STAR FORMATION AND SELECTIVE DUST EXTINCTION IN LUMINOUS STARBURST GALAXIES

BIANCA M. POGGIANTI AND ALESSANDRO BRESSAN
Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy

AND

ALBERTO FRANCESCHINI
Dipartimento di Astronomia, vicolo dell'Osservatorio 5, 35122 Padova, Italy

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ABSTRACT

We investigate the star formation and dust extinction properties of very luminous infrared galaxies whose spectra display a strong H$\beta$ line in absorption and a moderate [O $\text{II}$] emission [e(a) spectrum]. This spectral combination has been suggested to be a useful method to identify dusty starburst galaxies at any redshift on the basis of optical data alone. We compare the average e(a) optical spectrum with synthetic spectra that include both the stellar and the nebular contribution, allowing dust extinction to affect differentially the stellar populations of different ages. We find that reproducing the e(a) spectrum requires the youngest stellar generations to be significantly more extinguished by dust than older stellar populations and implies a strong ongoing star formation activity at a level higher than in quiescent spirals. A model fitting the optical spectrum does not necessarily produce the observed FIR luminosity, and this can be explained by the existence of stellar populations which are practically obscured at optical wavelengths. Models in which dust and stars are uniformly mixed yield a reddening of the emerging emission lines which is too low compared to observations: additional foreground reddening is required.

Subject headings: dust, extinction È galaxies: evolution È galaxies: starburst È infrared: galaxies

1. INTRODUCTION

The effects of dust extinction are crucial for interpreting the spectra of nearby and distant galaxies, particularly after new facilities from the ground (e.g., SCUBA on the James Clerk Maxwell Telescope) and from space (Infrared Space Observatory [ISO]) have established that the IR emissivity of galaxies was much enhanced in the past with regard to what is typically observed in local galaxy populations (Elbaz et al. 1999; Barger et al. 2000; Franceschini et al. 2000; Ivison et al. 2000; Smail et al. 2000). Further evidence about the very important role played by dust reprocessing during the evolution of galaxies was provided by the detection of a diffuse far-IR background likely originating from distant and primeval galaxies, whose dominance over the optical background testifies to hidden star formation at unexpectedly high rates (Puget et al. 1996; Dwek et al. 1998).

Waiting for future spectroscopic capabilities in the far-IR, which will be offered by a variety of missions (SIRTF, FIRST, and NGST), only indirect clues about the relation between dust and stellar population emissions can be gained from optical spectra.

In the local universe, a large fraction of the FIR-luminous galaxies are characterized by a peculiar combination of spectral features in the optical: a strong H$\beta$ line in absorption (EW $> 4$ Å) and a moderate [O $\text{II}$] emission (EW $< 40$ Å) (Poggianti & Wu 2000, hereafter PW00). Galaxies with this type of spectra were named “e(a)” galaxies$^1$ and were found to be quite numerous in the cluster and field environments at $z = 0.4$–0.5 (Dressler et al. 1999; Poggianti et al. 1999, hereafter P99). The equivalent width of their H$\beta$ line exceeds that of typical, quiescent spirals at low $z$, and their low [O $\text{II}$/H$\beta$] ratios are consistent with the emission-line fluxes being highly extincted by dust (P99; PW00).

Interestingly, the combination of moderate emission lines and strong early Balmer lines in absorption has been subsequently found also in the first spectroscopic surveys of the high-redshift galaxy populations detected by ISO (Aussel 1999; Flores et al. 1999). The association between the e(a) signature and the FIR-luminous galaxies seems to be confirmed at any redshift and suggests that the e(a) spectra—despite their moderate emission lines—actually belong to highly obscured, starburst galaxies. One of the most important pieces of information that is still missing is the physical origin of this type of spectra: what star formation and dust properties produce this peculiar spectral combination? P99 and PW00 proposed that the e(a) spectrum originates from “selective extinction” in a galaxy where the youngest stars in the H II regions are much more dust embedded than the older stellar populations, which are more widely distributed throughout the galaxy. Such an age-dependent obscuration would cause the emission lines to be highly extincted (hence producing the low blue-to-red emission-line ratios observed) and would allow the older, A-type stars to dominate the integrated spectrum at $\lambda \approx 4000$ Å (thus explaining the strong H$\beta$ line in absorption).

