SPITZER IRS SPECTRA OF VIRGO EARLY-TYPE GALAXIES: DETECTION OF STELLAR SILICATE EMISSION

A. Bressan, L. Buson, M. Clemens, G. L. Granato, R. Rampazzo, L. Silva, J. R. Valdes, O. Vega, and L. Danese

Received 2005 December 9; accepted 2006 January 31; published 2006 February 17

ABSTRACT

We present high signal-to-noise ratio Spitzer Infrared Spectrograph observations of 17 Virgo early-type galaxies. The galaxies were selected from those that define the color-magnitude relation of the cluster, with the aim of detecting the silicate emission of their dusty, mass-losing evolved stars. To flux calibrate these extended sources, we have devised a new procedure that allows us to obtain the intrinsic spectral energy distribution and to disentangle resolved and unresolved emission within the same object. We have found that 13 objects of the sample (76%) are passively evolving galaxies with a pronounced broad silicate feature that is spatially extended and likely of stellar origin, in agreement with model predictions. The other four objects (24%) are characterized by different levels of activity. In NGC 4486 (M87), the line emission and the broad silicate emission are evidently unresolved, and, given also the typical shape of the continuum, they likely originate in the nuclear torus. NGC 4636 shows emission lines superposed on extended (i.e., stellar) silicate emission, thus pushing the percentage of galaxies with silicate emission to 82%. Finally, NGC 4550 and NGC 4435 are characterized by polycyclic aromatic hydrocarbon (PAH) and line emission, arising from a central unresolved region. A more detailed analysis of our sample, with updated models, will be presented in a forthcoming paper.

1 INTRODUCTION

Bressan et al. (1998) have suggested that the presence of dusty circumstellar envelopes around asymptotic giant branch (AGB) stars should leave a signature, a clear excess at 10 μm, in the mid-infrared (MIR) spectral region of passively evolving stellar systems. Early detections of such an excess were suspected in M32 (Impey et al. 1986) from ground-based observations and in a few elliptical galaxies observed with ISO (Bregman et al. 1998). The first unambiguous confirmation of the existence of this feature, although barely resolved, was found in the Infrared Space Observatory (ISO) circular variable filter (CVF) spectrum of NGC 1399 (Bressan et al. 2001). Since AGB stars are luminous tracers of intermediate-age and old stellar populations, an accurate analysis of this feature has been suggested as a complementary way to disentangle age and metallicity effects among early-type galaxies (Bressan et al. 1998, 2001). More specifically, Bressan et al.’s models show that a degeneracy between metallicity and age persists even in the MIR, since both age and metallicity affect mass-loss and evolutionary lifetimes on the AGB. While in the optical age and metallicity need to be anticorrelated to maintain a feature unchanged (either color or narrowband index), in the MIR the opposite: the larger dust mass loss of a higher metallicity is the opposite; the larger dust mass loss of a higher metallicity. Thus, it is possible to separate the contribution of AGB stars to the optical and near-infrared spectra of passively evolving systems and to study the metallicity and age of these systems. A detailed analysis of the MIR spectra of the Virgo Cluster early-type galaxies, observed with the Infrared Spectrograph (IRS; Houck et al. 2004) of the Spitzer Space Telescope (Werner et al. 2004).

2 OBSERVATIONS AND DATA REDUCTION

The Spitzer IRS observations of 17 Virgo early-type galaxies were obtained during the first 2 months of the Spitzer General Observer Cycle. The objects were selected among those that define the color-magnitude relation of the Virgo Cluster (Bower et al. 1992). The observing log is given in Table 1. We also report, in the fourth and fifth columns, the number of cycles of 60 and 120 s exposures performed with SL1/2 and LL2, respectively. The spectra were extracted within a fixed aperture (3′ × 18′′) for the Short-Low (SL) module and calibrated using custom-made software, tested against the SMART software package (Higdon et al. 2004).

