Early Type Galaxies in the Mid Infrared

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Abstract. We are performing a systematic study of the properties of early-type galaxies in the mid infrared spectral region with the \textit{Spitzer Space Telescope}. We present here high S/N \textit{Spitzer} IRS spectra of 17 Virgo early-type galaxies. Thirteen objects of the sample (76\%) show a pronounced broad feature (above 10\(\mu\)m) which is spatially extended and likely of stellar origin. We argue that this feature is (mostly) due to silicate emission from circumstellar envelopes of asymptotic giant branch (AGB) stars. The remaining 4 objects, namely NGC 4486, NGC 4636, NGC 4550 and NGC 4435, are characterized by different levels and type of activity.

1. Introduction

With the advent of the \textit{Spitzer Space Telescope} new frontiers have been opened in the study of the stellar population content of early-type galaxies. In fact by means of mid infrared (MIR) observations it is possible to estimate the age and metallicity of the old stellar populations and to quantify both the presence of intermediate age stellar populations as well as even tiny amounts of ongoing star formation.

The MIR spectral region of old and intermediate age stellar populations is affected by the presence of mass-losing AGB giants. In fact, the dusty envelopes of oxygen-rich AGB stars show a clear emission feature around 10\(\mu\)m and Bressan, Granato & Silva (1998) and Piovan, Tantalo & Chiosi (2003), suggested that this emission feature should be clearly seen in relatively old populations. The studies by Bressan et al. (1998, 2001) have also shown that the MIR spectral region could be used to bypass the effects of the age-metallicity degeneracy because as the observed system gets younger and/or its metallicity increases the feature initially gets larger and then it dilutes into a more broad emission that extends up to 15\(\mu\)m. Contrary to optical indicators (e.g. colors or Balmer absorption lines), the above MIR feature shows an opposite behavior with respect to age and metallicity variations. As a consequence it can be used in combina-
tion with optical and UV observations to remove the age-metallicity degeneracy and to obtain an accurate ranking of the stellar population ages.

Ongoing star formation is easily detected in the MIR, from the presence of prominent emission features such as PAHs and atomic or molecular emission lines (e.g. Kaneda et al. 2005, Bressan et al. 2006a,b, Panuzzo et al. 2007). Moreover MIR nebular lines are a strong diagnostic to disentangle star formation and AGN activity and they also allow a direct and perhaps unique determination of the chemical abundance of the surrounding gas (Panuzzo et al. 2007).

On this basis we started a systematic study of the properties of early-type galaxies in the mid infrared spectral region with the Spitzer Space Telescope. Here we report on the results obtained with Spitzer IRS (Houck et al. 2004, Werner et al. 2004) MIR spectroscopic observations of a sample of early-type galaxies in the Virgo cluster (Bressan et al 2006a,b).

### Table 1. Virgo galaxies observed with IRS

| Name     | V_T   | SL1/2 cycles | LL2 cycles | S/N | Name     | V_T   | SL1/2 cycles | LL2 cycles | S/N |
|----------|-------|--------------|------------|-----|----------|-------|--------------|------------|-----|
| NGC 4339 | 11.40 | 20           | 14         | 39  | NGC 4486 | 8.62  | 3            | 3          | 80  |
| NGC 4365 | 9.62  | 3            | 3          | 57  | NGC 4550 | 11.50 | 20           | 14         | 42  |
| NGC 4371 | 10.79 | 9            | 10         | 40  | NGC 4551 | 11.86 | 20           | 14         | 47  |
| NGC 4377 | 11.88 | 12           | 8          | 54  | NGC 4564 | 11.12 | 4            | 6          | 51  |
| NGC 4382 | 9.09  | 3            | 3          | 59  | NGC 4570 | 10.90 | 3            | 5          | 42  |
| NGC 4435 | 10.66 | 3            | 5          | 35  | NGC 4621 | 9.81  | 3            | 3          | 63  |
| NGC 4442 | 10.30 | 3            | 3          | 46  | NGC 4636 | 9.49  | 3            | 5          | 30  |
| NGC 4473 | 10.06 | 3            | 3          | 55  | NGC 4660 | 11.11 | 3            | 5          | 40  |
| NGC 4474 | 11.50 | 20           | 14         | 38  |          |       |              |            |     |