The existence of a selective extinction in galaxies is well known, but it is usually ignored when dealing with the global effects of dust on the spectral energy distribution of galaxies. Stars are expected to spend the very beginning of their evolution deeply embedded in dusty environments, later drifting away from or dispersing the molecular clouds where they were born (Calzetti et al. 1994 and references

\footnotesize{$^1$ We stress that these are not the so-called E + A (or k + a) spectra, which by definition have no detectable emission lines (Dressler & Gunn 1983), at least at the level of the [O $\text{II}$] detection limit of the spectroscopic surveys of distant galaxies (typically 3 Å). Nevertheless, it is possible that some of the k + a spectra are e(a) galaxies with an extremely low [O $\text{II}$] (P99; Smail et al. 1999).}
As discussed in PW00, an age-dependent dust obscuration could explain the numerous observational studies which measure discrepant extinction values when using different spectral ranges/features (Israel & Kennicutt 1980; Viallefond et al. 1982; Caplan & Deharveng 1986; Fanelli et al. 1988; Bohlin et al. 1990; Keel 1993; Calzetti et al. 1994; Veilleux et al. 1995; Lancon et al. 1996; Mayya & Prabhu 1996; Calzetti 1997, 1998; Mas-Hesse & Kunth 1999). Moreover, Zaritsky (1999) found a clear trend of decreasing mean extinction with declining stellar effective temperature (i.e., stellar age) in the Large Magellanic Cloud.

So far, no attempt has been made to model the whole e(a) spectrum in a quantitative way. The aim of this work is to test whether the average e(a) spectrum can be modeled as a current starburst assuming a selective dust extinction that increases as the age of the stellar population decreases. In the following we employ a spectrophotometric model that includes both the stellar component and the thermal emission of the gas ionized by young stars. Such a model will be considered successful only if it is able to reproduce simultaneously the shape of the optical observed continuum (3600–6900 Å) and the strength of the most important emission/absorption lines: \([\text{O} \ II]\) λ3727, H\(\delta\) at \(\lambda = 4101\) Å, H\(\beta\) at 4862 Å, and Hz at 6563 Å.

The plan of the paper is as follows: in § 2 we present the spectroscopic catalog and the average observed e(a) spectrum and in § 3 we describe the ingredients and the structure of our model. The results are discussed in § 4, where we examine starburst models with selective extinction (§ 4.1), post-starburst models (§ 4.2), and models with constant extinction (§ 4.3). Our main conclusions are summarized in § 5.

2. OBSERVATIONS

The observed e(a) spectra are taken from the complete spectroscopic catalog of very luminous infrared galaxies [VLIRGs; \(\log (L_{\text{IR}}/L_\odot) \geq 11.5\)] presented in Wu et al. (1998a, hereafter W98a; 1998b). Among these, we selected those 19 galaxies with a secure e(a) spectrum and a spectral coverage extending below the \([\text{O} \ II]\) line and beyond the Hz line. These are nuclear spectra covering at least the central 2 kpc of the galaxy (see also § 4). None of these galaxies is an active galactic nucleus (AGN) (either Seyfert 1 or Seyfert 2) according to the emission-line ratios (PW00). The average e(a) spectrum is shown in Figure 1 and the equivalent widths of the main lines are listed in Table 3.

As mentioned in § 1, moderate emission lines and strong early Balmer lines in absorption have been found also in the spectra of the high-redshift IR populations. In fact, the average spectrum of the distant starburst galaxies detected at 15 μm by ISO in one of the fields of the Canada-France Redshift Survey (Flores et al. 1999) turns out to be very similar to the average e(a) spectrum. The comparison is presented in Figure 1 and shows that—the within the wavelength range in common (≈3700–5100 Å)—both the continuum shape and the strength of the \([\text{O} \ II]\), H\(\delta\), and H\(\beta\) lines are alike.

3. MODELS

Instead of employing a highly complex tool (i.e., a complete spectrophotometric model), we preferred to develop and use a “simplified model.” This model retains all the basic physical ingredients required by the complexity of an integrated spectrum but includes only those stellar populations that are a priori essential because they are known to affect the spectral features that we wish to reproduce.

The integrated model spectrum has been generated as a combination of 10 stellar populations of different ages, listed in Table 1. Each stellar generation is born with a Salpeter initial mass function (IMF) between 0.1 and 100