2.1 Flux Calibration for Extended Sources

The IRS pipeline version S12 (and older versions) is designed for point-source flux extraction. We present here an...
where \( X \) and \( Y \) are the coordinates along the major and minor axes of the galaxies, and \( b/a \) is the axial ratio taken from the literature. \( I_p \) and \( R_c \) are free parameters that are functions of the wavelength and are obtained by fitting the observations with the simulated profile. In order to get an accurate determination of the parameters of the profiles, several wavelength bins have been co-added. This procedure has a twofold advantage because it allows us to (1) reconstruct the intrinsic profile and the corresponding SED and (2) to recognize whether a particular feature is resolved or not. The spectrum, extracted in a fixed width around the maximum intensity, is corrected by the ratio between the intrinsic and observed profile. Since for the LL2 segment the above procedure is generally not as stable as for SL segments, we have preferred to fix \( R_c \) to the corresponding value derived in the nearby wavelength region of the SL segment.

An estimate of the signal-to-noise ratio (S/N) was performed by considering two sources of noise: the instrumental plus background noise and the Poissonian noise of the source. The former was evaluated by measuring the variance of pixel values in background-subtracted co-added images far from the source. The Poissonian noise of the source was estimated as the square root of the ratio of the variance of the number of electrons extracted per pixel in each exposure and the number of the exposures. The total noise was obtained by summing the two sources in quadrature and by multiplying by the square root of the extraction width in pixels. The corresponding S/N at 6 \( \mu \)m is shown in the sixth column of Table 1.

Finally, we notice that the overall absolute photometric uncertainty of IRS is 10%, while the slope deviation within a single segment (affecting all spectra in the same way) is less than 3% (see the Spitzer Observer Manual).

3. RESULTS

The final flux-calibrated spectra of the selected Virgo Cluster early-type galaxies are shown in Figures 1 and 2.

3.1. Silicate Emission from Evolved Stars

In Figure 1 we have collected the 13 galaxies (76% of the sample) whose IRS spectra are characterized by the presence of a broad emission feature around \( \lambda \sim 10 \mu m \) that extends toward longer wavelengths. These galaxies show neither PAH features nor emission lines. The observed spectra (\textit{solid lines}) are superposed on old SSP from Bressan et al. (1998) normalized at \( \lambda \sim 5.3 \mu m \). The dotted line is a 10 Gyr, \( Z = 0.02 \) (solar metallicity) SSP computed without accounting for dusty circumstellar envelopes. Dashed lines from bottom to top refer to 10 Gyr SSPs with increasing metallicity \( Z = 0.008 \), \( Z = 0.02 \), and \( Z = 0.05 \), respectively, computed with dusty silicate circumstellar envelopes. The models that account for dusty circumstellar envelopes show an extended feature due to silicate emission, which is very similar to that observed. The feature gets stronger at decreasing age and/or at increasing metallicity due to the corresponding higher dust mass-loss rate of the SSP. Since, in addition to the match with the models, the analysis of the intrinsic spatial profile indicates that the whole spectrum is extended, we argue that the observed features are of stellar origin and most likely arise from dusty circumstellar envelopes of mass-losing, evolved stars. To corroborate this possibility, we compare, in Figure 1, the normalized continuum-subtracted 10 \( \mu m \) silicate emission of the mean outflow oxygen-rich AGB star (Molster et al. 2002) and of U Cam (a carbon-rich star with SIC emission; Sloan et al. 1998) with that of NGC 4365. Although early-type galaxies are
expected to harbor carbon stars, given the wide metallicity spread within a galaxy, it seems that the dominant contribution comes from evolved M giants. More detailed models, fully accounting for the expected mixture of evolved stars, will be presented in a forthcoming paper.

