VARIABLE EVOLVED STARS AND YOUNG STELLAR OBJECTS DISCOVERED IN THE LARGE MAGELLANIC CLOUD USING THE SAGE SURVEY

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ABSTRACT

We present initial results and source lists of variable sources in the Large Magellanic Cloud (LMC) for which we detect thermal infrared variability from the Surveying the Agents of a Galaxy’s Evolution (SAGE) survey, which had two epochs of photometry separated by 3 months. The SAGE survey mapped a 7° × 7° region of the LMC using the Infrared Array Camera (IRAC) and the MIPS instruments on board Spitzer. Variable sources are identified using a combination of the IRAC 3.6, 4.5, 5.8, 8.0 μm bands and the MIPS 24 μm bands. An error-weighted flux difference between the two epochs is used to assess the variability. Of the ~3 million sources detected at both epochs, we find ~2000 variable sources for which we provide electronic catalogs. Most of the variable sources can be classified as asymptotic giant branch (AGB) stars. A large fraction (>66%) of the extreme AGB stars are variable and only smaller fractions of carbon-rich (6.1%) and oxygen-rich (2.0%) stars are detected as variable sources. We also detect a population of variable young stellar object candidates.

Key words: infrared: stars – galaxies: individual (LMC) – stars: AGB and post-AGB – stars: formation – stars: mass loss – stars: variables: other

Online-only material: machine-readable and Virtual Observatory (VO) tables

1. INTRODUCTION

The Spitzer survey, Surveying the Agents of a Galaxy’s Evolution (SAGE) of the Large Magellanic Cloud (LMC), provides an unprecedented opportunity to detect thermal infrared (IR) variability of the IR stellar population of the LMC. Optical variability studies of the LMC by the MACHO (Alcock et al. 1996) and Optical Gravitational Lensing Experiment (OGLE; Paczynski et al. 1994) monitoring projects have revealed the period and luminosity relations for a wide variety of variable stars in the LMC, for example, the long-period variables (Fraser et al. 2005). The 3 month time span between the two epochs of observations for the SAGE survey can detect and constrain the variability of long-period variables in the evolved star population and young stellar object (YSO) candidates. Thermal IR variability of such objects has been studied in the Galaxy with the Infrared Astronomical Satellite (IRAS) and the Infrared Space Observatory (ISO), and Spitzer’s improved sensitivity enables such studies in nearby galaxies. The 10 month IRAS mission surveyed most portions of the sky at least twice a year, separated by months and thus also constrained variability of the brighter IR sources in a similar way that the SAGE data samples the LMC’s stellar populations.

Most of the sources detected as variables in the thermal IR by IRAS or ISO are evolved stars in our Galaxy. For example, Harmon & Gilmore (1988) used the IRAS “probability of variability, v,” to determine the nature of the IRAS stellar population that delineates the Galactic bulge. In a statistical way, they simulated the periods that the IRAS data were sensitive to and found that the data were most sensitive to long-period variables, $P > 400$ days up to 1400 days. Essentially, large amplitude and long-period variations are easier to detect and are also associated with larger mass loss rates. They used this period to estimate the age and mass range for this evolved stellar population in the bulge. Later work by van der Veen & Habing (1999) also used the IRAS VAR to select and study OH/IR stars for ground-based measurements of IR light curves and found that these IRAS variables fit well into the period–luminosity relations found for Mira variables in Baade windows, confirming that OH/IR stars are more evolved forms of Miras. ISOGal-DENIS studies of the Galactic bulge included one field with multiple ISOCam images separated by 17–23 months (Omont et al. 1999). This study revealed a population of red giants with weak mass loss for which the brightest and most dusty red giants have variations at 7 and 15 μm. These sources are “intermediate asymptotic giant branch (AGB) stars,” that is, between early AGB and thermally pulsing AGBs, and have low mass loss rates, $10^{-10}$ to $10^{-11} M_\odot$ yr$^{-1}$.