Fig. 1.—Rest-frame comparison of the average e(a) spectrum of local very luminous infrared galaxies (thick line) and the spectrum of the ISO starburst galaxies at \(z \sim 0.5\) (thin line). The latter is taken from Fig. 12 in Flores et al. (1999) and is the average spectrum of five ISO-detected galaxies at \(z < 0.7\) whose spectral energy distributions at visible, near-IR, mid-IR, and radio wavelengths resemble those of highly reddened starbursts in the local universe (Schmitt et al. 1997); it has been normalized to the VLIRGs spectrum over the wavelength range in common. The spectral resolution is 10 Å (Wu) and 40 Å (Flores et al. 1999).
The ages of the 10 populations have been chosen considering the evolutionary timescales associated with the observational constraints: the youngest generations (10^6, 3 \times 10^7, 8 \times 10^8, 10^9 yr) are responsible for the ionizing photons that produce the emission lines, the intermediate populations (5 \times 10^7, 10^8, 3 \times 10^8, 5 \times 10^8, 10^9 yr) are those with the strongest Balmer lines in absorption, while older generations of stars (named "old" in Table 1) have been modeled as a constant star formation rate (SFR) between 1 and 12 Gyr before the moment of the observation and can give a significant contribution to the spectral continuum, hence affecting also the equivalent widths of the lines. This approach allows us to (a) reduce the number of parameters to a minimum: a complete spectrophotometric model finds the integrated spectrum summing over typically 50 single stellar populations of various ages, instead of 10; (b) explore also bursting, discontinuous star formation histories which more likely resemble the irregular histories of "real" starburst galaxies; adopting as star formation history an analytic function, plus a single or multiple burst would force us to restrict the parameter space investigated according to some a priori assumptions; (c) easily implement different extinctions for stellar populations of different ages, interpreting the results in a straightforward manner.

The composite (stars + gas) spectrum of each single generation has been produced with the spectrophotometric code of Barbaro & Poggianti (1997, hereafter BP97) that includes both the stellar component and the thermal emission of the ionized gas. This model is fully described in BP97; here we only summarize its salient characteristics. Between 3500 and 7500 Å, the stellar model is based on the stellar spectral library of Jacoby et al. (1984), which has enough resolution to study absorption features, such as the stellar lines of the Balmer series in absorption. The ionizing flux of the young stellar populations is computed using stellar atmosphere models (R. Kurucz 1993, private communication); from this, the luminosities of the nebular hydrogen lines (Balmer series) are derived assuming case B recombination (Osterbrock 1989) while the strength of other lines—such as [O II] \( \lambda 3727 \)—is calculated using H II region models (Stasinska 1990). When nonnegligible (for ages less than a few 10^7 yr), the nebular contribution (lines + nebular continuum) is added to the stellar component to give the total spectrum. For this project, both the stellar and the nebular components were found assuming solar metallicity. The model spectra were broadened with a Gaussian degrading the original model resolution (\( \sim 4 \) Å) in such a way to match the resolution of the observed spectra (\( \sim 10 \) Å).

Each single generation (SG) is assumed to be extincted by dust in a uniform screen according to the standard extinction law of the diffuse medium in our Galaxy \( E(B-V) = A_V / A_B = 3.1 \); Cardelli et al. 1989) unless otherwise stated (see § 4). The extinction value \( E(B-V) \) is allowed to vary from one stellar population to another, and the extincted spectral energy distributions of all the single generations are added up to give the total integrated spectrum.

Within a chosen star formation scenario (see § 4), the best-fit model was obtained by minimizing the differences between selected features in the observed and model spectra. A merit function was constructed considering \( N = 12 \) features: the equivalent width of four lines ([O II] \( \lambda 3727, H\delta, H\beta, \) and H\alpha) and the relative intensities of the continuum flux in eight almost featureless spectral windows (3770–3900 Å, 4020–4070 Å, 4150–4250 Å, 4600–4800 Å, 5060–5150 Å, 5400–5850 Å, 5950–6250 Å, and 6370–6460 Å):

\[
(MF)^2 = \sum_{i=1}^{N} W_i^2 \left( \frac{O_i - M_i}{E_i + E_0} \right)^2 ,
\]

where the quantities \( M_i, O_i, E_i, E_0, \) and \( W_i \) refer to the value predicted by the model, the observed value, the accuracy, the minimum error, and the weight assigned to the \( i \) feature, respectively. An accuracy of 1% and 10% was adopted for the flux in the continuum bands and for the equivalent widths, respectively. These are comparable to the observational uncertainties if we consider that the error on the relative flux calibration amounts to a few percent, the typical error in the measured equivalent widths is between 10% and 20%, and we are dealing with an average spectrum.\(^4\)

\(^3\) The EW(H\alpha) is always greater than 4 Å in the spectra of these intermediate populations.

\(^4\) In addition, we checked that assuming a lower accuracy (4% and 20% in the continuum and in the equivalent widths, respectively) does not modify our main conclusions.
All quantities were given a unit weight, but for the 3770–3900 Å continuum and for the [O II] λ3727 line, to which a lower weight was assigned (0.4 and 0.5, respectively). This choice is due to the enhanced flux calibration uncertainty of Jacoby’s spectra below 4000 Å and to the fact that, unlike the Balmer emission lines, the intensity of the [O II] λ3727 line is not related in a simple way to the star formation rate. In fact, the [O II] line is sensitive to several other factors such as the hardness of the ionizing spectrum and the local conditions in the nebula, the density, and the metallicity of the gas. We find that fitting the observed [O II] strength requires a line intensity higher than the one predicted by models of solar metallicity, unless the presence of hot Wolf-Rayet stars is included. At ages between 3 and 5 Myr these stars may enhance the ratio [O II] λ3727/Hβ by a factor of about 3 (Garcia Vargas et al. 1995), hence we chose to take this factor into account increasing the [O II] flux of the 3 Myr old single generation.