The MIR view of early-type galaxies proves to be a strong diagnostic for the population content of these galaxies. Recently, Temi et al. (2005) noticed that the Infrared Array Camera (IRAC) flux ratios at 8 and 3.6 μm or the Multiband Imaging Photometer for Spitzer (MIPS) 24 μm to IRAC 3.6 μm flux ratio remain fairly constant in early-type galaxies that otherwise show different Hβ strengths. They conclude that this disagreement supports a small rejuvenation episode. Although this is one of the possibilities invoked by Bressan et al. (1996) to explain early-type galaxies with strong Balmer line absorptions, caution must be paid before drawing definite conclusions. Indeed, we show in Figure 1 that a young (5 Gyr), more metal-poor (Z = 0.008) SSP (dot-dashed line) is very similar to an old, more metal-rich one. Thus, even the mid-infrared spectral region is degenerate, and in order to break the age-metallicity degeneracy in passively evolved systems, a careful combined optical (including possibly NIR) and MIR analysis is required.

To further illustrate the strength of this kind of analysis, we show in Figure 3 a comparison of the IRS spectra of NGC 4551 and NGC 4365. A recent optical spectroscopic study (Yamada et al. 2006) indicates that NGC 4551 is significantly younger and more metal-rich than NGC 4365. In this case we would expect NGC 4551 to be richer in bright mass-losing AGB stars than NGC 4365, and its silicate features to be more prominent. However, the opposite is observed, suggesting that NGC 4551 is either older or more metal-poor (or both) than NGC 4365. Evidently, the effects of degeneracy in the optical can be strong (see, e.g., Denicoló et al. 2005 and Annibali et al. 2006).

We finally notice that NGC 4473 was observed by ISO (Xilouris et al. 2004) and shows spatially extended emission at 6.7 and 15 μm. These authors measured a 15 μm excess with respect to SSP models without dusty circumstellar envelopes. The excess was interpreted as being due to hot diffuse interstellar dust. IRS spectra, such as those presented here, permit the disentangling of the contribution of evolved AGB stars and the presence of interstellar dust.

### 3.2. Active Galaxies

The remaining four galaxies (24% of the sample) display different signatures of activity in the MIR spectra (Fig. 2). These galaxies are classified as active from optical studies (from active galactic nucleus [AGN] to transition LINER H ii) at odds with the former group.

The spectra of NGC 4636 and NGC 4486 (M87) show emission lines ([Ar ii] 7 μm, [Ne ii] 12.8 μm, [Ne iii] 15.5 μm, and [S ii] 18.7 μμμ μμμ μμμ possibily of nonstellar origin. The broad continuum feature at 10 μm in NGC 4486 is not spatially extended and likely due to silicate emission from the dusty torus (Siebenmorgen et al. 2005; Hao et al. 2005). Line emission in NGC 4636 falls on top of the circumstellar emission SED, and as for NGC 4473, its excess at 15 μm is of stellar origin.
origin and not due to emission by hot diffuse dust as suggested by Ferrari et al. (2002).

The spectrum of NGC 4550 shows PAH emissions features (at 6.2, 7.7, 8.6, 11.3, and 12.7 \( \mu m \)) and the H\(_2\) S(5) 6.9 \( \mu m \) and S(3) 9.66 \( \mu m \) emission lines. NGC 4435 shows a typical star-forming spectrum (Kaneda et al. 2005). A preliminary interpretation suggests that an unresolved starburst is dominating the MIR emission.

4. CONCLUSIONS

We presented Spitzer MIR IRS spectra of early-type galaxies selected along the color-magnitude relation of the Virgo Cluster.

We have reconstructed the intrinsic SED of these galaxies from the observed spatial profile sampled by the slits, via a careful analysis of PSF effects. In this way we are also able to differentiate between spatially resolved and unresolved regions within the spectrum. This provides independent support for the interpretation of their nature.

Most of the galaxies (76\%) show an excess at 10 \( \mu m \) and longward that appears spatially extended and is likely due to silicate emission. This class of spectra does not show any other emission features. We argue that the 10 \( \mu m \) excess arises from mass-losing evolved stars, as predicted by adequate SSP models. A detailed modeling of these features together with the analysis of combined optical, NIR, and MIR spectra will be presented in a forthcoming paper.

