

Optical spectra of dusty starbursts

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Abstract. This contribution presents the optical spectral properties of FIR-luminous galaxies, whose distinctive feature is often the simultaneous presence in the spectra of a strong H δ line in absorption and of emission lines (e(a) spectra). A discrepancy between the star formation rate estimated from the FIR luminosity and that derived from the H α luminosity persists even after having corrected the H α flux for dust according to the observed Balmer decrement. It is shown that the e(a) spectrum can be reproduced assuming a current starburst and a dust extinction affecting the youngest stellar populations much more than the older stars.

1 Introduction

The most distinctive feature in the optical spectra of FIR-luminous galaxies is not the equivalent width of the emission lines¹, but the equivalent width of the H δ line in absorption, which is generally stronger than in the spectra of optically selected galaxies. In fact, emission line spectra with $EW(H\delta) > 4 \text{ \AA}$ (e(a) spectra) are frequent among FIR galaxies, while the great majority of nearby spirals in optical samples have $EW(H\delta) < 4 \text{ \AA}$ (e(c) spectra) (Poggianti et al. 1999 [P99]; Poggianti & Wu 2000 [PW00]). The e(a) spectral class differs from the so-called "k+a" (or "E+A") galaxies which only display a strong H δ line in absorption, but no emission lines.

What is the origin of the difference in the H δ strength between dusty starburst galaxies and quiescent spirals? What star formation and dust properties generate the peculiar spectral combination found in e(a) galaxies? In the following I will address these issues presenting the analysis of a spectroscopic survey of luminous IRAS galaxies (PW00) and the results of an effort to model the e(a) spectrum in detail (Poggianti, Bressan & Franceschini 2001).

2 FIR-luminous galaxies: spectral features and star formation properties

In PW00 we analyzed the spectral characteristics of a complete sample of IRAS galaxies (Wu et al. 1998a,b) comprising 73 Very Luminous Infrared galaxies (VLIRGs, $\log(L_{IR}/L_{\odot}) > 11.5$) with a median $\log(L_{IR}/L_{\odot}) = 11.72$ and 40 companion galaxies, selected from the 2 Jy redshift survey of Strauss et al. (1992). The great majority of these galaxies show evidence for a strong interaction or a merger (Wu et al. 1998b). The spectra typically cover the central 2 kpc of the galaxies at a $\sim 10 \text{ \AA}$ resolution.

¹ These are usually lower than those in HII galaxies and UV-bright starbursts.

Table 1 shows the fraction of VLIRGs as a function of the spectral class; a detailed description of each class can be found in PW00. More than half of these galaxies have an e(a) spectrum, about 1 out of 4 has an e(c) spectrum, and only 1 out of 10 has very strong [OII] emission (e(b) type). None of the e(a) spectra would be classified as a Seyfert1 or 2 according to the standard diagnostic diagrams of line intensity ratios. Notably no k+a spectrum is found among the FIR luminous galaxies, neither among their companions: all the VLIRGs display emission lines in their spectra.

A general characteristic of the e(a) spectra in all environments and at all redshifts appears to be the low [OII]/H α ratio (see Fig. 1): both the equivalent width and the flux ratios of these lines are a factor of 2 lower than the median ratios observed in nearby spirals. Though such low ratios may be caused by various reasons, the most likely explanation is reddening by dust: the color excess E(B-V) derived from the observed Balmer decrement (see Table 1) is consistent with – and fully accounts for – the observed [OII]/H α values. It is noteworthy that the difference in the *equivalent width* ratio between this sample and optically selected nearby spirals is entirely due to the difference in the average *flux* ratio of these two lines. This can be interpreted as an effect of *selective dust extinction* which affects the youngest stellar generations (still deeply embedded in large amounts of dust and responsible for the ionizing photons producing the emission lines) much more than older, less extinguished stellar populations producing the continuum underlying the lines: the net result is a low EW ratio. Additional evidence for a selective extinction will be discussed in Sec. 3.