In the LMC, the evolved stars are too faint for IRAS and ISO measurements to reliably detect variability. However, IRAS- and ISO-detected evolved stars have been followed up by

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ground-based near-IR variability monitoring programs. White-lock et al. (2003) monitored the IRAS-selected sample of AGB stars studied by ISO and found that larger amplitude variations in K are associated with redder stars. The IRAS and ISO photometry are sensitive measures of dusty mass loss of the AGB stars. Luminosity is sensitive with period and longer periods have higher amplitude variations. Thus, the thermal IR variability of the evolved stars can cause a systematic scatter in the mass loss rate determinations of these evolved stars in the LMC and in mass loss rate versus luminosity relations (Groenewegen et al. 2007).

In contrast to the evolved star populations, there have been few thermal IR variability measurements of young stellar objects (YSOs). IRAS measurements of variability of YSOs were at best difficult due to the low spatial resolution of IRAS and the confusion with diffuse interstellar medium (ISM) emission. Nevertheless, for isolated YSOs, there was a detection of variability at 12 μm and 25 μm for the Herbig Ae/Be stars AB Aur and WW Vul (Prusti & Mitskevich 1994). Intermediate mass pre-main-sequence stars, such as UX Ori stars, show large photometric and polarimetric variations (Natta et al. 1997). A concurrent ISO and ground-based optical monitoring program of UX Ori type stars, SV Cep, was performed by Juhász et al. (2007). Juhász et al. (2007) found that the mid-IR flux variations were anticorrelated with the optical variations, but that the far-IR flux variations were positively correlated with the optical variability. They used the IR variability to help discriminate between disk and disk-envelope models and found that disk models are in better agreement with the data. Ábrahám et al. (2004) used ISO to monitor the long-term IR evolution of seven FU Orionis stars. They detected variation in four sources, which provides tentative support for the Hartmann & Kenyon (1985) models for accretion outbursts in FU Ori objects as opposed to precessing jets (Herbig et al. 2003). Interestingly, more luminous stars that appear to have similar characteristics as the FU Ori stars have no detected outbursts. Chromospheric hot spots or accretion disk variability can cause optical variability in pre-main-sequence stars such as T Tauri stars, but these types of objects have very low IR excesses and are unlikely to be in our list. Our list would include earlier stages of YSOs that have more substantial IR excesses. Thus, while difficult to detect, thermal IR variability of YSOs will provide key insights into the structure of YSOs and the physical mechanisms of the star-formation process.

In this paper, we present initial results and source lists of SAGE point sources for which we have detected thermal IR variability between the epoch 1 and 2 photometry measurements. In Section 2, we outline the method of our approach to detect this variability. In Section 3, we discuss the results of the variable source selection and their identification of evolved stars and YSOs. In Section 4, we discuss implications of the results and summarize the main conclusions in Section 5.

2. METHOD: SOURCE SELECTION

SAGE is a Legacy project on the Spitzer Space Telescope (SST; Werner et al. 2004), which mapped a 7″ × 7″ region of the LMC using the IRAC camera in the [3.6] μm, [4.5] μm, [5.8] μm, and [8.0] μm bands (Fazio et al. 2004) and the MIPS camera in the [24] μm, [70] μm, and [160] μm filters (Rieke et al. 2004). The scientific goals of the survey focus on the life cycle of baryonic matter, as traced by dust emission, from its start in the ISM to the formation of new stars, to the death of these stars and the return to matter to the ISM. The survey was done over two epochs with a total observing time of 291 hr with IRAC and 217 hr with MIPS. The details of the survey are described in Meixner et al. (2006). The SAGE photometric data have been separately extracted from the two epochs, which are separated by 3 months. The IRAC epoch 1 data were taken on 2005 July 15–26 and epoch 2 on 2005 October 26–November 2, and the MIPS epoch 1 data were taken on 2005 July 27–August 3 and epoch 2 on 2005 November 2–9. The SAGE epoch 1 point source catalogs (PSCs)10 containing over 4 million sources of IRAC (SAGEcatalogIRACepoch1) and over 40,000 sources of MIPS 24 μm (SAGEcatalogMIPS24epoch1) have been merged with Two Micron All Sky Survey (2MASS) JHK and the Magellanic Clouds Photometric Survey (Zaritsky et al. 2004). Analysis of the colors and magnitudes of this catalog has revealed three general types of LMC point sources: stars without dust, dusty evolved stars, and YSOs (Meixner et al. 2006). A further classification of the SAGE sources by Blum et al. (2006) separated the dusty evolved star classes, such as supergiants (SGs), and AGB stars from the red giants. The YSO population has been identified in part by Whitney et al. (2008).