2. Observations and data reduction

Standard staring mode short (SL1 and SL2) and long (LL2) low resolution IRS spectral observations of 18 early-type galaxies, were obtained between January and July 2005. The galaxies were selected among those that define the color-magnitude relation of the Virgo cluster (Bower, Lucy & Ellis 1992), whose common explanation is in terms of a sequence of passively evolving coeval objects of decreasing metallicity. The number of ramp cycles (of 60s or 120s) and S/N reached at 6 µm are shown in Table 1. The spectra were extracted within a fixed aperture (3.6”×18” for SL and 10.2”×10.4” for LL) and calibrated using our own software, tested versus the SMART software package (Higdon et al. 2004), as described in detail in Bressan et al. (2006a). For SL observations, the sky background was removed by subtracting observations taken in different orders, but at the same nod position. LL segments were sky-subtracted by differentiating the two nod positions. Since the adopted IRS pipeline (version S12) is specifically designed for point source flux extraction, we have devised a new procedure to flux calibrate the spectra, that exploits the large degree of symmetry that characterizes the light distribution in early-type galaxies. The intrinsic surface brightness profile has been derived by fitting to the data a bi-dimensional

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model convolved with the point spread function (PSF) at several wavelengths. This procedure has a twofold advantage because it allows us both to correctly reconstruct the intrinsic SED, and to recognize whether a particular feature is spatially extended or not. Since for the LL segment the above procedure is quite unstable, we have preferred to fix one of the parameters of the profile (usually $R_c$) to the value derived in the nearby wavelength region of the SL segment.

3. Passive early-type galaxies.

Thirteen galaxies (76%) of our sample have a MIR spectrum that is dominated by the presence of a broad emission feature above 10 µm, without any other narrow emission feature. The spectra of these galaxies are collected in Figure [1]. The analysis of the IRS spectra indicates that the 10 µm feature has an extended spatial distribution, consistent with that obtained in the spectral range dominated by stellar photospheres (below 8 µm). This has been confirmed by the analysis of Spitzer IRS Peak-Up imaging observations in the blue (16 µm) filter of selected galaxies (Annibali et al. in preparation). It is also in agreement with previous ISOCAM observations that indicated spatially resolved emission at both 6.7 and 15 µm (Athey et al. 2002, Ferrari et al. 2002, Xilouris et al. 2004). In view of these considerations and based on preliminary fits with our models of passively evolving old simple stellar populations, we have argued that we have detected the 10 µm features, due to silicate emission from the circumstellar envelopes of mass losing AGB stars, as predicted by Bressan et al. (1998).

However, the observed 10 µm feature appears broader than that predicted by the models of Bressan et al. (1998). A rather better fit is obtained by a simple superposition of an M giant model spectrum (MARCS, Gustafsson et al. 2002), meant to represent the photospheric contribution of the red giant population, and dust (silicate) emission from moderately thick circumstellar envelope models (Bressan et al. 2006b), as shown in Figure [1]. It is surprising that the observations indicate that the major contribution comes from envelopes in a quite narrow range of optical depths ($\tau_{1\mu m} \simeq 3 - 5$), at variance with isochrones that account for a distribution of envelopes of varying optical depth. Possible ways out of this discrepancy are either the inclusion of a different dust mixture and/or the use of a more detailed description for the advanced phases (e.g. the recent AGB evolution by Girardi & Marigo 2006).

As far as the dust mixture is concerned, there is evidence that Al dust grains are present in circumstellar envelopes of AGB stars (Blommaert et al. 2006, Lebzelter et al. 2006). In the sample of Bulge AGBs observed by Blommaert et al. (2006) with ISO, Al$_2$O$_3$ constitutes a large fraction of the obscuring material (up to 100% in many cases). Since Al$_2$O$_3$ has an emission maximum at about 12 µm, one may suspect that a suitable combination of silicate and Al$_2$O$_3$ dust grains may broaden the 10 µm emission feature to the level of reproducing the observations of our passive galaxies.