As in all FIR luminous samples, there is a deficiency of H α luminosity at a given FIR luminosity as compared to optically selected spirals (Fig. 2) and this scarcity of H α flux translates directly into a difference in the SFR estimate: even applying to the H α flux the dust correction derived from the Balmer decrement is not sufficient to reconcile the two estimates of current star formation obtained from the FIR and H α luminosities (Fig. 3). After dust correction, the SFR_{H α} is still a factor of ~ 3 lower than the SFR_{FIR}; it is unlikely this discrepancy is entirely due to the limited aperture of the spectroscopic slit and I will come back to this point in Sec. 3.

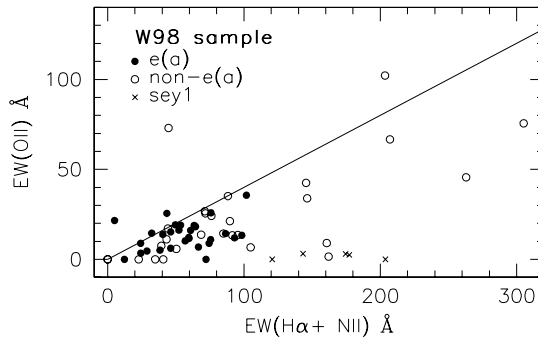


Fig. 1. Line represents the fit for normal field galaxies in the local Universe ($EW([OII])=0.4 EW(H\alpha + NII)$).

FRACTION OF GALAXIES AND E(B-V) AS A FUNCTION OF THE SPECTRAL CLASS.

Class	%	Median E(B-V)	Comments (see PW00 for details)
e(a)	0.56 ± 0.10	1.11	Strong Balmer absorption plus emission
e(c)	0.25 ± 0.07	0.68	Weak/moderate Balmer absorption plus emission
e(b)	0.10 ± 0.04	0.62	Strong emission ($EW([OII]) > 40 \text{ \AA}$)
sey1	0.10 ± 0.04	–	Seyfert1 from broad hydrogen lines in emission

The analysis presented so far refers to a well defined sample of IRAS luminous galaxies, but the e(a) phenomenon appears to be widespread among IR luminous galaxies at any redshift (see PW00 for a census of the e(a) occurrence). As an example, Fig. 4 shows that the average e(a) spectrum of Wu’s sample is very similar to the average spectrum of distant starburst galaxies detected at 15 micron by ISO, both in the continuum shape and in the strength of the [OII], H δ and H β lines.

3 Physical origin: modelling e(a) spectra

A selective dust extinction has been proposed as the physical origin of the e(a) spectra (P99, PW00): dust obscuration affects the youngest stellar generations more than the older stars. This is expected to explain both the observed [OII]/H α ratio, as discussed in the previous section, and the H δ strength because the stellar populations responsible for this line (with ages a few times $10^7 - 1.5 \cdot 10^9$ yr) have had time to drift away from or disperse the dusty molecular clouds where they were born and their emission can dominate the integrated spectrum at 4000 \AA if younger stars are more heavily obscured. Furthermore, a selective extinction appears to be the most plausible explanation for the fact that, even within the same spectrum, different values of extinction are measured depending on the spectral region/feature used to estimate it: for example, the dust attenuation of the UV/optical stellar continuum is often measured to be lower than the obscuration of the emission lines (see PW00 for a reference list).

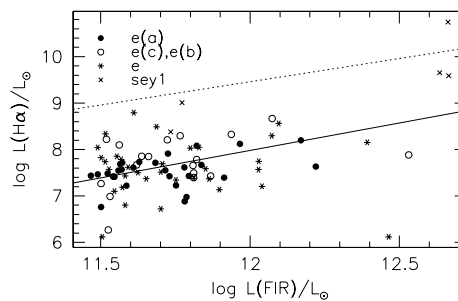


Fig. 2. FIR and H α luminosities in solar units. No dust correction has been applied. The best fit to the datapoints is shown as a solid line. The relation found by Devereux & Young (1990) for a sample of field spiral galaxies in the local Universe is extrapolated to the FIR luminosities of the present dataset and is shown as a dotted line. ”e” spectra are those with at least one detected emission line, but H δ unmeasurable.

