THE STAR FORMATION HISTORY OF THE VIRGO EARLY-TYPE GALAXY NGC 4435: 
THE SPITZER MID-INFRARED VIEW

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ABSTRACT

We present a population synthesis study of NGC 4435, an early-type Virgo galaxy interacting with NGC 4438. We combine new spectroscopic observations obtained with the Spitzer Space Telescope IRS instrument with IRAC archival data and broadband data from the literature. The IRS spectrum shows prominent polycyclic aromatic hydrocarbon (PAH) features, low-ionization emission lines, and H2 rotational lines arising from the dusty circumnuclear disk characterizing this galaxy. The central spectral energy distribution (SED), from X-ray to radio, is well fitted by a model of an exponential burst superimposed on an old simple stellar population. From the lack of high-excitation nebular lines, the [Ne II] /15.5 [Ne II] /12.8 ratio, the temperature of molecular hydrogen, and the fit to the full X-ray-to-radio SED we argue that the present activity of the galaxy is driven by star formation alone. The active galactic nucleus contribution to the ionizing flux is constrained to be less than 2%. The age of the burst is found to be around 190 Myr, and this is fully consistent with the notion that the star formation process was triggered by the interaction with NGC 4438. The mass involved in the rejuvenation episode turns out to be less than 1.5% of the stellar galaxy mass sampled in a 5’’ central aperture. This is enough to render NGC 4435 closely similar to a typical interacting early-type galaxy with inverted Ca ii [H+K] lines that will later turn into a typical cluster E+A galaxy and reinforces the notion that these objects are the result of a recent rejuvenation episode rather than a genuine delayed formation.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: individual (NGC 4435) — galaxies: stellar content

Online material: color figures

1 INTRODUCTION

NGC 4435 (VCC 1030), an early-type SB0(7) galaxy (Sandage & Tamman 1981) member of the Virgo Cluster, is of great interest because it is a nearby example of galaxy interactions in the cluster environment. NGC 4435 is experiencing an off-center encounter with NGC 4438, a bulge dominated late-type galaxy lying at a projected separation of 4.3’ (i.e., 20 kpc, adopting a Virgo distance of 16.1 Mpc from Kelson et al. 2000). Evidence of the strong ongoing interaction comes from the well-developed stellar tidal tail (=30 kpc) of NGC 4438 but also from the structure of the interstellar medium (ISM) of both galaxies. He+[N II] images (Kenney et al. 1995) reveal several ionized gas filaments starting from the disk of NGC 4438 and extending out of the disk up to 10 kpc. The study of the distribution of the cold gas shows that CO and H I are displaced west of the center of NGC 4438, although CO is also present in the center of NGC 4435. Vollmer et al. (2005) proposed a model of the encounter based on the combined picture from the ISM observations and simulations. These latter authors indicate that the evolution of NGC 4438 has been influenced by its passage through the intracircular medium (ICM), where ram pressure stripped the H I in about 100 Myr. During this period, NGC 4435 passed through the disk of NGC 4438 at a high velocity (=800 km s⁻¹), but the ISM-ISM interaction of the two galaxies had a less important effect on the final distribution of the gas than the cluster ram pressure stripping exerted by the ICM.

If the above is the general picture of the NGC 4435/NGC 4438 encounter, its effects on the evolution of NGC 4435 are less clear. Domingue et al. (2003) showed that in low-density environments early-type galaxies show little or no IR or optical signatures of star formation when physically paired to a gas-rich companion. However, some of the early-type members do show significant levels of IR and Hα emission, which indicate both thermal (star formation) and nonthermal (AGN) activity. These pairs are among the best candidates for direct interaction fueling of both starburst and AGNs.

NGC 4435 currently has ISM. Hubble Space Telescope (HST) images reveal the presence of a circumnuclear disk of 4” radius (360 pc, inclination 44°; Ho et al. 2002; Capetti & Balmaverde 2005). Moreover, nebular emission lines were detected by several authors (Kenney et al. 1995; Ho et al. 1995, 1997); in particular, Ho et al. (1997), using the classical diagnostic diagrams, classified this galaxy as T2/H; i.e., a transition object between a type 2 LINER and H II.

Coccati et al. (2006) studied the ionized gas kinematics using HST STIS in the central 2”, looking for a supermassive black hole (SMBH). The rotation curve is very symmetric, indicating a regular rotation. Their analysis indicates that the mass of the SMBH (upper limit 7.5 × 10⁶ M☉) is lower than that expected from the MVH–MvH–LVH relations. Coccati et al. suggest that the SMBH in NGC 4435 could be of the “laggard” type, as discussed in Vittorini et al. (2005), although these seem to lurk among galaxies that spend most of their lifetime in the field, at least apparently at odds with NGC 4435’s cluster location.
In this paper we study the \textit{Spitzer Space Telescope} IRS mid-infrared (MIR) spectra of NGC 4435 presented in Bressan et al. (2006) and perform a comprehensive analysis of the entire spectral energy distribution (SED) of the galaxy. In particular, the study of the MIR region, rich in spectral features (emission lines, polycyclic aromatic hydrocarbon [PAH], dust emission, etc.), provides an independent view of the nature of the nuclear activity of this galaxy (Genzel et al. 1998; Lutz et al. 1998; Roussel et al. 2001). Combined with the analysis of the panchromatic SED, it allows the characterization of the star formation activity and the estimation of the mass of stars formed during this interaction, shedding light on the rejuvenation mechanism in interacting early-type galaxies.

