Spitzer/IRAC Observations of AGB stars

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Abstract. We present here the first observation of galactic AGB stars with the InfraRed Array Camera (IRAC) onboard the Spitzer Space Telescope. Our sample consists of 48 AGB stars of different chemical signature, mass loss rate and variability class. For each star we have measured IRAC photometry and colors. Preliminary results shows that IRAC colors are sensitive to spectroscopic features associated to molecules and dust in the AGB wind. Period is only loosely correlated to the brightness of the stars in the IRAC bands. We do find, however, a tight period-color relation for sources classified as “semiregular” variables. This may be interpreted as the lack of warm dust in the wind of the sources in this class, as opposed to Mira variables that show higher infrared excess in all IRAC bands.

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INTRODUCTION

The Spitzer Space Telescope [1], and in particular its InfraRed Array Camera (IRAC, [2]), is an ideal facility to study the distribution of AGB stars in our own and other galaxies, due to its proficiency in surveying vast areas of the sky in a short time and its ability to detect sources with infrared excess. The IRAC colors of AGB stars, however, are not known very well. The Infrared Space Observatory (ISO) Short Wavelength Spectrometer (SWS, [3]) observed a sample of AGB stars, finding numerous molecular absorption features in the spectral region covered by the IRAC photometric system [4]. Just to mention a few, H₂O, SiO, CO₂, CO and silicate dust features have been detected in stars with atmospheric C/O ratio < 1, while C₂H₂, HCN, CS, C₃ and carbonaceous dust (SiC and amorphous carbon) have been found in carbon stars, having C/O > 1. The presence and strength of these spectral features depends on the chemistry of the stellar atmosphere [5, 6] and the mass loss rate, and can change with time [7] because AGB stars are Long Period Variables generically classified as Mira, semiregular or irregular pulsators.

As a result of dust and molecular features, the IRAC colors of AGB stars can be quite different from the “reddened photospheres” that one would expect for mass-losing giants of late spectral type. Simulations we made, based on the available ISO SWS spectra [8], show that AGB stars with different chemical signature can in some case be differentiated on the basis of the IRAC colors alone. IRAC colors also appear to be sensitive to the mass loss rate of the sources, which has also been noted by [9]. Given the importance of reliably identifying AGB stars in already available IRAC data from galactic and extragalactic surveys, the need to study in detail the color variations of AGB stars is clear.
With this in mind we proposed the observations of a representative sample of well characterized AGB stars as part of the Cycle-3 IRAC Guaranteed Time Observations. The goal of the program was to obtain high-precision IRAC absolute magnitudes and colors. The sample was chosen to explore the variations of IRAC photometry with time, variability class, chemical type and mass loss rate. This will enable longer term goals such as identifying AGB stars in other IRAC datasets, allowing more detailed studies of the AGB phase as part of galactic population synthesis models and studies of the galactic chemical evolution of the diffuse matter in the interstellar medium. Reliable prescriptions for discriminating AGB stars from other classes of red sources will also help other projects whose samples are contaminated by background AGB sources. Given that a fraction of our targets (∼ 60%) have been observed with ISO, and their SWS spectra are publicly available, our observations will also provide an independent dataset for the cross calibration between IRAC and the ISO SWS. This is particularly important in the case of “red” point sources as mass losing AGB stars, since IRAC has been absolutely calibrated by using a sample of “bluer” stars of spectral type A [10]. The results of this program will be used to improve the absolute calibration of IRAC for red stellar sources.

The program will be completed in the first months of 2008, and we are presenting here the first results derived from ∼ 74% of the total scheduled observations. Once the whole sample of stars will be observed, the catalog will be made available to the community, with the goal of aiding the identification of AGB stars in already available and future IRAC survey.

TARGET SELECTION

Our target list was selected from a number of AGB star catalogs available in the literature ([11,12,13,14,15] and references therein) with the intention of representing all main categories of AGB stars. An important requirement for the selection was the availability of reliable distance estimates, to allow for the measurement of absolute magnitudes. The distances for our target stars were derived either from astrometric [16] or interferometric [17,18] observations or from models of radio emission and bolometric luminosity [14]. The distance of our selected targets varies from 0.17 to 4.1 kpc.

The sample is divided in 4 categories: 22 O-rich AGB stars (MIII spectral type), 7 intrinsic S stars, 19 carbon stars and 4 M-type cool supergiants. The supergiants have been added as a comparison sample of red mass-losing stars with O-rich chemistry outside the AGB. In each category we have a similar number of Mira, semiregular and irregular variables, with period ranging from 50 to 822 days. The mass loss rates of our target stars (estimated from radiative transfer modeling of their circumstellar emission, see [11] and references therein) range from $10^{-8}$ to $10^{-4}$ $M_\odot$/yr in each category.

