MIRI CMDs. H II regions are among the reddest sources in the [F1000W]–[F1500W] CMD (Figure 3(B)), due to their sharply rising continuum. The [F1280W]–[F1800W] color (Figures 3 and 4, panels E and B, respectively) is one of the best filter selections for identifying H II regions. The limited overlap with a small number of YSOs in this color space is probably due to the limited angular resolutions of Spitzer’s IRS that caused ambiguity in the spectral classification between (ultra)compact H II regions and evolved YSOs; consequently, (ultra)compact H II regions were classified as YSOs by Woods et al. (2011a).

3.1.11. Background Galaxies

Background Galaxies are major contaminants to studies of IR stellar populations in the Local Group, particularly at low flux levels. In the JWST era, this problem will be further exacerbated as we push the resolved stellar population studied to greater distances. One way of excluding galaxies to examine each individual source in the image to see if it is marginally resolved; this can be done in a quantitative manner by fitting an elliptical shape to the source.

The constituents and morphologies of the individual galaxies in the background sample are described by Brown et al. (2014). These galaxies cover wide ranges in classes and have spectra that are composed of the composite stellar population for that galaxy. Quiescent galaxies tend to have blue colors and occupy a similar region as dust-free stars in MIRI CMDs. Conversely, galaxies undergoing active star formation populate a large range of MIRI color space, due to their strong 6.2 and 7.7 μm PAH features and their steeply rising SEDs. As such, star-forming galaxies have overlapping colors with YSOs.

The MIRI CMDs and CCDs highlight the difficulty in distinguishing between YSOs and unresolved background sources in the same color-magnitude space; nonetheless, a careful choice of filter combinations can be used to separate galaxies from other stellar populations. Many classes of extragalactic objects will be quite red in the MIRI bands, and we find that the [F770W]–[F1000W] versus [F1500W]–[F2550W] CCD (Figure 4, panel D) is good discriminant between galactic and non-galactic sources. This CCD also highlights the diversity in galaxy colors.

4. Applicability to Local Volume Galaxies

JWST/MIRI’s unparalleled sensitivity and spatial resolution at 5–28 μm will enable resolved stellar population studies out to ~4 Mpc; more than 100 galaxies fall within this volume. Going beyond the Local Group with detailed studies of resolved stellar populations will enable us to measure star formation histories, probe active star formation regions, ascertain the age of the oldest stellar populations, and determine the chemical and dust enrichment of galaxies with properties very different from our own.

Local volume galaxies span a wide range in metallicity (~2.72 < [Fe/H] < 0.5). This large metallicity baseline provides a foundation for understanding which types of objects produce dust, and the significance of their dust production as galaxies evolve. Insights into the connection between resolved stellar populations and galaxy evolution can be used to study the early universe. For instance, it is unclear if intermediate- and high-mass stars can account for the substantial dust abundances observed at z > 6.4 (Beelen et al. 2006; Valiante et al. 2009; Gall et al. 2011).

JWST will be able to obtain moderately deep multi-band stellar photometry for the M81 group at 3.6 Mpc and the Sculptor filament at 3.9 Mpc. In Table 5 we list the 10σ magnitude limits for long-duration observations of faint sources with the MIRI filters. In Figure 7 we have scaled the MIRI photometry of the LMC to that of a galaxy at 3.6 Mpc and over-plotted the MIRI sensitivity limits for a 10σ detection in 10,000 s on the [F1000W] versus [F1000W]–[F1280W] CMD. At this distance, only the brighter red objects, such as RSGs, AGB stars, PNe, massive YSOs (M > 10 M⊙), and H II regions, can be detected. The depth/detection limit of JWST observations of galaxies at 3 Mpc would be comparable to those of the WISE for the LMC (e.g., Wright et al. 2010; Nikutta et al. 2014). From these observations, we would be able to study the formation of new stars, characterize the largest dust producers, and probe substructures within a galaxy.

IR surveys similar to the Spitzer SAGE (Meixner et al. 2006; Gordon et al. 2011) legacy programs, which conducted census of all objects in the Magellanic Clouds brighter than 15 mag at 8 μm, are achievable (in 10,000 s per filter, per pointing), with JWST out to ~450 kpc. The decline in source density toward fainter magnitudes in Figure 7 is a limitation of the Spitzer spectroscopic sample, rather than an observation effect, which would be due to JWST/MIRI. Colors of fainter populations (e.g., low-mass YSOs and evolved stars) can be inferred from scaling the models presented in Section 3 to the required distance and comparing these to the sensitivity limits derived in Table 5.