In order to verify whether the hypothesis of selective extinction in a starburst galaxy can indeed account for the e(a) spectrum, a simplified spectrophotometric model, including only 10 stellar populations, has been developed (Poggianti, Bressan & Franceschini 2001). This represents the minimum set of stellar populations that are known to be essential because they affect the spectral features that we wish to reproduce: four young generations ($10^6, 3 \cdot 10^6, 8 \cdot 10^6, 10^7$ yr) responsible for the ionizing photons that produce the emission lines; five intermediate populations ($5 \cdot 10^7, 10^8, 3 \cdot 10^8, 5 \cdot 10^8, 10^9$ yr) with the strongest Balmer lines in absorption, and older stars modelled as a constant star formation rate between 1 and 12 Gyr before the moment of the observation which can give a significant contribution to the continuum. The spectrum of each stellar generation is found from a spectrophotometric model that includes both the stellar and the nebular contribution (Barbaro & Poggianti 1997) and it is extinguished with its own extinction value – that is allowed to vary from a stellar population to another – assuming a dust screen with a standard Galactic extinction law and a Salpeter IMF between 0.1 and $100 M_{\odot}$. The results of this model are compared with the average e(a) spectrum of the VLIRGs discussed in Sec. 2; the quality of the fit is assessed considering the differences between the model and the observed spectrum in the equivalent widths of four lines ([OII] λ 3727, H δ , H β and H α) and the continuum flux in eight spectral windows in the range 3770–6460 Å. On the basis of our models we find the following results:

1) the e(a) spectrum is consistent with the starburst/selective extinction scenario. The upper left panel of Fig. 5 presents the comparison between the average e(a) spectrum and a model of a burst that began 2×10^8 yr ago; the extinction of the starburst populations is significantly higher than that of the

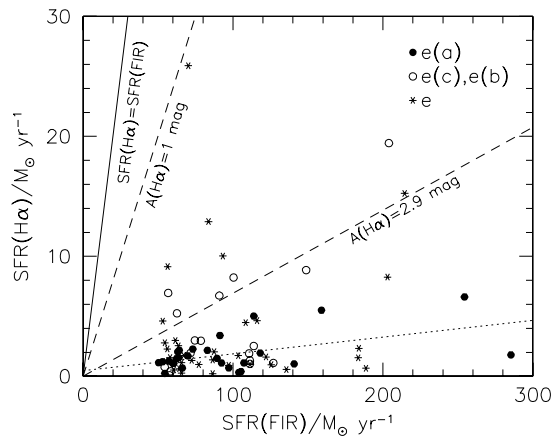


Fig. 3. The SFR derived from the observed H α flux versus the FIR-based estimate. The dotted line is the fit to the e(a) population. The solid line shows the relation $SFR_{H\alpha} = SFR_{FIR}$, and the dashed lines are found for 1 mag extinction at H α (average extinction in nearby spirals) and for the average extinction in e(a)'s in W98 sample as determined by the Balmer decrement ($E(B-V)=1.1$, $A(H\alpha) = 2.9$ mag)

older generations (see the right panel in Fig. 5). The fit is remarkable, both as far as the line equivalent widths and the continuum are concerned.²

2) The model described above can only account for about 1/3 of the observed FIR luminosity. Different effects can contribute to this discrepancy:

a) Slit aperture effects i.e. a mismatch in the galactic area sampled by the optical spectrum (central 2 kpc) and by IRAS (integrated). Given that the IR emissivity is usually concentrated in the central regions of luminous infrared galaxies, it is hard to envisage how slit effects can account for the discrepancy between the modelled and the observed IR flux.

b) Dusty starburst galaxies often have star forming regions which are completely obscured at optical wavelengths, hence give no contribution to the spectrum but produce a significant fraction of the FIR luminosity (e.g. Mirabel et al. 1998). The observed FIR/V ratio can be reproduced by starburst models with regions that are highly obscured by dust with an $E(B-V)$ even greater than in the models of Fig. 5.

3) No strong constraint can be placed on the burst duration. Models with a starburst as short as a few times 10^6 yr and as long as 10^9 yr are able to fit the observed e(a) spectrum as long as: a) the youngest populations are highly extincted and b) the old population provides a contribution but does not overwhelm the intermediate age contribution at 4000 \AA . As an example, the lower left panel in Fig. 5 shows the excellent fit obtained with a current burst that began $\sim 10^7$ yr ago. In the case of short bursts ($< 5 \times 10^7$ yr), the strong $H\delta$ line is not produced by the stars born during the starburst event, but by the previous stellar populations.