The SAGE 2-epoch PSCs for IRAC (SAGEcatalogIRACepoch1 and SAGEcatalogIRACepoch2) and MIPS (SAGEcatalogMIPS24epoch1 and SAGEcatalogMIPS24epoch2) were used for this study. Variable sources were identified using the matching and selection criteria described below and a variability index. We define the variability index V as the error-weighted flux difference in each SAGE band:

\[ V = \frac{(f_1 - f_2)}{\sqrt{\sigma f_1^2 + \sigma f_2^2}} \]

where \( f_1 \) and \( f_2 \) are fluxes in the two epochs and \( \sigma f_1 \) and \( \sigma f_2 \) are the associated errors, respectively. We also defined a fractional flux (fF) for each band, the fractional change in the flux:

\[ fF = \frac{f_1 - f_2}{(f_1 + f_2)/2} \]

where \( f_1 \) and \( f_2 \) are fluxes in the two epochs. The criteria for inclusion of sources into the catalog and the archive version are detailed in Meixner et al. (2006). The source lists are stored in the SAGE database, a system implemented with Microsoft SQL server 2000. We developed scripts in Structured Query Language (SQL) for creating the interepoch matching sources and for subsequent checks on, and quality control of, the variable source lists.

2.1. Interepoch Matching of Sources

All four IRAC bands and the MIPS 24 μm, 2 epoch data were used for this study. To find the variable IRAC sources in SAGE, the IRAC epoch 1 and epoch 2 catalogs were matched using a 2″ search radius. Sources with multiple matches and sources with any neighboring sources within 3″ were excluded as careful consideration revealed that the PSF characteristics of the IRAC detectors make the measured fluxes of sources with neighbors closer than 2″ less reliable. Furthermore, to avoid possibility of a mismatch between the epochs, only matches within 0′9 (the 3σ value for IRAC photometry) were retained. We also used the following magnitude cuts to only include sources with highly reliable fluxes in our lists: 16 mag, 16 mag, 14 mag, and 13.5 mag at 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm respectively.

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10 Catalogs that combine 2MASS JHK (Skrutskie et al. 2006), IRAC, and MIPS 24 μm data are available at the Spitzer Science Center Web site http://ssc.spitzer.caltech.edu/legacy/all.html.
For MIPS, the 24 μm PSCs SAGEcatal0gMIPS24epoch1 and SAGEcatal0gMIPS24epoch2 were used for this study. We used a 1" matching between the two epochs to eliminate wrong interepoch matches. Both the individual epoch catalogs have their astrometry matched to IRAC catalogs, which have been matched to the 0.3 accuracy 2MASS catalog. We also note here that the MIPS24 catalogs are conservative catalogs that report only sources with reliable fluxes. With only two epochs of data, we do not aim to produce a complete list of IR variable sources in the LMC; nonetheless, we aim for a highly reliable one and require variability in more than one band. Figure 1 shows a histogram of the variability \( |V| \) for the interepoch matched sources for all the IRAC and MIPS 24 μm bands. \( |V| < 3 \) probably indicates “random” errors in flux and \( |V| > 3 \) a population being dominated by a systematic trend. Different bands are shown in different colors, and the vertical lines at \( |V| = 3 \) indicate the reliability cuts for the SAGE variables.