In the remaining smaller fraction (24\%), we detect signatures of activity at different levels. We observe line emission superposed on the stellar silicate features in NGC 4636, unresolved line and silicate emission in M87 that likely originates in the dusty torus, and unresolved PAH emission in NGC 4550 and NGC 4435. The latter galaxy displays the main characteristics of a nuclear starburst (P. Panuzzo et al. 2006, in preparation).

If we exclude M87, which is a well-known AGN, only two out of 16 early-type galaxies observed show PAHs, which corresponds to quite a low fraction (\( \sim 12\% \)) of the observed sample. It is premature to conclude that such a low fraction of galaxies with PAHs is representative of the cluster early-type galaxy population, especially if we consider that our investigation is limited to the brightest cluster members (the upper 2 mag of the color-magnitude relation). A detailed comparison of our results with those obtained for field galaxies will cast light on the role of environment in the galaxy evolution process.

This work is based on observations made with the Spitzer Space Telescope, which is operated by the JPL, Caltech, under a contract with NASA. We thank J. D. T. Smith for helpful suggestions on the IRS flux calibration procedure and the anonymous referee for useful suggestions. A. B., G. L. G., and L. S. thank the INAOE for their warm hospitality.

REFERENCES

Annibali, F., Bressan, A., Rampazzo, R., Danese, L., & Zeilinger, W. W. 2006, A&A, submitted
Athey, A., Bregman, J., Bregman, J., Temi, P., & Sauvage, M. 2002, ApJ, 571, 272
Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, MNRAS, 254, 601
Bregman, J. N., Athey, A. E., Bregman, J. D., & Temi, P. 1998, AAS Meeting, 193, 09.03
Bressan, A., Aussel, H., Granato, G. L., Rodighiero, G., Panuzzo, P., & Silva, L. 2001, Ap&SS, 277, 251
Bressan, A., Chiosi, C., & Tantalo, R. 1996, A&A, 311, 425
Bressan, A., Granato, G. L., & Silva, L. 1998, A&A, 332, 135
Denicoló, G., Terlevich, R., Terlevich, E., Forbes, D. A., & Terlevich, A. 2005, MNRAS, 358, 813
Elson, R. A. W., Fall, S. M., & Freeman, K. C. 1987, ApJ, 323, 54
Ferrari, F., Pastoriza, M. G., Macchetto, F. D., Bonatto, C., Panagia, N., & Sparks, W. B. 2002, A&A, 389, 355
Hao, L., et al. 2005, ApJ, 625, L75
Higdon, S. J. U., et al. 2004, PASP, 116, 975
Houck, J. R., et al. 2004, ApJS, 154, 18
Impey, C. D., Wynn-Williams, C. G., & Becklin, E. E. 1986, ApJ, 309, 572
Kaneda, H., Onaka, T., & Sakon, I. 2005, ApJ, 632, L83
Kennicutt, R. C., Jr., et al. 2003, PASP, 115, 928
Molster, F. J., Waters, L. B. F. M., & Tielens, A. G. G. M. 2002, A&A, 382, 222
Siebenmorgen, R., Haas, M., Krügel, E., & Schulz, B. 2005, A&A, 436, L5
Sloan, G. C., Little-Marenin, I. R., & Price, S. D. 1998, AJ, 115, 809
Temi, P., Brighenti, F., & Mathews, W. G. 2005, ApJ, 635, L25
Werner, M. W., et al. 2004, ApJS, 154, 1
Xilouris, E. M., Madden, S. C., Galliano, F., Vigroux, L., & Sauvage, M. 2004, A&A, 416, 41
Yamada, Y., Arimoto, N., Vazdeksis, A., & Peletier, R. F. 2006, ApJ, 637, 200