MIRI observations would allow detailed studies of individual YSOs and H II regions. YSOs can be identified with only MIRI two colors; however, multi-band photometry is required to constrain the physical processes in the protostar, circumstellar disk, and collapsing outer envelope via radiative transfer modeling of its SED. By observing red-luminous populations, we can also determine star formation rates for a much larger volume (≥100) of galaxies than is currently possible with Spitzer (e.g., Whitney et al. 2008; Sewiło et al. 2013). These studies extrapolate the mass function derived from star counts and SED fitting with a standard IMF, to derive an empirical limit for the current star formation rate of a galaxy. Furthermore, MIRI observation of YSOs in conjunction with H I, Hα, and CO gas tracers will reveal the initial conditions and process of star formation across a range of galactic environments.

The IR emission from evolved stellar populations of local volume galaxies measured by JWST can be compared with the ISM dust masses obtained from global flux measurements (Draine et al. 2007) by the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). Determining the nature
of interstellar dust as galaxies evolve in metallicity is essential, as its origin and rate of destruction by supernova shocks (e.g., Temim et al. 2015) is uncertain. Dust-production rates of evolved stars can be estimated from mid-IR colors (Matsuura et al. 2009; Jones et al. 2015a) or via SED fitting with model grids (Riebel et al. 2012; Srinivasan et al. 2016). This can constrain the luminosities, dust chemistry, and current dust-production rate of each star in the sample. The rate of dust injection by the evolved stellar population can be compared with the current ISM dust mass to determine the timescale at which stellar sources replenish ISM dust. This will directly constrain dust models (e.g., Dwek & Chercneff 2011) and provide the foundations for deciphering JWST observations of more distant galaxies in the high-redshift universe.

To ensure representation, samples selected based on photometric data need to be confirmed with spectroscopic observations. With JWST we will be able to conduct detailed spectroscopic studies of point sources within the Local Group. Spectroscopic surveys will provide critical information about the dust compositions, spectral types, and ages of each star. By linking the MIRI colors of LMC objects to their dust characteristics and infrared spectral type (see Section 3.1), we can effectively distinguish between sources of similar color and efficiently select candidates for JWST spectroscopic observations through the careful use of MIRI CMDs. This will ensure that there is a high success rate of JWST spectroscopically observing targets with the desired object class and chemistry. Furthermore, spectroscopic observations with JWST can evaluate and refine our proposed photometric classification scheme, to ensure clean subdivisions between stellar classes.

5. Summary

JWST is expected to revolutionize our understanding of composite stellar populations in the Local Volume. In this paper we have used more than 1250 Spitzer-IRS spectra from the SAGE-Spec legacy program and model spectra from the GRAMS and YSO grids to calculate synthetic MIRI fluxes and magnitudes for IR-bright stellar populations and background galaxies. These results can be used to select JWST filters, which will provide good photometric sampling of SEDs, used to measure the stellar and circumstellar properties of the stars.

We have developed color-color and color-magnitude classification schemes for JWST/MIRI to identify and select samples of similar objects for future studies. These results can easily be adapted for use in other galaxies (e.g., the M81 group) to probe composite stellar populations across a range of galaxy types, metallicities, and star formation environments, beyond the boundaries of the Local Group. In Section 3.1 we assessed the best filters to target specific stellar populations throughout a galaxy, and discussed how to remove foreground and background contamination based on their JWST broadband colors. We highlight the F1000W and F2100W MIRI filters, as they provide a clean separation between evolved stars, young stellar objects, and background galaxies.

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Appendix
Flux Calibration of the Spitzer Spectra

Prior to joining the different modules of the Spitzer IRS spectra together, flux uncertainties in the Spitzer sample are carefully propagated using formal uncertainties in the mean (σ/√N). To photometrically calibrate the spectra, the mean flux density is converted to Jy using IRS observations of the standard stars HR 6348 (K0 III) for the short-low data, and HR 6348 and HD 173511 (K5 III) for the long-low data (Sloan et al. 2015). Spectra observed with the short-high and long-high modules were extracted using a full-slit extraction and calibrated using ξ Dra (K2 III) as a standard.

The flux calibration was applied to each individual spectral nod and order. Here the spectroscopic (i.e., the point-to-point) uncertainty in the flux is better than 0.5% at most wavelengths (Sloan et al. 2015). When combining the spectra from the nod positions, the larger of the propagated uncertainties from the two nods or the uncertainty in mean was adopted. This combination introduces several systematic errors in the flux (Lebouteiller et al. 2011), which depends on source geometry (G. Sloan 2016, private communication). The error in the absolute flux calibration is generally around ~5%; however, this can be considerably more for extended sources or bad pointings.

To produce the final spectrum, a scalar multiplicative correction was applied to each spectral segment, to remove discontinuities that arise from pointing errors. Segments are normalized upward (using the wavelengths where they overlapped), to align with the best-centered segment. This correction is typically less than 10% and has no dependence on wavelength. Data at the ends of the segment that could not be calibrated reliably were trimmed from the spectra. As with the low-resolution modules, short-high data were stitched to the long-high data, but no orders were adjusted relative to other orders within the same module, as they were obtained at the same time with identical telescope pointings. For more details on this procedure, see Woods et al. (2011b), Lebouteiller et al. (2011), and Sloan et al. (2015).

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