### 2.2. Variability Criteria

Our criterion for a variable source is \( |V| > 3 \) in at least two consecutive bands in the same direction. The IRAC-selected sources were matched with the interepoch-matched 24 μm sources, 24 μm sources with \( |V_{24}| > 3 \) and \( |V_{8.0}| > 3 \) in the same direction are deemed 24 μm variables. Table 1 explains the criteria used to identify the variable sources. The first part of the table characterizes the source catalogs. For each band, the number of sources with valid fluxes in the band at both epochs, the number and percentage of sources having \( |V_{\text{band}}| > 3 \), and the number and percentage of sources expected statistically to have \( |V_{\text{band}}| > 3 \) are given. The second part describes the selection criteria and the statistical significance of the variable sources. Here, for each band, the sources have valid fluxes in not only both epochs for a given band but also a neighboring band. Once again, both the numbers and percentages of sources meeting the variability criterion and those that might do so based purely on statistical considerations (and, therefore, likely to be false variables) are given. Assuming that the measurement of the flux for any source follows a Gaussian distribution characterized by the error in the flux, the probability that two measurements of the flux of a nonvariable source will not be within 3σ of each other is 0.27%. This applies for every band. We see that for all bands, the number of sources with \( |V| > 3 \) is more than that expected from statistical variations. Requiring that the sources have \( |V| > 3 \) in at least two bands in the same direction considerably reduces the chances of random misclassification as a variable source. First, a source has to have valid fluxes at both epochs in at least two neighboring bands and, second, have \( |V| > 3 \) in both of these bands in the same direction. Statistically, this has a probability of 0.0004% for bands with a single neighboring band and 0.0007% for bands with two neighbors. For example, at 24 μm, less than one source would be classified as a variable source due to random chance alone. The argument could be made that the flux measurement of sources does not follow a Gaussian distribution, but this simple, idealized statistical approach gives us lower limits on the number of false variables in the list. We perform other tests on the

### Table 1

| Criteria | 3.6 μm | 4.5 μm | 5.8 μm | 8.0 μm | 24 μm |
|----------|--------|--------|--------|--------|-------|
| # of sources with valid fluxes | 2962938 | 1939173 | 354290 | 133655 | 25412 |
| # with | 15341 | 9857 | 2395 | 1647 | 1625 |
| % with | 0.52 | 0.51 | 0.68 | 1.23 | 6.39 |
| # expected statistically | 8000 | 5236 | 957 | 361 | 69 |
| # expected statistically | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| # of sources with valid fluxes | In neighboring bands | 1787038a | 2121027b | 458607c | 124618d | 13901e |
| # meet variability criterion | 1520 | 1827 | 1582 | 1316 | 623 |
| % meet variability criterion | 0.09 | 0.09 | 0.34 | 1.06 | 4.48 |
| # expected statistically | 8 | 15 | 3 | < 1 | < 1 |
| % expected statistically | 0.0004 | 0.0007 | 0.0007 | 0.0004 | 0.0004 |

Notes.  

a Valid fluxes at 3.6 and 4.5 μm.  
b Valid fluxes at 3.6 and 4.5 μm or at 4.5 and 5.8 μm.  
c Valid fluxes at 4.5 and 5.8 μm or at 5.8 and 8.0 μm.  
d Valid fluxes at 5.8 and 8.0 μm.  
e Valid fluxes at 8.0 and 24 μm.

![Figure 1](image-url)  

Figure 1. Histogram of all the SAGE sources matched between two epochs for the different bands of IRAC and MIPS 24 μm band. Sources with \( |V| > 3 \) in at least two consecutive bands are classified as variable sources.
3. SOURCE CLASSIFICATION

Using the variability criteria discussed in Section 2 we find 1967 SAGE variables at IRAC and MIPS 24 μm bands. 514 sources are variable (|V| > 3) in all five bands. Table 2 lists the properties of the 1967 SAGE variables.