² There is a small discrepancy around 5000 \AA but this is only at the 4% level.

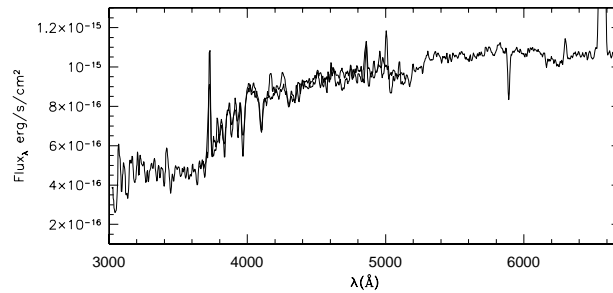


Fig. 4. A rest-frame comparison of the average e(a) spectrum of Very Luminous Infrared galaxies (thick line) and the spectrum of the ISO starburst galaxies at $z > \sim 0.5$ (thin line). The latter is taken from Fig. 12 in Flores et al. (1999) and has been normalized to the VLIRGs spectrum over the wavelength range in common. This is the average spectrum of 5 ISO-detected galaxies at $z < 0.7$ whose spectral energy distributions at visible, near-IR, MIR and radio wavelengths resemble those of highly reddened starbursts in the local universe. The spectral resolution is 10 \AA (Wu) and 40 \AA (Flores).

4) We also considered a family of "post-starburst models" with extinction, assuming a galaxy is seen *after* a strong starburst phase when a small amount of residual star formation activity is still ongoing. This type of models – besides accounting for not more than $\sim 1/10$ of the observed FIR luminosity – fail to reproduce simultaneously the $H\alpha$ and the $H\beta$ lines, either underestimating the former or overestimating the latter.

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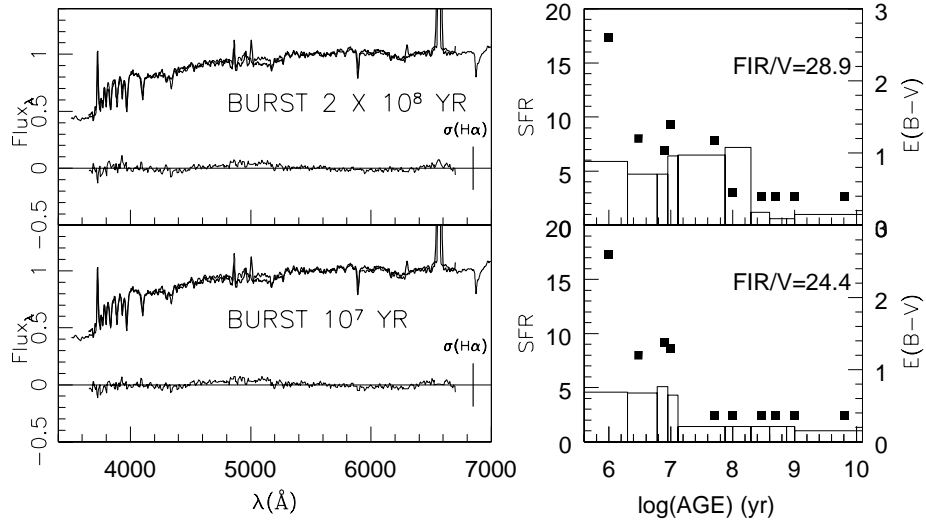


Fig. 5. *Left:* Comparison between the average observed spectrum of the e(a) galaxies (thick line) and the spectrum of two starburst models (thin lines), normalized at 5500 Å. The emission lines included in the models are those of the Balmer series and the [OII] line. The difference between the model and the observed spectrum is also shown (at Flux ~ 0). The vertical segment on the right side represents the 1σ error in $H\alpha$. *Right:* SFR (histogram, normalized to =1 in the old population) and $E(B-V)$ (dots) of the models whose spectrum is shown in the left panel. The observed FIR/V ratio is =88.0.