The paper is organized as follows. In § 2 we provide details of the observations and data-reduction methods. In § 3 we describe the results of the study of the spectrum in the MIR region, while in § 4 we extend the modeling to the entire galaxy SED. In § 5 we discuss the results of our analysis and compare them with other studies. Finally, in § 6 we summarize the conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. IRS Spectra

\textit{Spitzer} IRS spectral observations of NGC 4435 were obtained during the first \textit{Spitzer} General Observer Cycle on 2005 June 1 as part of a program (PID 3419; Bressan et al. 2006) to study early-type galaxies that belong to the color-magnitude relation of the Virgo Cluster (Bower et al. 1992). The observations were performed in standard staring mode with low resolution ($R \sim 64-128$) modules SL1 (7.5-15.3 \(\mu\)m), SL2 (5-7.6 \(\mu\)m), and LL2 (14.1-21.3 \(\mu\)m), with 6 exposures of 60 s for each SL module and 10 exposures of 120 s for the LL2 module.

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 reduction procedure is described in detail in Bressan et al. (2006); here we only summarize the main steps.

For the SL observations, the sky background was removed by subtracting observations taken in different orders but at the same nod position. The LL segments were sky-subtracted by differencing the two nod positions.

We obtained new $e^- \cdot s^{-1}$ to Jy flux conversions by applying a correction for aperture losses (ALCF) and a correction for slit losses (SLCF) to the flux conversion tables provided by the \textit{Spitzer} Science Center (SSC; e.g., Kennicutt et al. 2003). By applying the ALCF and SLCF corrections, we obtained the flux received by the slit.

For each galaxy of the program, we simulated the corresponding observed linear profile along the slits by convolving a wavelength-dependent bidimensional intrinsic surface brightness profile with the instrumental point-spread function (PSF). The adopted profile is a two-dimensional modified King law (Elson et al. 1987). By fitting the observed profiles with the simulated ones, we can reconstruct the intrinsic profiles and the corresponding intrinsic SED. This procedure also has the advantage of recognizing whether a particular feature is spatially extended or not.

Finally, the spectrum was extracted in a fixed width (18" for SL and 10.2" for LL) around the maximum intensity. In order to account for the different extraction area, the LL spectrum has been rescaled to match that of SL (3.6"\(\times\)18"). In Figure 1 we overplot the extraction area and the IRS slit positions on an \textit{HST} WFPC2/F814W image of the NGC 4435 nucleus by Coccato et al. (2006).

The uncertainty on the flux was evaluated 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 sources was estimated as the square root of the variance of the number of $e^-$ 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. 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 \textit{Spitzer} Observer’s Manual).

2.2. IRAC and MIPS Images

Infrared Array Camera (IRAC) and Multiband Imaging Photometer (MIPS) images of NGC 4435 were retrieved from the SSC archive. They were taken as part of the PID 3649. Fluxes at 3.6, 4.5, 5.8, and 8 \(\mu\)m were measured from the IRAC images as output from the “post-BCD” pipeline. The proximity of NGC 4435 to NGC 4438 results in a weak contaminating flux component. This was treated by estimating the median background flux from the image containing NGC 4435 so that the subtracted background included the contaminating light. Fluxes were extracted in circular apertures centered on the brightest pixel at each wavelength. Given that the calibration of extended sources for IRAC is still somewhat uncertain, the fluxes so extracted have errors of $\sim$10\% (Dale et al. 2005). Similarly, we measured fluxes at 24, 70, and 160 \(\mu\)m from MIPS mosaics as output from the “post-BCD” pipeline. Fluxes were extracted in circular apertures centered on the brightest pixel at each wavelength, subtracting the median background flux measured far from the source. Uncertainties for MIPS fluxes are quoted to be $\sim$20\% (Dale et al. 2005; see also the \textit{Spitzer} Observer’s Manual). It is worth noting that in
all MIPS images the galaxy appears almost as a point source; in particular, at 24 μm, where the angular resolution is highest, the galaxy image is only slightly larger than the instrumental PSF (6′).

3. ANALYSIS OF THE MID-IR SPECTRUM

The final flux-calibrated IRS spectrum of NGC 4435 is shown in the top left panel of Figure 2. The spectrum is dominated by numerous PAH features and shows several nebular emission lines, [Ar II] 7 μm, [Ne II] 12.8 μm, [Ne III] 15.5 μm, and [S III] 18.7 μm, and molecular hydrogen rotational lines, H₂ S(3) 9.66 μm and H₂ S(1) 17.04 μm.

In order to measure the fluxes of emission lines and to identify the PAH features, we fitted the spectrum via decomposition into various components: PAH emission features, emission lines, and underlying continuum. For all the PAH features but those at 11.2 and 12.5 μm, we assumed a Drude profile. The features at 11.2 and 12.5 μm are very asymmetric; thus, we have used the profiles observed by Houy et al. (2001) convolved to the SL1 resolution. It is worth noting that the emission profiles derived by Houy et al. (2001) do not account for the blending of the wings of the PAH features. Consequently, our underlying continuum shows a broad feature. However, since the main purpose of this section is to estimate the emission-line intensities, this does not affect our conclusions.

For the emission lines we adopted a Gaussian profile with a FWHM given by the resolving power of the corresponding IRS module (see the Spitzer Observer’s Manual, v. 6.0, § 7.1.6). The resulting fits of the three most interesting spectral regions are shown in Figure 2.