Most of the SAGE variables can be classified as AGB stars, a small number as YSOs, and a number of sources that are presently unclassified but could be OB stars, red giant branch (RGB) stars, post-AGB stars, planetary nebulae (PNe), background active galaxies, or other classes of variables such as Cepheids, RR Lyrae stars, or WR stars. We choose three color–magnitude diagrams (CMDs) to classify the SAGE variable sources. In Figure 2, all the sources in the SAGE epoch 1 catalog are used to plot the Hess diagram shown in grayscale. Blum et al. (2006) showed that the [8.0] – [24] versus [8.0] CMD was most useful for seeing the separation of the O-rich, C-rich, and extreme AGBs based on the classification scheme of Cioni et al. (2006) and Blum et al. (2006). The features in the underlying CMD (grayscale) are labeled “A”, “B”, and “C” (see Blum et al. 2006; Nikolaev & Weinberg 2000): “A” being the OB star locus at the bluest, faint end of the diagram. The first prominent finger (labeled “B”) corresponds to young A–G SGs. The finger “C” consists mainly of foreground dwarfs and giants. The next finger to the right in the figure represents late-type (mostly M) SGs and luminous, O-rich M stars (Blum et al. 2006). The rest of the region above the tip of the RGB is divided into O-rich, C-rich, and extreme AGB zones. Keeping these divisions in mind lets us classify most of the variable sources as evolved stars. To identify the YSO population, we cross-correlate the variable sources with the SAGE-YSO list from Whitney et al. (2008) and find 29 YSO candidates. Sources that are not classified as evolved stars or YSO candidates are plotted in yellow and will be discussed further in Section 3.1.

Meixner et al. (2006) showed that the [8.0] – [24] versus [8.0] CMD was most appropriate for separating the dusty objects based on mass loss. Figure 3 shows the [8.0] – [24] versus [8.0] CMD for the SAGE variables, with the same color scheme used for the classification as in Figure 2. Figure 4 shows the [4.5] – [24] versus [24] CMD for the SAGE variables. This CMD is the one of the most useful ones to delineate the LMC stellar population from the background population. We see that most of the unclassified sources are among the redder and fainter population in this CMD and are likely to be external galaxies. These sources are further discussed in Section 3.1.

| Designation       | Designation     | E (deg) | R.A. (deg) | Decl. (deg) | Class | 3.6 μm | 4.5 μm | 5.8 μm | 8.0 μm | 24 μm |
|-------------------|-----------------|---------|------------|-------------|-------|--------|--------|--------|--------|-------|
| SSTISAGE1C...     | SSTIM1SAGE1...  | 1       | 79.9337    | −69.9940    | X     | 108.80 | 5.08   | 4.1    | 0.25   |       |
| SSTISAGE2C...     | SSTIM1SAGE2...  | 2       | 79.9335    | −69.9941    |       | 85.05  | 2.71   |        |        |       |
| SSTISAGE1C...     | SSTIM2SAGE1...  | 2       | 79.9421    | −68.8979    | Y     | 0.72   | 0.04   | −4.4   | −0.29  |       |
| SSTISAGE2C...     | SSTIM2SAGE2...  | 2       | 79.9422    | −68.8979    |       | 0.96   | 0.04   |        |        |       |
| SSTISAGE1C...     | ...             | 1       | 79.9643    | −72.6359    | U     | 4.93   | 0.18   | −5.4   | −0.29  |       |
| SSTISAGE2C...     | ...             | 2       | 79.9646    | −72.6359    |       | 3.67   | 0.15   |        |        |       |
| SSTISAGE1C...     | ...             | 1       | 79.9718    | −69.6882    | O     | 5.23   | 0.18   | 5.0    | 0.29   |       |
| SSTISAGE2C...     | ...             | 2       | 79.9719    | −69.6883    |       | 6.97   | 0.30   |        |        |       |
| SSTISAGE1C...     | ...             | 1       | 79.9811    | −69.3925    | C     | 25.27  | 0.63   | 3.3    | 0.10   | 22.83 |
| SSTISAGE2C...     | ...             | 2       | 79.9813    | −69.3925    |       |        |        |        |        | 0.39  |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)
Table 3
SAGE Variable Population