The merit function was minimized with the method of the simulated annealing (routine AMEBSA in Numerical Recipes), which is particularly suited to avoid the rapid convergence to a local minimum. The free parameters (the relative intensity of the SGs and the extinction values) were let to vary within specified ranges defined by the kind of evolutionary scenario considered.

In principle, the observed FIR/optical luminosity ratio could be treated as a further constraint of the model, hence, in order to predict the FIR emission, we computed a new set of single stellar populations by extending the Jacoby stellar spectra below 3510 Å and above 7400 Å using R. Kurucz (1993, private communication) stellar atmosphere models, with a procedure similar to that adopted by Longhetti et al. (1999). Once the parameters of a best-fit model were determined, the FIR luminosity was evaluated as the difference between the total unextinguished spectrum and the final (extinguished) spectrum.

4. RESULTS

In this section we show the results of some selected models whose best-fit parameters are listed in Tables 1 and 2. For each model, the left column (SF) gives the star formation rate (mass per year, after having normalized to 1 yr$^{-1}$ in the old population) and the right column gives the color excess $E(B-V)$. The visual comparison of these models with the average $a(\alpha)$ spectrum is shown in Figures 2, 3, and 4 while Table 3 presents the equivalent widths of the four lines considered, the FIR/optical luminosity ratio, and the current star formation rate of each model.

Different evolutionary scenarios have been examined in order to address the following questions:

1. Can the starburst, selective extinction scenario explain the $a(\alpha)$ spectra?
2. What constraints can be placed on the burst duration and strength?

5 We note that a metallicity below solar produces a stronger [O II] line than the solar case but causes also an enhancement of the [O II] λ25007 line which instead is quite weak in the $a(\alpha)$ spectrum.

6 The FIR luminosities given by W98a are computed from the IRAS 60 and 100 μm fluxes as $F_\nu = 1.75(2.55S_{60} + 1.01S_{100})10^{-14}$ W m$^{-2}$ and are approximately total FIR luminosities in the range 1–1000 μm.

3. Can the post-starburst scenario explain the $a(\alpha)$ spectra?
4. Can the $a(\alpha)$ spectrum be fitted by models with a constant value of extinction?

4.1. Can the Starburst Selective-Extinction Scenario Explain the $a(\alpha)$ Spectra?

At first we consider models in which the star formation rate is roughly constant (within a factor $\sim$ 1.5) during the current starburst and much lower before that (models A and B in Table 1 and Fig. 2). The extinction varies with the age of the population, being significantly higher at younger ages.

Model A is an example of a starburst that began $2 \times 10^8$ yr ago. The quality of the fit can be assessed from the difference between the model and the observed spectrum in Figure 2: both the line strengths and the highly reddened continuum are well reproduced, except for the continuum level around 5000 Å where the discrepancy is only at the 4% level. This problem is common to all the models, regardless of the chosen set of parameters (Figs. 2, 3, and 4).

Model A can only account for about $\frac{1}{3}$ of the observed average FIR luminosity ($L_{\text{FIR}}/L_\nu = 28.9$ instead of 88.0). There can be several reasons for this disagreement: first of all, it should be kept in mind that the observed spectra refer only to the central region of the galaxy as it appears in the optical. However, also the IR emissivity is usually concentrated in the central regions of luminous infrared galaxies (see, e.g., Soifer et al. 2000; Kennicutt 1998 and references therein), therefore aperture effects are not likely to be responsible for the remaining $\frac{2}{3}$ of FIR emission.

Moreover, there might be star-forming regions that are completely obscured at optical wavelengths. This is known to be a common situation in luminous infrared galaxies and a spectacular example is the image of the Antennae galaxies (Mirabel et al. 1998). The most intense starburst in this merging system takes place in a region that is inconspicuous at optical wavelengths and coincides neither with any optically bright region nor with the dark lanes observed in the optical image. Such a starburst would give no contribution to our modeled spectrum, while accounting for a significant fraction of the FIR luminosity; therefore, our estimate of the current star formation rate relative to the old stellar generations would be correspondingly underestimated.