3.1. PAH Features

In the IRS spectrum of NGC 4435 we can identify many PAH emission features already known from Infrared Space Observatory (ISO) and pre-ISO studies, at 6.2, 7.7, 8.2, 8.6, 11.2, 11.9, 12.7, 13.5, 14.5, 15.9, and 16.4 μm (e.g., Li & Draine 2001; Sturm et al. 2000). Besides those features, we also see a number of new components that have been revealed by recent Spitzer observations. These are the feature at 10.7 μm and, most notably, the complex around 17 μm (Fig. 2, bottom right panel) is similar to that observed in the spiral galaxy NGC 7331 and in the extended emission of M82 (Engelbracht et al. 2006). This complex is superimposed on the H₂ S(1) emission,
but in our case, since the H$_2$ S(1) emission is fainter than that seen in NGC 7331 and M82, we can more accurately extract the underlying emission components. In fact, while Smith et al. (2004) claimed the presence of a new broad emission feature at 17.1 µm, in our spectrum this feature appears to be a blend of two components: a narrow component centered at 17.4 µm with a FWHM of 0.33 µm and a broad component centered at 16.9 µm with a FWHM of 1.16 µm. Note that the component centered at 17.4 µm was observed by Van Kerckhoven et al. (2000) in various Galactic star formation regions. Thus, our observations indicate that the new PAH emission feature is centered at 16.9 µm. In the same spectral region we also find an emission feature at 19.07 µm, which was observed in the NGC 7023 reflection nebula by Werner et al. (2004).

3.2. Emission Lines

In the MIR spectrum of NGC 4435 we detect only low-ionization emission lines. The corresponding intensities are listed in Table 1. The reported uncertainties in the line fluxes are 1σ, as derived from the line fitting. For some interesting higher excitation emission lines we can only provide 3σ upper limits. In the following sections we discuss the main implications of our detections.

3.2.1. Constraints on AGN Excitation

Nebular emission lines provide a powerful diagnostic tool to determine the nature of the source of energy powering the emission. Classically, the determination is done using optical emission lines. Optical spectra of the nuclear region of NGC 4435 were observed by Ho et al. (1995). Using the diagnostic diagrams of Veilleux & Osterbrock (1987), Ho et al. (1997) classified NGC 4435 as a transition object between LINER and H ii regions. Revisiting the classification using the AGN/H ii transition/ ionization emission lines we can only provide 3σ upper limits. In our case, since the H$_2$ 0–0 S(3) transition nebula by Werner et al. (2004).

| Transition/Ion | $\lambda_{\text{rest}}$ (µm) | Flux $(10^{-17}$ W m$^{-2}$) |
|----------------|-----------------------------|--------------------------------|
| H$_2$ 0–0 S(5) | 6.9095                      | 0.505 ± 0.411                  |
| [Ar ii]        | 6.9853                      | 3.787 ± 0.378                  |
| H P$\alpha$    | 7.4599                      | 1.567                         |
| H$_2$ 0–0 S(3) | 9.6649                      | 1.055 ± 0.288                  |
| [Ne ii]        | 12.8136                     | 6.972 ± 0.252                  |
| [Ne iii]       | 15.5551                     | 2.666 ± 0.168                  |
| H$_2$ 0–0 S(1) | 17.0348                     | 1.808 ± 0.163                  |
| [S ii]         | 18.7130                     | 2.248 ± 0.119                  |
| [Fe ii]        | 5.3402                      | <1.92                         |
| H$_2$ 0–0 S(7) | 5.5112                      | <1.76                         |
| H$_2$ 0–0 S(4) | 8.0250                      | <1.53                         |
| [Ar iii]       | 8.9914                      | <1.03                         |
| [S iv]         | 10.5105                     | <0.60                         |
| H$_2$ 0–0 S(2) | 12.2786                     | <0.96                         |
| [Ne v]         | 14.3217                     | <0.41                         |
| [Fe ii]        | 17.9360                     | <0.34                         |

$^a$ We quote here the measurement of Pf $\lambda_{\text{rest}}$ intensity provided by the fitting procedure; however, its value is unreliable because it falls in the wing of the broad PAH 7.7 µm emission feature.

In Table 1 we provide the intensity of detected H$_2$ rotational lines. The first excited rotational state of H$_2$ that can provide a transition toward the fundamental level has an angular moment $J = 2$ and an energy of 510 K; thus, the H$_2$ does not radiate for temperatures typical of the cold molecular medium (~10 K) but only for temperatures above 100 K. The state of warm molecular gas can be investigated using the excitation diagram, shown in Figure 3, where the natural logarithm of the number of molecules in state $i$ ($N_i$) divided by the statistical weight of the state ($g_i$) is plotted against the energy ($E_i$) of the excited state with respect to the ground state. The number of molecules in state $i$ is given by (assuming a density smaller than the critical density)

$$ N_i = \frac{L_i}{A_i h \nu_i}, $$

where $L_i$ is the luminosity of the line emitted by the transition starting from state $i$, $A_i$ is the transition probability, and $\nu_i$ is the frequency of the transition.

Assuming local thermal equilibrium, the ratio between the number of molecules in state $i$ and the total number of H$_2$ molecules per unit of volume is given by the Boltzmann equation (Parmar et al. 1991):

$$ \frac{n_i}{n_{H_2}} = g_i \frac{h c B}{2 k T} \exp\left(-\frac{E_i}{k T}\right), $$

where $B$ is the H$_2$ rotational constant. For an isothermal gas, all the data in the excitation diagram of Figure 3 should lie on a
linear relation \( y = a + bx \) with \( b = -1/T \). However, the observed values do not lie on the same line, suggesting the presence of two (or more) components at different temperatures, a “warm” component at \( T \leq 240 \) K traced by the S(1) line [and the S(2) upper limit] and a “hot” component at \( T \approx 630 \) K, traced by lines at shorter wavelengths. With equations (1) and (2) we can estimate the mass of the “warm” and “hot” components. Assuming a temperature of 200 K for the warm component, we find a mass of \( 6.3 \times 10^6 M_\odot \), while for the hot component we find a mass of \( 7.1 \times 10^5 M_\odot \). The excitation mechanism for hot and warm molecular gas in galaxies is commonly attributed to UV flux from young stars in photodissociation regions (PDR), shocks, or X-ray flux from an active nucleus (Burton et al. 1992; Rigopoulou et al. 2002).