| Source Type      | SAGE Variables | SAGE Epoch 1 Sources | % Detected as a Variable |
|------------------|----------------|----------------------|--------------------------|
| Total            | 1967           | 4338548              | 0.05                     |
| O-rich AGB       | 353            | 17875a               | 1.975                    |
| C-rich AGB       | 426            | 6935b                | 6.14                     |
| Extreme AGB      | 820            | 1240b                | 66.1                     |
| YSO candidate    | 29             | 990b                 | 2.93                     |
| Unclassified     | 335            | 4311508              | 0.008                    |

Notes.

a Classified by Blum et al. (2006).

b Classified by Whitney et al. (2008).

3.1. Unclassified Sources

Using 2MASS and 3.6 μm color criteria, most of the variable sources are classified as evolved AGB stars (with O-rich, C-rich, and extreme subclasses). Using the Whitney et al. (2008) YSO candidate list, we also identify YSO candidates as IR variables. The classification of the variable sources that do not fall under any of these subclasses is more challenging. Approximately 17% of the variables remain unclassified and ~70% of them remain so mainly because they are missing IRAC and/or 2MASS fluxes. This could be because (1) they are undetected being dust enshrouded, for example, very dusty YSOs, (2) extremely bright and therefore saturated in IRAC, or (3) spatially extended at IRAC wavelengths and thus missing from the PSC. In preliminary follow-up work, we have identified 20 unclassified sources as Cepheids detected in the MACHO survey. Some of the other “unclassified” variables fall on distinct regions of the CMD and could be variable OB stars, RGB stars, or O-rich stars that were too faint to be detected in the 2MASS survey. The other sources could be YSOs, post-AGB sources, PNe, background galaxies, or other classes of variables such as Cepheids, RR Lyrae stars, WR stars, quasi-stellar object (QSOs), or an active galactic nucleus (AGN). Further follow-up work is required to identify the specific nature of these sources.

4. DISCUSSION

In this first paper, we identify IR variable sources in the LMC and provide an approximate classification as to their nature as discussed in Section 3. In this section, we discuss the nature of these sources and some implications of their IR variability for SAGE studies. In particular, we focus on the evolved AGB star population and YSO candidates. The total number of variables identified as SAGE variables is 1967 or ~0.06% of the ~3 million IRAC point sources that are common to both epoch 1 and 2 catalogs. These fractional numbers suggest that we preferentially detect as variable the redder or dustier sources that tend to be AGB stars or YSOs. In Table 3, we summarize the different categories of sources we have detected as variables and compare them to other work done on the classification of SAGE sources as evolved stars (Blum et al. 2006) and YSO candidates (Whitney et al. 2008) and discuss them below.
Figure 5. Histogram showing the variability distribution among the different classes of SAGE IRAC variables. Average variability in all four bands of IRAC and MIPS 24 μm band has been plotted. C-rich stars in green, O-rich stars in blue, extreme AGBs in red, YSO candidates in cyan, and the unclassified sources in black.

Figure 6. Spatial distribution of the variable sources in the LMC classified as AGB stars plotted on the 3.6 μm map. Note the correlation of the spatial distribution of the variable population with the stellar density function (3.6 μm). This confirms that most of these sources are indeed stars. The colors represent the same classification of the sources as used in Figure 2.