Given the variability of the sources, we have requested two epochs (six months apart, as constrained by the Spitzer visibility windows) for each target, in order to check for variations in the IRAC photometry on timescales of several months. As of November 2007, 48 sources have been observed in at least one epoch (with 4 carbon stars missing), with 29 targets (56% of the total) observed in both epochs.
DATA PROCESSING

The processing of this dataset presented peculiar challenges, due to the brightness of the sources. Even though we selected our targets to have a K magnitude larger than 3, to avoid excessive saturation of the IRAC images, all our stars still saturate the IRAC arrays. The choice of AGB stars in this brightness range was motivated by the necessity of having nearby targets, the ones for which a reliable estimate of the distance is available. Each source was observed with 5 dithered 2 sec full frame exposures, to limit excessive saturation while avoiding sub-array exposure that, while in many cases still saturated, have less field of view for PSF fitting photometry.

Starting from the Basically Calibrated Data (BCD) provided by the Spitzer Science Center, we have produced a mosaic image for each source, in each band and for each one of the two epochs, separately, using our own post-BCD software IRACproc [19].

Due to saturation, aperture photometry was not feasible, so we used a Point Spread Function (PSF) fitting technique developed specifically to treat IRAC images with heavy saturation. As described in [8], we have generated a high dynamic range image of the IRAC PSF in each band, by combining the individual images of a set of stars with different brightness (Sirius, Vega, Fomalhaut, ε Eridani, ε Indi and the IRAC calibrator BD+681022). This PSF is rescaled to the actual image of Vega, providing an absolute photometric reference. By fitting the unsaturated parts (diffraction spikes and PSF “tails”) of each target star image, we have measured the flux ratio between the stars in our sample and Vega, which we have then converted into Vega magnitudes for each source. The typical uncertainty of this procedure is of the order of 1–3%, better than the typical absolute aperture photometry of unsaturated stars with IRAC.
FIGURE 2. IRAC [3.6]-[8.0] vs. [3.6]-[4.5] color diagram of all the available observations to-date. The tracks are models from [9]. Dotted line is for carbon stars with carbonaceous circumstellar dust of increasing optical depth. Solid and dashed line are for silicate envelopes around stars of M0 III and M10 III spectral type respectively.

FIGURE 3. Same as Figure 2 but with colors including the IRAC 5.8 μm band, causing dispersion of "naked photospheres" carbon stars from the sequence of carbon stars with higher mass loss.
IRAC COLORS OF AGB STARS

Figure 2 and 3 show IRAC colors for all the available observations as of November 2007. The sources for which both epochs are already available have been represented by two separate points in the diagrams.

As shown in [8] using synthetic IRAC colors derived from ISO SWS spectra, and by [9] using radiative transfer modeling of dusty circumstellar envelopes, the IRAC colors appear to be sensitive to the optical thickness of the dusty shells surrounding the sources. The [3.6]-[8.0] color, in particular, provides the largest spread in function of the optical thickness of the envelope, due to the thermal radiation from the circumstellar dust, source of the infrared excess which “flattens” the spectrum in the IRAC wavelength range. The [3.6]-[4.5] color shows a similar trend, and the combination of these two colors describes a sequence of increasing excess closely following the model tracks derived by [9]. The diagrams show a separation of carbon stars from stars with silicate envelopes (M and S AGB stars, and red supergiants) for sources with [3.6]-[8.0] color in excess to 1 mag. Inspection of ISO SWS spectra of individual AGB stars with different chemistry shows that this is caused by two simultaneous factors: sources with higher excess present a growing 10 $\mu$m silicate feature that is partially contributing to the 8.0 $\mu$m IRAC band, while at the same time the 3.6 $\mu$m flux is depressed by deeper H$_2$O features. Carbon stars, lacking any prominent dust feature in the IRAC wavelength range, for the same amount of [3.6]-[4.5] color have a smaller [3.6]-[8.0] excess, causing them to be aligned on a sequence above the sources with O-rich chemistry. The infrared excess, for sources with [3.6]-[8.0] > 1, correlates well with the mass loss rate of the individual stars, albeit with a large scatter which can be attributed to the large uncertainties in the mass loss rate estimates.