The upper limit on the temperature derived from S(1) and S(2) lines excludes AGN excitation. In fact, Rigopoulou et al. (2002) find that in Seyfert galaxies the temperature from these lines is typically around 350 K. Indeed, the temperature we find is compatible with PDR models by Burton et al. (1992). Finally, it is worth noting that the mass of the warm gas is only a tiny fraction (<0.06%) of the total molecular gas observed in NGC 4435 from CO lines (<10^8 M_\odot ; Vollmer et al. 2005). This fraction is also significantly smaller than that found in typical powerful starbursts (1%–10%) or in Seyfert galaxies (up to 30%; Rigopoulou et al. 2002). This is consistent with our finding that the star formation in NGC 4435 has already declined and is more characteristic of a poststarburst phase, as we discuss in the following sections.

Note that the above values are not corrected for dust attenuation. However, the attenuation we derive from the model fit to the global SED in the following sections is quite low (\( A_J \sim 0.1–0.2 \)) at these wavelengths.

### 3.2.3. Abundance Determinations

From the intensity of the Pf\( \alpha \) line, neon, and argon lines we could obtain an estimate of the metallicity of the ionized gas, following the procedure outlined in Verma et al. (2003). In fact, for a generic element X, as long as the current density is lower than the critical density for collisional de-excitation of the involved transitions, the abundance relative to hydrogen is given by

\[
\frac{X}{H} = \frac{J_{P\alpha}}{J_{P\alpha}} \left( \frac{F_{\text{XII}}}{q_{\text{XII}} h \nu_{\text{XII}}} + \frac{F_{\text{XIII}}}{q_{\text{XIII}} h \nu_{\text{XIII}}} + \cdots \right),
\]

where \( J_{P\alpha} \) is the emissivity for Pf\( \alpha \) line, and \( q_{\text{XII}} \) is the collisional excitation rate of the [X II] transition (for electronic density near zero). The above abundances can be translated into metallicity estimations by dividing them by standard ISM abundances.

We note, however, that while we are confident of the determination of metal-line intensities, Pf\( \alpha \) falls in the wing of a broad PAH emission feature. The measurement of Pf\( \alpha \) intensity is thus unreliable, even if the fitting procedure gives a small uncertainty (reported in Table 1). For this reason we do not proceed with a direct determination of the abundances in this way. However, an alternative way to exploit the good measurements of metallic lines in order to derive the metallicity is to use the hydrogen-line intensity as predicted from the fit to the global SED of the galaxy. This will be discussed in a following section.

### 4. ANALYSIS OF THE PANCHROMATIC SED

The analysis of the MIR spectrum made in the previous section indicates that a star formation activity is present in the circumnuclear disk of NGC 4435. In order to better characterize the emission mechanisms and the stellar population content of this galaxy we model the panchromatic SED of NGC 4435 by means of our spectrophotometric code GRASIL\(^5\) with the recently updated treatment of PAH emission based on ISO data (for details on GRASIL see Silva et al. 1998; Silva 1999; Granato et al. 2000; Bressan et al. 2002; Panuzzo et al. 2003, 2005; Vega et al. 2005).

The panchromatic SED was constructed by combining the IRS spectra (including the main nebular lines) with archival data matching as far as possible the IRS apertures. The \( J, H, \) and \( K_s \) fluxes within an aperture of a 5" radius were taken from the Two Micron All Sky Survey (2MASS) database at IRS.\(^6\) IRAC fluxes in the 3.6, 4.5, 5.8, and 8.0 \( \mu m \) bands were extracted from the same aperture from archival images as explained in § 2.2. \( IRAS \) 60 and 100 \( \mu m \) fluxes (obtained from the NASA/IPAC Extra-galactic Database [NED]) were used to define the far-infrared SED together with MIPS total fluxes. Although the apertures of MIPS and \( IRAS \) are larger than the IRS aperture, the above fluxes are dominated by emission from the dusty circumnuclear disk, as clearly shown by the 24 \( \mu m \) MIPS image. This is not true, however, at 12 \( \mu m \), where we expect a significant contribution from the old stellar population; thus, the 12 \( \mu m \) \textit{IRAS} flux has not been included in the SED. We also excluded the \( IRAS \) 25 \( \mu m \) flux (0.22 Jy, from NED) because it is not compatible with the 24 \( \mu m \) MIPS flux; this is probably due to an incorrect background subtraction due to the poor resolution of \( IRAS \). Radio data were taken from Nagar et al. (2000), Wrobel & Heenschen (1991), Becker et al. (1991), Dressel & Condon (1978), and the Faint Images of the Radio Sky at Twenty cm (FIRST) Very Large Array (VLA) survey. The SED is completed with Galaxy Evolution Explorer (GALEX) UV fluxes extracted within a 5" aperture (Boselli & Cortese, private communication). The broadband fluxes are given in Table 2.