Figure 7. SEDs showing the two epochs of a sample of variable O-rich AGB stars. SAGE epoch 1 fluxes are connected by dotted lines and epoch 2 by dashed lines. The sources are marked with solid, blue diamonds on the CMDs. The 2MASS data are connected by solid lines and in many instances appear disjoint from either of the epochs, which is due to IR variability as these data represent a different phase far removed from either of the SAGE epochs.
the LMC 3.6 μm image, which predominantly traces the old stellar population of the LMC (Blum et al. 2006) and supports our identification of the variables as evolved stars. In particular, the highest density of sources is located in the main stellar bar of the LMC. The color coding of the point sources on this image follows that of the CMDs. The extreme AGB stars, shown in red, dominate both the spatial distribution of variable sources and the CMDs (Figures 2–4). Looking at the numbers of sources detected per category (Table 3), we find that the extreme AGB stars outnumber the O-rich or C-rich AGB stars by a factor of 2. Moreover, the percentage of variables changes dramatically across the classified AGB sources. Only 2.0% of the O-rich AGB stars have been detected as a variable. This percentage increases to 6.1% for the C-rich AGB stars. For the extreme AGB stars, the percentage jumps to 66%. This increase in percentage follows an evolutionary trend of the AGB. All stars on the early AGB start off as O-rich. As they evolve to higher luminosities, their pulsational periods increase, and many become C-rich AGB stars. At the highest luminosities, the periods are the longest and these extreme AGB stars are characterized by significant circumstellar dust emission. Thus, the fractional number of AGB stars identified as a variable increases as the star becomes more evolved on the AGB.

This preferential detection of the AGB stars evolved is similar to that in the IRAS variability studies in our Galaxy because our sampling period of two measurements separated by 3 months is similar to the IRAS sampling. As Harmon & Gilmore (1988) found in our Galaxy, we preferentially find the more evolved, dusty AGB stars, which probably have longer periods. This preference is at least in part due to the sensitivities of detection and of time sampling. Because they are more luminous and dust enshrouded, the extreme AGB stars are easier to detect and their variability is easier to reliably measure in the IRAC and MIPS bands. In addition, the period of the variability for the extreme AGB stars, ~400–500 days, is well matched to our two sample points in time separated by 3 months (~90 days) such that we could more likely than not measure a detectable flux difference in the two epochs.

Even though we do not detect all the AGB stars as IR variables, we do know that they are all variables (e.g., Fraser et al. 2005). The detected IR variability reported here provides a constraint on the possible range of the IR flux in these types of AGB stars. The fractional difference in fluxes we detect has a range of 0.1–1.5 of the total flux. These changes in the IR flux will have significant implications for the analysis of SAGE data on the AGB stars. Estimates of the IR excesses for this population will have some systematic errors because of the IR variability. The mass loss rates of the evolved stars will be derived from model fits to the spectral energy distributions (SEDs) of these sources, and the IRAC and MIPS 24 μm photometry provide constraints on the dusty shells. The IR variability of the three different classes of AGB stars is revealed in the 2 epoch SEDs of a few O-rich, C-rich, and extreme AGB stars selected from our sample (Figures 7–9). The SEDs show the SAGE epoch1 data connected by dotted lines and epoch2 data by dashed lines. The 2MASS data are connected by solid lines and in many instances appear disjoint from either of the epochs, which is due to IR variability as these data represent a different phase far removed from either of the SAGE epochs.

4.1. Evolved Stars

As expected, the variable source population is dominated by evolved stars, in particular the AGB stars. The SAGE variables have > 81% AGB stars, classified as either O-rich, C-rich, or extreme AGB stars. The spatial distribution of the SAGE variables, as shown in Figure 6, correlates approximately with the LMC 3.6 μm image, which predominantly traces the old stellar population of the LMC and these extreme AGB stars are characterized by significant circumstellar dust emission. Thus, the fractional number of AGB stars identified as a variable increases as the star becomes more evolved on the AGB.

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Some of the brightest variables are not classified because they are saturated in the IRAC 3.6 μm band or 2MASS bands, which we use for classification purposes. The drop in flux in the Raleigh-Jeans tails of the SED enables them to be detected at the longer IRAC bands (4.5 μm, 5.8 μm, and 8.0 μm) and MIPS 24 μm without saturation.