A breakthrough in this respect is constituted by the Spitzer spectroscopy of AGB stars in the globular cluster 47-Tuc (Lebzelter et al. 2006). This work highlights how the dust content changes during the ascent of the AGB: at the beginning only a tiny MIR excess (at $\lambda \sim 12\mu m$), due to amorphous Al$_2$O$_3$ and crystalline MgAl$_2$O$_4$, is observed; then the excess due to silicates begins to show
Figure 1. IRS spectra (solid lines) of passively evolving early-type galaxies in the Virgo cluster. Superimposed are best fits (dashed line) obtained by means of simple models composed of an M giant star spectrum (dotted line) from (MARCS, Gustafsson et al. 2002) and a dusty silicate circumstellar envelope (dot-dashed line) from Bressan et al. (1998). Data and models are normalized at 5.5µm. The fractional contribution of the circumstellar envelope at 10µm ("d") and its optical depth at 1µm ("τ") are indicated in the figure. In those cases where a combination of two dusty envelopes is needed, their optical depth at 1µm and relative fractions ("f") are specified.
Figure 2. Comparison of IRS spectra of the early-type galaxy NGC 4551 with the semi-empirical one of 47-Tuc and SSP models with and without dusty AGB envelopes. The upper panel shows the MIR excess with respect to the old SSP model computed without dusty AGB envelopes while the lower panel show absolute values, normalized at 5.5$\mu$m (see text for details).

up and finally dominates the MIR spectra (at $\lambda \sim 10\mu$m) of the most luminous and mass-losing AGB stars.

Besides that, these observations constitute a potential test for our SSP models. By summing up the observed spectra we can obtain the integrated MIR light of AGB stars in 47-Tuc. We can then subtract the integrated photospheric component to obtain the integrated MIR excess, that can be directly compared with our observations and models. We have thus re-analyzed the original data of Lebzelter et al. (2006), co-added the spectra and subtracted a pure photosphere model normalized at 8$\mu$m (note that this is different from the excess derived by Lebzelter et al., that instead have used a blackbody fit to the NIR flux of the single stars). The excess is shown in the upper panel of Figure 2. The thin solid line is the observed excess obtained by simply co-adding the spectra observed by Lebzelter et al. (2006). In the same panel the dotted line is the MIR excess of a 12 Gyr old SSP for Z=0.006, as suggested from the abundance pattern observed in 47-Tuc (Gratton et al. 2006). The SSP is normalized to the observed integrated flux of 47-Tuc in the K band. The crosses are the measured excess of one of our sample galaxies, NGC 4551, after normalization of its spectrum to that of the SSP at 5.5$\mu$m. However the sample observed by Lebzelter et al. (2006) is only a subsample of the variable stars detected by Lebzelter & Wood (2005), lacking in particular the majority of lower luminosity and shorter period variables. To get a more representative MIR spectrum of 47-Tuc, we have weighted the spectra of Lebzelter et al. (2006), with the number of neighboring variables in the K-Log(Period) plane as derived from Lebzelter & Wood (2005). The resulting excess is the dashed line -labelled b)- in the upper panel. Finally, the solid thick line is the latter excess -b)- multiplied by a factor of four, to match the observations of NGC 4451.
In the lower panel we show the integrated spectra normalized to the old SSP. The three dot-dashed line represents the pure photospheric SSP spectrum used to estimate the MIR excess.

From this simple exercise we may draw a few interesting conclusions. We expect that the real 47-Tuc integrated spectrum is characterized by typical silicate emission, because it is dominated by its brightest objects. In fact already from the spectra of Lebzelter et al. (2006) it appears that the excess due to silicates is about one order of magnitude larger than that due to Al grains. Nevertheless, the contribution of the less luminous but more numerous variables, mainly showing Al$_2$O$_3$ emission, has the effect of broadening the 10µm peak.

In particular an excess four times larger than that obtained for 47 Tuc, would fairly well match the shape of that observed in the galaxy NGC 4551 (and other passive galaxies of Fig. [1] as well, with slightly different factors). This suggests that the mismatch between the shape of the model spectra and the observations could be mainly caused by the lack in the model of Al dust grain emission arising from low mass loss rate AGB stars.

On the other hand, this experiment shows that the comparison of SSPs models with integrated globular cluster spectra must be done with care, because of the large stochastic effect introduced by the very small number of bright AGBs. In fact we have checked that by only shifting a single bright AGB star from its post-pulse luminosity dip to its quiescent interpulse luminosity, results in a variation of about 30% in the integrated excess at 10 µm.

Given the above results, we are now computing new isochrones and SSP models that account for a more realistic description of the AGB phase and of their dusty envelopes. Particularly useful are the new models by Girardi & Marigo (2006) that are able to predict not only a more detailed evolution in the HR diagram, but also the transition between the first overtone and the fundamental mode of pulsation, that seems to separate the pure Al dust sequence from the silicate dominated dust sequence (Lebzelter et al. 2006).