[^5]: Available at http://adlibitum.oats.inaf.it/silva/default.html or http://web.ompd.inaf.it/granato/grasil.html.
[^6]: The NASA/IPAC Infrared Science Archive is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
4.1. The Models

Since the broadband SED obtained in the previous section is produced by the star-forming circumnuclear disk and the old population, including also the stars seen in projection, we adopted a simple composite model for the fit: a starburst plus an old stellar population. The old stars are modeled as an unattenuated simple stellar population (SSP) with given age and metallicity. The SSPs are based on Padova stellar models and include the contribution from dusty circumstellar envelopes around asymptotic giant branch stars. This fact may be relevant because these old stars leave an excess around 10 μm (Bressan et al. 1998, 2001, 2006).

The starburst contribution was modeled with GRASIL, assuming different values for the age ($t_b$), metallicity, and star formation history. The latter was assumed as an exponentially decreasing star formation rate (SFR) parameterized by the e-folding time, $\tau_b$. We consider two phases for the ISM: the molecular clouds (MCs) that surround young star clusters, and the diffuse component. For the distribution of both the diffuse ISM and stars we adopted a disk geometry, with an inclination of 45° with respect to the line of sight (as suggested by observations, e.g., Coccato et al. 2006). The density of dust and stars is assumed to be exponential in both the radial and vertical directions, with different scales for dust and stars (Silva et al. 1998 for more details).

Among the GRASIL physical quantities that mostly affect the shape of the SED we recall (1) the total gas mass ($M_{\text{gas}}$), (2) the fraction of molecular mass to total gas mass ($M_{\text{mol}}/M_{\text{gas}}$), (3) the optical depth of molecular clouds at 1 μm ($\tau_{1}$), and (4) the escape timescale of newly born stars from their parent MCs ($t_{\text{esc}}$). The dust composition and optical properties are set to reproduce the extinction and emission properties observed in the diffuse ISM of our Galaxy. The gas-to-dust mass ratio ($M_{\text{gas}}/M_{\text{dust}}$) is set proportional to the metallicity ($Z$), with $M_{\text{gas}}/M_{\text{dust}} = 110$ for solar metallicity.

For the nebular lines we adopted the large H II region library computed by Panuzzo et al. (2003). Finally, the adopted initial mass function (IMF) is a Salpeter IMF (Salpeter 1955) in the mass range from 0.1 to 100 $M_\odot$.

4.2. Results of the SED Fit

We computed a large grid of simulated SED with GRASIL. In Table 3 we list the ranges of values used for the library. Among these models, we identified the best-fitting model as the one that maximizes a likelihood function. The likelihood function was built using UV, MIPS, IRAS, radio data, and their uncertainties, quoted in Table 2, and the intensities of the observed lines Hα, Hβ (from Ho et al. 1997), and [Ne ii] 12.8 μm. The best-fit model is shown in Figure 4, where the left panel shows the panchromatic fit from the UV-to-radio wavelengths, while the right panel is a zoom into the MIR spectral region. The corresponding parameters and some important derived quantities are displayed in Tables 4 and 5, respectively.

The wide-wavelength coverage of the SED imposes strong constraints on the model, because different spectral regions probe the age sequence of the stellar populations. Broadly speaking, nebular emission lines are dominated by massive stars, and radio

![Figure 4](image-url)
emission is contributed by stars younger than about 50 Myr, while the FIR SED includes also a significant contribution from intermediate-mass stars. The UV/FIR ratio implies that the burst luminosity is almost completely reprocessed by dust and emitted in the FIR; thus, the FIR luminosity fixes the bolometric luminosity. Intermediate-mass stars. The UV/FIR ratio implies that the burst emission is contributed by stars younger than about 50 Myr, timescale. AGN component, which adds further support for the lack of AGN activity in NGC 4435. In the following we discuss in more detail the results of the fit.

5. DISCUSSION

5.1. The Star Formation History and Starburst Luminosity

The old stellar component is well fitted by a solar metallicity SSP of 8 Gyr and a mass of $8.2 \times 10^8 M_\odot$. Note that the value here derived for the stellar mass depends on the adopted IMF. Coccato et al. (2006) give an estimate of the mass-to-light ratio ($M/L$) of the population that can be directly compared with our old stellar population. Using the $I$ band, they measured $M/L(1) = 2.2 M_\odot/L_\odot(1)$, while for our old stellar population it is $M/L(1) = 2.98 M_\odot/L_\odot(1)$. The discrepancy in the $M/L$ can be solved by changing the slope of the IMF at lower masses (as in the Kroupa IMF; Kroupa 1998) or adopting a higher lower mass limit (e.g., 0.2 $M_\odot$) without changing the predicted SEDs.

The nuclear disk is in a poststarburst phase ($\tau_b = 55$ Myr and $t_b = 186$ Myr) with a current star formation rate (SFR, = 0.089 $M_\odot$ yr$^{-1}$) about one order of magnitude smaller than the average star formation rate (SFR, = 0.75 $M_\odot$ yr$^{-1}$). The quality of the radio data, however, prevents a determination of $\tau_b$ better than $\pm 20\%$; this results in an uncertainty on the age of the starburst $t_b$ of the same order. The mass of gas converted into stars during a burst is $M_\odot = 1.40 \times 10^8 M_\odot$; however, with the adopted IMF, only $\sim 80\%$ still survive. The star forming component emits $32\%$ of the bolometric luminosity in the central 5$''$ of the galaxy while accounting for $1.4\%$ of the stellar mass. Most of the starburst luminosity is provided by A stars, reprocessed by the diffuse dust, and re-emitted in the 8–1000 $\mu$m spectral region ($L_\nu \approx 5.5 \times 10^{35}$ W).