4.2. YSO Candidates

We have discovered a YSO candidate population with IR variability. The fact that this phenomenon was not noticed earlier is not surprising given that little work has been done on IR variability of YSOs and most of it has been follow-up of known optically variable sources. These variable YSO candidates comprise at least 3% of all the YSO candidates. We say...
Figure 9. SEDs showing the two epochs of a sample of variable extreme AGB stars. SAGE epoch 1 fluxes are connected by dotted lines and epoch 2 by dashed lines. The sources are marked with solid, red diamonds on the CMDs. The 2MASS data are connected by solid lines and in many instances appear disjoint from either of the epochs, which is due to IR variability as these data represent a different phase far removed from either of the SAGE epochs.

at least because there are a large number of sources in the same CMD space that are “unclassified.” The spatial distribution of YSO candidates spatially correlates with the LMC MIPS 24 μm emission, which traces massive star formation, supporting the identification of these variables as YSOs (Figure 10). Also interesting is the spatial distribution of the “unclassified” sources (Figure 10). These sources also closely follow the 24 μm emission. Further follow-up work on extending the list of YSO variables that is in progress will help clarify if some of these unclassified sources are YSOs.

In this study, the variability for this YSO population most prominently shows in the MIPS 24 μm band (24 of 29 YSO candidates have |V24| > 3). The reason for the predominance of the MIPS 24 μm band variability becomes clear when we examine the SEDs of a few variable YSO candidates (Figure 11). The SEDs show the SAGE epoch 1 data connected by dotted lines and epoch 2 data by dashed lines. The 2MASS data are connected by solid lines and in many instances appears disjoint from either of the epochs, which is due to IR variability as these data represent a different phase far removed from either of the SAGE epochs. Most of these sources are very faint in the 2MASS and IRAC bands, and increase rapidly in flux at the longer wavelengths. In fact, while our SEDs end at 24 μm, the trend suggests that for some of these YSOs, the SEDs actually peak at even longer wavelengths. Thus, our sensitivity to these sources is greatest at 24 μm and the lower number of IRAC variable YSO candidates in the SAGE data may be

Figure 10. Spatial distribution of variable massive YSOs and the unclassified sources plotted on SAGE 24 μm image. The YSO candidates are shown in red and the unclassified candidates in cyan.
Figure 11. SEDs of a sample of YSO variable sources. The sources are marked as solid, cyan diamonds on the CMDs. SAGE epoch 1 fluxes are connected by dotted lines and epoch 2 by dashed lines. The sources show SEDs consistent with embedded objects with dust emission. The sources are marked with solid, red diamonds on the CMDs. The 2MASS data are connected by solid lines and in many instances appear disjoint from either of the epochs, which is due to IR variability as these data represent a different phase far removed from either of the SAGE epochs.

due to the lower sensitivity in the IRAC bands to detect the variability.

Whitney et al. (2008) have completed a candidate list of over 990 YSO candidates identified in the SAGE epoch 1 catalog. This list is a lower limit to the total number of YSOs in the LMC because the selection was conservative and avoided regions in CMD space densely populated by other types of sources, for example, AGB stars and background galaxies. Our variable YSO candidates comprise ~3% of the larger 990 YSO candidate list. It is difficult to assess if this percentage is a lower or upper limit because the number of YSOs and variable YSOs is rather uncertain in different directions. Nevertheless, the percentage is significant enough to catch our attention as a new class of IR variables. With only two epochs of observation spread 3 months apart, we cannot distinguish between a periodic and a more stochastic phenomenon for the YSOs. Clearly, further study of these sources is required to understand the nature of their variability.

5. CONCLUSIONS

We have detected IR variable stars in the LMC using the SAGE survey. The variable source population is dominated by evolved stars, in particular the AGB stars (81% of the SAGE variables). We preferentially find the more evolved, dusty AGB stars, which probably have longer periods. We also present the discovery of a YSO candidate population with IR variability. These variable YSO candidates comprise about 3% of all the SAGE variables.

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