Model B is an example that describes a starburst with a high-FIR/V ratio as a result of some practically obscured regions. In the merging model A, the starburst began $2 \times 10^8$ yr ago, but both the SFR during the burst and the extinction of the two youngest stellar generations are higher than in A. The fit of the observed spectrum is again remarkable, with a small difference in Hz being well within the $1 \sigma$ error (Fig. 2). Thus, model B can simultaneously account for the optical properties and the FIR luminosity.

7 In a typical FIR galaxy, about $\frac{1}{3}$ of the observed Hα luminosity come from regions more than 1 kpc from the nucleus (Armus et al. 1990). Nevertheless, considering that the color excess measured from the Balmer decrement strongly decreases with radius (Veilleux et al. 1995; Kim et al. 1998) and that the primary mechanism for ionizing the emission-line gas outside of the nucleus could be shock excitation from outflowing winds instead of heating by young stars (Armus et al. 1989), the majority of the intrinsic Hα luminosity (after correcting for extinction) related to star formation should arise from the central regions.
For a standard Salpeter IMF in the range 0.1–100 $M_\odot$, in model B about 60% of the total mass in stars is formed during the burst. Assuming a top-heavy IMF during this phase would substantially reduce the mass fraction in young stars: for example, with a Salpeter IMF lower mass limit = 1 $M_\odot$, the starburst in model B forms about 40% of the total stellar mass.\(^8\)

Within the starburst scenario with selective extinction, we find an excellent agreement between the model and the observed spectrum as far as both the continuum shape and the strength of the lines are concerned. A model that fits the optical spectrum does not necessarily reproduce the observed FIR/optical ratio, but the modeled and observed ratios can be reconciled taking into account young stellar populations mostly obscured by dust at optical wavelengths.

4.1.1. Nonstandard Assumptions Regarding the Dust: Extinction Law and Relative Distribution of Dust and Stars

The models described so far have been computed assuming a standard Galactic extinction law and a dust screen around each stellar generation. It is interesting to investigate whether a satisfactory fit can be found under other assumptions regarding the dust properties.

In model C we consider a $2 \times 10^8$ yr starburst and an extinction law with $R_V = A_V/E(B-V) = 5$ as observed toward some dense clouds in our Galaxy (Mathis 1990). The fit to the e(a) spectrum is still acceptable, but the fit of the continuum around the H\(\alpha\) line worsens, and there is a small difference in the H\(\alpha\) emission at the $\sim 1 \sigma$ level (Fig. 2).

### TABLE 2

| Model   | PSB1 ($R_V = 3.1$) | PSB2 ($R_V = 3.1$) | CE1 ($R_V = 3.1$) | CE2 ($R_V = 3.1$) |
|---------|-------------------|-------------------|-------------------|-------------------|
| AGE (yr) | SF | $E(B-V)$ | SF | $E(B-V)$ | SF | $E(B-V)$ | SF | $E(B-V)$ |
| $10^8$ | 0.6 | 1.02 | 0.6 | 0.79 | 0.05 | 0.56 | 8.3 | 0.56 |
| $3 \times 10^8$ | 0.6 | 0.81 | 0.1 | 0.46 | 0.2 | 0.56 | 8.3 | 0.56 |
| $8 \times 10^8$ | 0.2 | 1.18 | 0.1 | 0.10 | 4.5 | 0.56 | 8.6 | 0.56 |
| $10^9$ | 0.1 | 0.32 | 0.8 | 0.70 | 4.4 | 0.56 | 8.3 | 0.56 |
| $5 \times 10^9$ | 5.7 | 0.65 | 5.8 | 0.68 | 13.6 | 0.56 | 13.1 | 0.56 |
| $10^9$ | 4.7 | 0.72 | 5.8 | 0.68 | 1.4 | 0.56 | 0.1 | 0.56 |
| $3 \times 10^9$ | 2.6 | 0.21 | 1.6 | 0.16 | 11.5 | 0.56 | 22.2 | 0.56 |
| $5 \times 10^9$ | 2.5 | 1.22 | 1.7 | 0.64 | 3.8 | 0.56 | 22.3 | 0.56 |
| Old | 2.3 | 0.59 | 2.1 | 0.99 | 0.1 | 0.56 | 18.9 | 0.56 |

\(^8\) The spectral energy distribution of a young (e.g., $\leq 2 \times 10^8$ yr) stellar generation with an IMF between 0.1 and 100 $M_\odot$ is identical to that of a population with an IMF truncated at low masses (e.g., $m_{\text{min}} = 1 M_\odot$) because the contribution of stars with $M < 1 M_\odot$ is negligible at these ages. Hence, a model with a standard IMF (any of those presented in this paper) gives the same results of a model with a truncated IMF during the burst with the same set of $E(B-V)$ values and the same star formation rate in stars more massive than 1 $M_\odot$; the only difference between these two models will be the total star formation rate during the starburst, with the truncated model missing stars below 1 $M_\odot$.