Figure 3 shows a trend similar to Figure 2, with a twist: carbon stars with very small mass loss rate align on a separate sequence with bluer [4.5]-[5.8] and redder [5.8]-[8.0] colors. This was already shown in [8], and attributed to a broad absorption feature depressing the 5.8 $\mu$m flux. Based on [4] we give a tentative identification of the feature as being C$_3$ developing in the atmospheres of these dust poor carbon stars. The feature disappears in stars with thicker circumstellar envelopes, either because it is filled by the continuum dust emission, or because the molecule responsible is depleted. As noted in [8], this feature appears to be transient, as some sources observed with ISO in multiple epochs do not show it in all spectra. This may be an indication that the feature variability can be related to changes in the abundances of the molecule in the stellar atmosphere as the star pulsate, rather than changes in the dust content of the circumstellar envelope (which is unlikely to show large scale variations on the short time-scales of the ISO repeated observations).

IRAC COLORS AND VARIABILITY

Figure 4 shows the 8.0 $\mu$m absolute magnitude of all sources plotted against their Mira (circles) or semiregular (triangles) period. Again, sources already observed in both epochs have separate points, one above the other (same period, different brightness). Note that all semiregular variables (characterized by small amplitude) show very little
FIGURE 4. Period - 8.0 µm absolute magnitude relation for all the observations available to-date. Circles are sources classified as Mira variables in the GCVS [21]. Triangles are sources classified as semiregular. The solid line is the best linear fit for all data, with $RMS$ dispersion of $\sim 1.2$ mag indicated by the two dotted lines.

FIGURE 5. Period - [3.6]-[8.0] color relation for all the observations available to-date. Symbols are as in Figure 4. The dashed line is the best fit for the color - period relation of semiregular stars, while the best fit for Miras is indicated by a solid line. The dotted lines show the dispersion in the best fit relations.
change between the two IRAC epochs. Only Miras (larger amplitude and longer periods) show variations that can be as high as \(\sim 1\) mag. The plot shows that there is a trend between the period and the luminosity at 8.0 \(\mu\)m (dashed line), with longer period sources (generally Mira variables) having higher brightness. The dispersion of \(\sim 1.2\) mag may be a consequence of the varying amount of mass loss of the different stars, not necessarily correlated to their period, responsible for different degrees of infrared excess. Diagrams made with other IRAC bands show a similar trend.

The IRAC period - color relation of all the observed sources is instead shown in Figure 5. As color we have chosen the [3.6]-[8.0] combination, which is the most sensitive to dust thermal emission from the circumstellar envelope. Again, Mira variables are plotted with a different symbol than semiregulars. We have derived separate linear fits for the period - color relation of the two classes. Mira and semiregulars show a very different trend: the former have a very steep relation (solid line) with a large dispersion (\(\sim 0.38\) mag), while the latter follow a very tight (RMS \(\sim 0.13\) mag) trend (dashed line).

**DISCUSSION AND CONCLUSIONS**

The IRAC photometry of the observed sources is in general agreement with models of AGB photospheres surrounded by dusty circumstellar envelopes of different optical depths, as modeled by [9]. As expected, the main trend shown by IRAC colors is an increasing infrared excess for larger optical thickness of the dust shell, and separation between sources with silicate or carbonaceous dust. With enough photometric accuracy, however, the data show deviations from the models that can be attributed to molecular spectral features in the stellar atmosphere or wind. These features show time variability when observed at different phases of the star.

The IRAC absolute magnitudes and colors are also correlated with the Mira or semiregular period of the stars. In general longer period variables are brighter, but there is a rather large spread in this relation, probably due to the variations in mass loss rate, and thus infrared excess, generated by the dusty envelope.

While the overall mass loss rate distribution of Mira and semiregular variables in our sample is similar, the period - color relation shows different trends. This may be interpreted as lack of hot dust around semiregular variables which translates in a smaller infrared excess. In [22] a similar result was suggested by the shape of the silicate feature in a large sample of O-rich AGB stars, and was interpreted as a sign of time-variability in the silicate dust production in semiregulars. The new IRAC data supports this interpretation and extends it to carbon stars (making more unlikely that this effect is due to differences in the dust composition between semiregulars and Miras).

The GCVS [21] Mira/semiregular classification is somewhat outdated, and a more accurate description of the AGB variability should be done in terms of pulsational modes and amplitudes. In these terms we can rephrase the above conclusions by noticing that semiregular variables are the ones with smaller amplitudes, while Miras have in general longer periods and amplitudes. This may imply that the stars with larger amplitudes may have more efficient dust production rates, resulting in larger quantities of hot dust in proximity of the stellar photosphere, which are responsible for the observed larger IRAC infrared excess.
The observing program is scheduled for completion for the first months of 2008. Once the data for all stars, both epochs, will be available, the complete dataset will be published as template photometry of galactic AGB stars, for general use of the community.

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