Finally we need to analyze the luminosity difference in the MIR excess between early-type galaxies and 47-Tuc. This difference can be explained as due to the higher metallicity of the selected early-type galaxies. In fact the MIR excess of the brightest 47-Tuc variable, V1, requires a very thin circumstellar envelope, $\tau_{0.55\mu m} \approx 0.15$ (van Loon et al. 2006), corresponding to $\tau_{1\mu m} \approx 0.04$ in the spectral region of maximum photospheric emission. It is easy to show that as long as $\tau_{1\mu m} \ll 1$ the MIR excess over an M-giant spectrum increases linearly with $\tau_{1\mu m}$. Narrow band indices, colors and a recent direct measurement based on our Spitzer data for NGC 4435 (Panuzzo et al. 2007) suggest that the metallicity of luminous ETGs is solar or beyond. Thus the four times larger MIR excess found in early-type galaxies can be entirely due to the larger dust/gas ratio of old AGB stars with a metallicity which is around four times that of 47-Tuc. However the metallicity may affect other physical processes that are relevant to the prediction of the dusty AGB phase, such as the pulsation properties, the mass-loss rate and, for the younger populations, the set up of the third dredge-up phase.

In order to analyze the importance of all those processes and possibly to cope with the stochastic effect, a much larger AGB sample must be considered. In particular Bulge stars constitute the most natural sample to be analyzed.
and compared with stellar evolutionary models, because they are old and their metallicity is approximately solar. Since a large region of the Bulge has already been observed with Spitzer (IRAC and MIPS imaging) we are expecting new exciting results to come soon. We suggest however that the best strategy to highlight (even modest) dust effects would be to complement IRAC and MIPS observations with IRS Blue Peak-Up observations, since the latter band ($\lambda_c \sim 16\mu m$) is centered right in the middle of the MIR excess of mass-losing stars.

4. Active galaxies.

Among bright Virgo cluster ETGs observed by our team, a significant number are not passively evolving but show various levels of activity. This is clearly the case for the other four galaxies shown in Figure 3. They constitute 24% of our sample. Spectra of NGC 4636 and NGC 4486(M87) are dominated by emission lines ([ArII]7µm, [NeII]12.8µm, [NeIII]15.5µm and [SIII]18.7µm), while those of NGC 4550 and NGC 4435 by PAH emission (at 6.2, 7.7, 8.6, 11.3, 11.9, 12.7 and 16.4µm). The broad continuum features at 10µm (and perhaps at 18µm) in M87 are unresolved and their likely cause is silicate emission from the dusty torus (Siebenmorgen et al. 2005, Hao et al. 2005). NGC 4435 shows also emission lines (and H2 S(3) 9.66µm, H2S(2) 12.3µm and H2S(1)17.04µm).

The analysis of the MIR spectrum of NGC 4435 together with its global SED, indicates that the nucleus of this galaxy is in a post-starburst phase. The rejuvenation episode is of low intensity ($\sim 0.3\%$ of the total mass of the galaxy) and was likely triggered by the interaction with NGC 4438 (Panuzzo et al. 2007). The strengths of MIR nebular emission lines imply that $\sim 98\%$ of the ionizing flux is of stellar origin. At the same time they allow an accurate determination of the metallicity of the gas in the nuclear disk which turns out to be of solar composition.
5. Conclusions

We have obtained Spitzer mid infrared IRS spectra of early-type galaxies selected along the colour-magnitude relation of the Virgo cluster. In most of the galaxies (76%) the emission looks spatially extended and presents an excess longward of 10\(\mu\)m, which is likely due to silicate emission from mass losing evolved stars. The observed MIR excess is about four times larger than that estimated for 47-Tuc, on the basis of IRS spectroscopy of its brightest AGB stars. This could be the consequence of a higher dust/gas ratio, in agreement with the higher metallicity of early-type galaxies. However, since other important physical processes are affected by metallicity, a thorough comparison between new Spitzer data and new models of the advanced phases are needed. Ideal workbenches for the models would be colour-magnitude and colour-colour diagrams of the Bulge stellar population, especially in the wavelength range of the IRS Blue Peak-Up.

In the remaining fraction of galaxies (24%) we detect signatures of activity at various levels. The analysis of the IRS spectrum of NGC 4435 testifies to the superb capability of Spitzer to probe the nature of this type of activity.

A detailed comparison of these results with those obtained for field early type galaxies will certainly cast light on the role of environment in the galaxy evolution process.

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