A population of A stars in the central $\sim 550$ pc has already been detected by optical observations (Kenney et al. 1995). More recently, Sarzi et al. (2005) estimated that the contribution of the young burst from 3000 to 5700 A in the nuclear region (0.13$''$ radius) is around 12%. In the same spectral region we estimate that the fractional contribution of the starburst is only 6%. It is, however, difficult to compare the two estimates because our value refers to a much larger region (5$''$). Indeed, it is sufficient that in the very central region the attenuation be reduced (estimated by Sarzi et al. 2005) to eliminate this discrepancy without affecting significantly the constraints from the other spectral bands.

The strongly declining SFR makes this galaxy a typical case in which different SFR indicators, probing different timescales, provide estimates that are apparently discrepant. In fact, with the classical SFR estimation based on the IR luminosity provided by Kennicutt (1998) we get $SFR_{IR} = 0.25 M_\odot$ yr$^{-1}$, in between the average SFR and the current one. Using the 1.4 GHz flux with the Panuzzo et al. (2003) calibration we get $SFR_{1.4GHz} = 0.117 M_\odot$ yr$^{-1}$. This value is more similar to the current SFR value than the IR-based estimate because the radio emission is due to free-free emission from H II regions and synchrotron emission from core-collapse supernovae.

5.2. The Geometry and the Attenuation Law

Although the star formation history is well constrained by the fit of the total SED, a further refinement to the relative spatial distribution of stars and dust can be obtained by comparison of the predicted and observed H$\alpha$- and H$\beta$-line intensities. It has been shown in previous works that a system with an equal spatial distribution of stars and dust produces a much smaller reddening than a “screen” geometry (e.g., Witt & Gordon 2000). With the assumption of equal scales for stars and dust, and given the strong
attenuation implied by the observed UV/FIR ratio, the Hα intensity predicted by our best-fit model would be much smaller than the observed value \( I(\text{H}_\alpha) = 2.82 \times 10^{-17} \text{ W m}^{-2} \) (Ho et al. 1997) and the predicted gas mass about twice the quoted value \( 10^8 M_\odot \) (Vollmer et al. 2005). To solve this discrepancy we need to decrease the attenuation in the optical band, leaving unchanged that in the UV. Without modifying the optical properties of dust grains, this can be achieved by assuming a geometry in which the diffuse dust is more extended than the stellar distribution. This has the effect of increasing the reddening because it reddens the attenuation law, making it more similar to the extinction of a uniform slab. Adopting a radial (vertical) scale length of 160 (22) pc for the diffuse dust and of 70 (14) pc for the stellar component, the predicted intensities for Hα and Hβ are \( I(\text{H}_\alpha) = 2.70 \times 10^{-17} \text{ W m}^{-2} \) and \( I(\text{H}_\beta) = 4.99 \times 10^{-18} \text{ W m}^{-2} \), in good agreement with the observed value (4.99 \( \times 10^{-18} \) W m\(^{-2} \) for Hβ from Ho et al. 1997). The required dust mass is 1.23 \( \times 10^6 M_\odot \). For a solar metallicity, as predicted by other observables in the present case. In fact, from the SFR obtained from the fit of the SED, GRASIL also computes the ionizing flux, and thus the observed intensity of the main emission lines. This can be considered as an alternative method to obtaining the ionizing flux from a direct measurement of the hydrogen recombination lines. Adopting solar metallicity and standard ISM abundances, we obtain the predicted intensities \( I(\text{Pf}_\alpha) = 3.46 \times 10^{-18} \text{ W m}^{-2} \), \( I(\text{Ne ii}) = 7.01 \times 10^{-17} \text{ W m}^{-2} \), \( I(\text{Ar ii}) = 2.60 \times 10^{-17} \text{ W m}^{-2} \), \( I(\text{Ar ii}) = 3.17 \times 10^{-17} \text{ W m}^{-2} \) and \( I(\text{S ii}) = 1.71 \times 10^{-17} \text{ W m}^{-2} \). For the metallic lines, these figures are in good agreement with the observed values reported in Table 1, thus providing an independent confirmation that the gas metallicity is solar. The value found for Pfσ is much lower than that derived from the fit of the line, suggesting that the blend with PAH prevents an accurate measurement (see § 3.2.3).

5.4. PAHs and IRS Continuum

The left panel of Figure 4 shows a detailed comparison of the MIR Spitzer spectrum and the model. The continuum and PAH features up to 13 μm are well fitted by the starburst model. At wavelengths longward of 13 μm, while the predicted continuum matches fairly well that observed, the predicted PAH features are in disagreement with those observed, both in central wavelength and strength. Only the 16.4 μm feature is reproduced.

We recall that our model for PAH emission is based on the Li & Draine (2001) model, which predicts PAH features at 3.3, 6.2, 7.7, 8.6, 11.3, 11.9, 12.7, 16.4, 18.3, 21.2, and 23.1 μm. The model of PAH features at \( \lambda < 13 \) μm was based on ISO data for the diffuse galactic medium, while the FWHM and the cross sections for the features at \( \lambda > 13 \) μm were taken from the theoretical study of 40 families of PAHs driven by Moutou et al. (1996), because of the lack of corresponding observational data.