### TABLE 3

| Description | $W(\text{H}z + \text{N} ii)$ | $W(\text{H}\beta)$ | $W(\text{H}\alpha)$ | $W([\text{O} \ ii])$ | $L_{\text{FIR}}/L_V$ | SFR | W(H\(\alpha\)) |
|-------------|-----------------|---------------|-----------------|-----------------|------|------|--------------|
| Starburst Models | | | | | | | |
| Model A | -65.05 | 0.72 | 5.52 | -11.40 | 28.9 | 38 | 2 $\times 10^8$ yr burst |
| Model B | -61.26 | 0.30 | 5.65 | -11.69 | 85.0 | 102 | 2 $\times 10^8$ yr burst, high FIR/5500 |
| Model C | -56.97 | 0.72 | 5.13 | -12.71 | 93.7 | 117 | Different extinction law |
| Model D | -59.46 | 0.43 | 5.33 | -12.23 | 62.8 | 126 | 10$^7$ yr burst |
| Model E | -59.03 | 0.55 | 5.72 | -12.24 | 8.3 | 9 | $\sim$ Constant SFR |
| Post-Starburst Models | | | | | | | |
| Model PSB1 | -46.50 | 0.71 | 5.81 | -12.36 | 10.1 | 4 | Post-SB 1 |
| Model PSB2 | -56.68 | -2.06 | 5.25 | -13.05 | 9.5 | 4 | Post-SB 2 |

| Models with Constant Extinction | | | |
| Model CE1 | -37.64 | -0.44 | 4.94 | -15.49 | 9.7 | 0.2 | Constant extinction, free SF |
| Model CE2 | -379.54 | -64.47 | -6.97 | -152.86 | 12.3 | 13 | Constant extinction, SB model |

* All equivalent widths are in 
\(\AA\), negative in emission and positive in absorption. The model $W(\text{H}z + \text{N} ii)$ was found adopting $\text{N} ii$ = 0.2 Hz, which is the mean value observed by Tresse et al. 1999 for this Hz strength.

$^{b}$ $L_{\text{FIR}}/L_V = L_{\text{FIR}}/(5500 \times L_{5500})$, where $L_{\text{FIR}}$ (ergs s$^{-1}$) is the total FIR luminosity and $L_{5500}$ (ergs s$^{-1}$ \(\AA^{-1}\)) is the luminosity at 5500 \(\AA\) as derived from the spectrum.

$^c$ Current star formation rate in $M_\odot$ yr$^{-1}$ derived from the model fitting the observed luminosity at 5500 \(\AA\) assuming a Salpeter IMF ($x = 2.35$, 0.1–100 $M_\odot$).

$^{d}$ Errors quoted are standard deviations of the bootstrap median value within the sample of 19 galaxies.
In this case the observed FIR/optical ratio is fully reproduced even with $E(B-V)$ values generally lower than in B because, for a given $E(B-V)$, the optical flux is much more extinguished.

Finally, we modified the assumptions regarding the relative distribution of dust and stars: instead of adopting a dust screen, we examined the case of internal dust, in which dust grains and stellar populations are uniformly mixed, for a standard extinction law ($R_V = 3.1$). In this case, the relation between the observed intensity $I_j$ and the intrinsic intensity $I_j^0$ is the following: $I_j = I_j^0(1 - e^{-\tau_j(\lambda)})/\tau_j(\lambda)$, where $\tau_j(\lambda)$ is computed according to Calzetti et al. (1994).

Interestingly, it was impossible to find a good fit to the observed spectrum. This is due to the fact that in the internal dust models increasing the obscuration (i.e., the intrinsic optical depth) does not yield a corresponding increase in the reddening of the spectrum: the latter saturates to an asymptote, and the asymptotic reddening value [$E(B-V) \sim 0.18$]...
is too low to be able to account for the observed emission line ratios \([E(B-V) \sim 1.1]\) from the observed Balmer decrement; W98a). This saturation of the mixed case was noted by Calzetti et al. (1994, § 5.3) and our asymptotic value of \(E(B-V)\) is in agreement with their asymptotic value of the measured Balmer optical depth (\(\tau_B = 0.24\)). This result can be easily understood considering that the most heavily reddened stars are those most heavily obscured, hence they cannot provide the dominant contribution to the emerging light, which instead must come from the outermost layers (Witt et al. 1992; Calzetti 1998): in the internal dust model this effect gives rise to a natural limit to the reddening. While the existence of regions where dust and stars are mixed can remove the contribution to the optical spectrum of entire stellar populations (those most deeply embedded), these regions do not appear to determine the characteristics of the emerging spectrum, which requires a higher reddening at least partly because of foreground dust.