More recently, ISO extended the observed wavelength range, confirmed the feature at 16.4 μm, and also found new features at 14.2 and 17.4 μm, as well as a weak plateau between 15 and 20 μm (Moutou et al. 2000; Sturm et al. 2000; Van Kerckhoven et al. 2000). This plateau is attributed to a blend of many emission features provided by the interstellar PAH families present in the sources, and its variation can be accommodated by variations in the PAH populations (Peeters et al. 2004a). Lately, the higher sensitivity of Spitzer confirmed the existence of PAH features at 14.2, 16.4, and 14.7 μm, and a new and prominent feature at 17.1 μm, among other, weaker ones (e.g., Brandl et al. 2004; Smith et al. 2004; Werner et al. 2004). However, the lack of features at 18.3 μm, 21.2 μm, and 23.1 μm has been confirmed.

The disagreement between model and data was already noticed by Peeters et al. (2004b), Smith et al. (2004), and Dale et al. (2005), who, on the other hand, found very good agreement between the Li & Draine model and the data for \( \lambda < 13 \) μm. They attributed the disagreement at wavelengths longward of 13 μm to the large sensitivity of these features to the global structure of PAH molecules, since they involve the motion of the molecules as a whole and therefore are very dependent on the exact PAH species in the emitting source. Work is in progress to improve our PAHs emission model based on new Spitzer observations.

5.5. Total Aperture SED

We have also compared our models with the total aperture SED of the galaxy. The total aperture SED includes the U, B, V, J, H, and K bands from GOLDMINE,\(^8\) the LW2 (6.75 μm) and LW3 (15 μm) ISO bands from Boselli et al. (2003), the UV (2000 Å) from Deharveng et al. (2002), all IRS bands (with the exception of 25 μm), and the radio measurement described in § 4. These data are complemented by our IRAC flux measurements and GALEX data for the full aperture. The data are reported in Table 6.

\(^8\) Galaxy On Line Database Milano Network, http://goldmine.mib.infn.it.
The fit to the total aperture SED was done simply by changing the amount of the old stellar population and using the same starburst component that fits the central SED, as derived in the previous sections. The resulting total mass of the old stellar population is $M_{\text{tot}} = 4.66 \times 10^{10} M_{\odot}$. Moreover, the star forming component emits 8% of the total bolometric luminosity of the galaxy, while its stellar mass is only 0.3% of the total stellar mass of the galaxy. It is worth noting that the starburst in NGC 4438 (the late-type companion) accounted for a smaller fraction (about 0.1%) of its total stellar mass (Boselli et al. 2005).

The comparison between the observed full-aperture SED and the model is shown in Figure 6. The full aperture SED is well reproduced at all wavelengths. We stress that the old stellar component provides a significant contribution to $GALEX, ISO$ LW2 and LW3, and $IRAS$ 12 $\mu$m broadband fluxes.

### 5.6. X-Rays

As a final step in the SED analysis we briefly consider the X-ray emission of NGC 4435, observed with Chandra by Machacek et al. (2004). The X-ray spectrum was fitted with a thermal component in the soft (0.3–2 keV) band attributed to hot gas and a nonthermal component responsible for the 2–10 keV band emission. The hard component, with a luminosity of $L_{\text{X}} = 3.9 \times 10^{32}$ W, is mostly concentrated within 3 $''$ from the galaxy center. This emission was attributed to a possible low-luminosity AGN (as suggested by Ho et al. 1997) plus recent star formation activity.

The observed hard X-ray luminosity of NGC 4435 is about 5 times larger than that expected from the FIR luminosity and the X-ray–FIR correlation found for starburst galaxies (Ranalli et al. 2003). Moreover, adopting the calibration by Ranalli et al. (2003), the SFR implied by the observed hard X-ray luminosity turns out to be $SFR_{\text{X}} = 0.78 M_{\odot} \, \text{yr}^{-1}$, one order of magnitude higher than the current SFR derived from the fit to the global SED.

Although this seems to support the AGN nature of the hard emission component, we need to consider the peculiar star formation history of NGC 4435. In fact, due to the much higher SFR at the beginning of the burst, the average SFR is consistent with the X-ray estimate. For this reason we expect a significant contribution to the X-ray luminosity from intermediate-mass stars accreting onto neutron stars and/or black holes through Roche-lobe mass transfer. To check this possibility we have computed the X-ray emission expected from the star formation activity derived previously with the synthesis model of Silva et al. (2003). The resulting value is consistent with the observed hard X-ray luminosity of NGC 4435. Moreover, we notice that the X-ray luminosity is much less dependent on the age of the stellar population (the turnoff mass of the stars) than the FIR luminosity. This implies that in post starburst galaxies the X-ray–FIR luminosity ratio tends to be larger than that of pure starbursts, which are dominated by massive stars.

Another indication of the strength of the AGN comes from the comparison of the hard X-ray luminosity and $H_{\alpha}$ emission. Using the relation between $L_{\text{X}}$ and $L_{\text{H}\alpha}$ derived for AGNs (Ho et al. 2001), the expected $H_{\alpha}$ luminosity would be $L_{\text{H}\alpha}^{\text{AGN}} \sim 6.6 \times 10^{31}$ W. This value is about 15% of the observed $L_{\text{H}\alpha}$ corrected for extinction via the Balmer decrement. This contribution to the ionizing flux is higher than the limit derived from MIR nebular lines (§ 3.2.1). However, it must be considered a generous upper limit because, on the one hand, all the X-ray luminosity has been attributed to the AGN, and on the other, it is known that the Balmer decrement provides only a lower limit to the attenuation (e.g., Panuzzo et al. 2003). In fact, if we correct...
the observed L_{H\alpha} with the attenuation derived from our best fit model, we obtain an upper limit to the AGN contribution of ~5%, consistent with what is found from the [Ne iii]/[Ne ii] ratio.