Fig. 3.—Results of the post-starburst models listed in Table 2. Symbols as in Fig. 2. In the lower panel, the 1σ error bar in Hβ is shown on the left side.

Fig. 4.—Results of the models with constant extinction listed in Table 2. Symbols as in Fig. 2.
4.1.2. Burst Duration and Strength

How long (short) can the burst be? It is interesting to investigate whether an e(a) spectrum (in particular, its H$\alpha$ strength) requires a quite long starburst involving intermediate-age populations ($10^8$–$10^9$ yr). Contrary to the most intuitive expectations, this is not the case. As an example of this, we present the good fit obtained for a starburst that began only $\sim 10^6$ yr ago (model D). In this case the strong H$\alpha$ line is not produced by the stars born in the starburst event but by the previous stellar generations. We find that starbursts as short as a few times $10^6$ yr and as long as $10^9$ yr are able to produce the e(a) spectrum as long as (a) the youngest populations ($\leq$ a few $10^6$ yr) must be highly extincted and (b) there must be a contribution of the “old” population, but this should not overwhelm the intermediate-age contribution at $\sim 4000$ Å.

Model D has a FIR/V = 62.8, therefore accounts for more than $\frac{1}{4}$ of the observed FIR luminosity, but as for longer starbursts (models A and B), a good fit to the optical spectrum can be obtained with short starburst models spanning a wide range in FIR/V ratio, simply modifying the amount of “hidden star formation.”

As an extreme example of what we have just shown and to further illustrate the degeneracy in the physical solutions allowed by optical data, we consider a galaxy with a practically constant SFR during its whole evolution (model E), and we show that this can still fit the e(a) spectrum reasonably well—with a slight mismatch in H$\alpha$ and in the continuum around it (Fig. 2)—if we adopt high extinction values for the young populations and a quite strong extinction of the old population [$E(B-V) = 0.5$]. It is worth stressing that the E model does not represent a “spiral-like” star formation history, because in all but the latest spiral types the SFR at recent times is known to be lower than the mean SFR during the previous evolution (Kennicutt 1998). We also tried to fit the e(a) spectrum assuming a spiral-like history in which the SFR of the old population is at least twice as much the maximum SFR allowed in the old population. This model cannot fit the observed spectrum unless we allow the extinction of the “old” population to be unphysically high, higher than that of the intermediate-age populations and much higher than the average observed even in the H II regions of nearby spiral galaxies [about 1 mag at H$\alpha$, corresponding to $E(B-V) \sim 0.4$].

Although model E is able to reproduce the optical spectrum, its FIR/V is a factor of 10 lower than what is observed, and in this case (i.e., for an approximately constant star formation) no young obscured population can be invoked to explain the missing FIR flux: any additional current star formation would qualify such a model as a starburst.

4.2. The Post-Starburst Hypothesis

Here we consider another family of models, in which the galaxy is seen after a strong starburst during the post-starburst phase (Table 2 and Fig. 3). As discussed in P99, the two spectral features that define an e(a) spectrum (a strong H$\alpha$ line and a moderate [O II]) can be reproduced by dust-free models of a post-starburst galaxy with some residual star formation, but on the basis of the FIR properties of the e(a) galaxies and of their unusually low [O II]/H$\alpha$ ratios, the same authors concluded that e(a) spectra more likely belong to starburst galaxies that are highly extincted by dust.\(^9\) Here we contemplate post-starburst models with a small residual star formation activity and including extinction by dust. This family of models shows a tendency either to underestimate the H$\alpha$ strength or to overestimate H$\beta$ (see models PSB1 and PSB2 in Figure 3 and in Table 3): the emission in at least one of these two lines is more than 1 $\sigma$ away from the observed value. The reason for this is that the observed H$\alpha$/H$\beta$ ratio requires a high extinction of the lines [the extinction measured from this line ratio is $E(B-V) \sim 1.1$], but such a high extinction in a post-starburst galaxy would produce too weak emission lines, i.e., there is not enough current star formation to give the observed strength. Although the discrepancy between the model and the observed H$\alpha$/H$\beta$ strength in model PSB2 is not dramatic on an absolute scale (still less than 3 Å), the post-starburst interpretation is not favored even on the basis of the optical data alone (without taking into account the strong FIR emission) if the whole spectrum including the H$\alpha$ line is examined. In addition, the FIR luminosity produced by these models is just a small fraction of the observed value and, similarly to model E, within the post-starburst scenario no young obscured population can be invoked to explain this discrepancy.

4.3. A Reference Case: Models with Constant Extinction

So far we have only considered models in which the $E(B-V)$ is allowed to vary from one stellar population to another. In this section we contemplate more “canonical” models which have a common value of extinction for all the stellar generations, showing that these fail to reproduce the e(a) spectrum.

Having imposed the extinction to be the same for all the 10 populations and to be within the range 0 < $E(B-V)$ < 3 mag, the model was let free to find a fit without imposing any constraint on the star formation rate of the various generations. The “best-fit” model obtained in this way (CE1) is shown in the top panel of Figure 4 and in Tables 2 and 3: while the shape of the continuum can be fitted with an $E(B-V) = 0.56$, this extinction cannot reproduce the equivalent widths of the emission lines and the model H$\alpha$ line is too weak compared to the one observed.

For comparison, we also present a starburst model with a constant extinction (model CE2, lower panel of Figure 4, Tables 2 and 3): having imposed a current burst,\(^10\) the best-fit model can reproduce the continuum with the same extinction as model CE1, but presents far too strong emission lines. In conclusion, while a fit to the continuum can be found with an $E(B-V)$ at most $\sim 0.6$ (as shown by these models with constant extinction), the line ratios necessitate a color excess greater than 1, as proved by the observed Balmer decrement. Selective extinction is required to reproduce simultaneously the strength of the lines and the shape of the continuum of e(a) spectra.

5. CONCLUSIONS

Spectra with a strong H$\alpha$ line in absorption and a moderate [O II] line in emission—named e(a) spectra—are numer-

\(^9\) The post-starburst interpretation has been mentioned by Flores et al. (1999) (see § 2), who consider their data to be consistent with the last phases of a burst following strong star formation episodes, where the mid-IR emission is still high because of dust heating by intermediate-mass stars ($M = 1–3 M_\odot$).

\(^10\) This was done imposing that the SFR during the last $10^7$ yr was at least twice as much the maximum SFR allowed in the old population.
ous among luminous infrared galaxies. We have shown that the optical e(a) spectrum can be well reproduced by a spectrophotometric model that includes both the stellar component and the emission lines and continuum of the ionized gas, assuming dust extinction to vary with the age of the stellar population.

The main conclusions of this work can be summarized as follows:

1. On the basis of our models, two conditions are necessary to explain the e(a) spectra:

   i) The youngest stellar generations (age \( \leq 10^7 \) yr) in e(a) galaxies must be highly obscured by dust. Their extinction values are significantly higher than those applying to the previous stellar populations. Models with a constant value of extinction are unsuccessful in fitting the optical spectrum.

   ii) These galaxies must host strong ongoing star formation at a level higher than in quiescent spirals. Post-starburst models with a small residual star formation fail to explain simultaneously the strength of the Hz and of the H\( \beta \) lines.

2. The degeneracy of the optical spectrum hinders a quantitative estimate of the burst duration and intensity. The spectrum is consistent with, but does not require, a "long" starburst that began \( 10^8 - 10^9 \) yr ago.

3. A model fitting the e(a) spectrum does not necessarily produce the FIR/optical ratio observed: the optical spectrum (including the observed Hz luminosity and H\( \beta \)/H\( \beta \) ratio) does not constrain the current star formation rate. The observed FIR/V can be explained by starburst models if a significant fraction of the FIR luminosity originates in regions that are practically obscured at optical wavelengths.

4. All the results listed above refer to the case of a dust screen placed in front of each stellar generation. Models in which dust and stars are uniformly mixed fail to fit the e(a) spectrum, producing too low a reddening of the emerging emission lines. The observed reddening seems to be at least partly because of foreground dust.

5. The extinction correction factor at Hz found from the Balmer decrement in the e(a) very luminous infrared galaxies of our sample [\( E(Hz) \approx 15 \), corresponding to a median \( E(B-V) = 1.1 \); W98a] is in agreement with that derived with the same method in other FIR luminous samples (Kim et al. 1998; Veilleux et al. 1995; median \( E(B-V) \) for non-AGN galaxies = 1.13 and 1.05, respectively). This factor is about 6 times higher than the average \( E(Hz) = 2.5 \) in nearby spirals (Kennicutt 1992). Ignoring the fact that the slit might have missed a fraction of the Hz luminosity and applying the extinction correction to derive the total current star formation rate from the relation SFR(M\( \odot \) yr\(^{-1}\) = \( 0.8 \times 10^{-41} E(Hz) \times L(Hz) \) erg s\(^{-1}\) (Kennicutt 1992),\(^{11} \) yields a value of the SFR that is still underestimated by a factor \( \sim 3 \) compared to the SFR derived from the FIR luminosity.

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\(^{11}\) For a Salpeter IMF (\( x = 2.35, 0.1-100 \) M\( \odot \)) and a standard Galactic extinction law (\( R_V = 3.1 \)).

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