5.7. NGC 4435 and the Phenomenology of the Galaxy-Galaxy Interaction

NGC 4435 is interacting with NGC 4438; in particular, simulations by Vollmer et al. (2005) suggest that NGC 4435 passed through the disk of NGC 4438 about 100 Myr ago at a radial distance of 5–10 kpc. With such an impact parameter the interaction of the ISM of the two galaxies is unavoidable.

The age of the starburst t_s derived from our fit is larger than the (dynamically estimated) time since the ISM-ISM collision (around 100 Myr), but it is consistent with the epoch of the onset of interaction. This suggests that the star formation was triggered by the interaction (as often seen in galaxy-galaxy simulations, e.g., Barnes 2004), possibly producing a relevant activity also before the ISM-ISM collision. We cannot, however, draw strong conclusions on the relative importance of the tidal interaction and ISM-ISM collision, because it is difficult to derive the detailed shape of the star formation history during the burst.

Another phenomenon that may be triggered by galaxy-galaxy interaction is AGN activity (see, e.g., Hopkins et al. 2006). However, the various lines of evidence shown in this work indicate a lack of current AGN activity.

The age of the circumnuclear starburst is several times larger than the typical duration of the AGN phase, and we cannot rule out the possibility that an AGN was once active in NGC 4435. However, the surrounding gas is predominantly in a cold phase, with only a fraction in a hot component (\sim 3 \times 10^7 M_\odot, Machacek et al. 2004), and it is supported by circular motion (Coccato et al. 2006), indicative of a relaxed ISM. We conclude that the feedback from the possible AGN was not strong enough to halt the star formation process, which is now fading as a result of the gas consumption.

Alternatively, the AGN activity has not been triggered yet (and perhaps will not be triggered at all). Coccato et al. (2006) provide a 3 \sigma upper mass limit of 7.5 \times 10^6 M_\odot for the possible central SMBH, an order of magnitude lower than the value obtained from the M_{BH} - \sigma and M_{BH} - L_{Bol} relations. In this case NGC 4435 could be a prototype of the so called “laggard” SMBHs, which are believed to undergo slow gas fueling of the galactic center and limited growth of the SMBH mass (Vittorini et al. 2005).

The above picture sketched for the evolution of NGC 4435 would suggest that the star formation activity could inhibit the AGN-feeding both by consuming the gas and by supernova feedback. Both cases point toward a relatively low efficiency of the AGN feedback with respect to that of the supernovae in intermediate- or small-mass galaxies like NGC 4435 (see, e.g., Granato et al. 2004).

6. CONCLUSIONS

We have performed a thorough spectrophotometric study of the early-type galaxy NGC 4435 using new Spitzer IRS spectra combined with IRAC and MIPS archival data and existing broadband measurements from X-ray-to-radio wavelengths. The IRS spectrum is dominated by PAH features, nebular emission lines, and molecular hydrogen rotational lines, which originate in the circumnuclear disk that characterizes this galaxy. The PAH features in the spectrum are very similar to those observed in other star forming galaxies. In particular, we report the detection of the PAH feature observed at 17.1 \mu m (Smith et al. 2004), which, due to the lower contamination by the H_2 S(1) rotational line, we show is actually a blend of two distinct components.

The panchromatic SED of the central 5\arcsec region was analyzed with the spectrophotometric code GRASIL. This SED is well reproduced from the UV to radio by a model of a fading starburst superimposed on a simple stellar population of 8 Gyr and solar metallicity. The analysis of IRM nebular lines, combined with that of the SED, allow a direct estimate of the gas metallicity, which also results as solar.

Although a low level-nuclear activity has been suspected in NGC 4435 from optical (Ho et al. 1997, 2002) and X-ray (Machacek et al. 2004) observations, we collect the following evidence for the lack of AGN excitation:

1. We have not detected high-excitation nebular emission lines in the MIR spectrum
2. The [Ne iii] \lambda 15.5/[Ne ii] \lambda 12.8 ratio constrains the contribution of a possible AGN to the ionizing flux to be less than 2%.
3. The upper limit on the temperature derived from H_2 S(1) and S(2) rotational lines is lower than expected for AGN excitation.
4. The X-ray emission is within the range expected from X-ray binaries from the starburst.

The age of the starburst, 186 \pm 37 Myr, corresponds to the epoch of the last encounter with NGC 4438 derived from dynamical simulations, suggesting that this interaction has triggered the observed star formation event (Combes et al. 1988). However, we cannot draw strong conclusions as to the relative importance of the tidal interaction and ISM-ISM collision, because of the difficulty in deriving the detailed shape of the star formation history during the burst.

The combination of Spitzer observations with the analysis of the complete SED allows an accurate determination of the mass and epoch of the rejuvenation episode. The mass of the starburst (\sim 1.4 \times 10^9 M_\odot) corresponds to about 1.4% of the stellar mass sampled by the central 5\arcsec aperture. The young component makes the optical spectrum of NGC 4435 closely similar to a typical interacting early-type galaxy with inverted Ca ii [H+K] lines (Longhetti et al. 1999; Sarzi et al. 2005) that will later turn into a typical cluster E+A galaxy. This study supports the notion that early-type galaxies with relatively strong hydrogen absorption features are due to recent small rejuvenation episodes rather than being the result of delayed galaxy formation (Bressan et al. 1996).

Finally, the total SED of NGC 4435 is fitted by simply adding to the starburst a larger fraction of the old stellar population. The starburst provides only 0.3% of the total stellar mass of the galaxy but 8% of the bolometric luminosity.

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