RECENT STAR FORMATION IN VERY LUMINOUS INFRARED GALAXIES

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Abstract
Among star forming galaxies, a spectral combination of a strong Hδ line in absorption and a moderate [OII] emission has been suggested to be a useful method to identify dusty starburst galaxies at any redshift, on the basis of optical data alone. On one side it has been shown that such a spectral particularity is indeed suggestive of obscured starburst galaxies but, on the other, the degeneracy of the optical spectrum has hindered any quantitative estimate of the star formation and extinction during the burst. The optical spectrum by itself, even complemented with the information on the far-IR flux, is not enough to identify univocal evolutionary patterns. We discuss in the following whether it is possible to reduce these uncertainties by extending the spectral analyses to the near infrared spectral region.

1. Introduction
Recent observations in the IR/mm have revealed that luminous and ultra luminous IR galaxies (LIRGs and ULIRGs) constitute a major cosmological component during the past epochs of the universe: in spite of their short duration, the transient IR-active phases are responsible for a large fraction of the energy emission and metal production at high redshifts. With luminosities spanning the range $10^{11}$–$10^{13}$ L⊙ and space densities similar to those of quasars (Soifer et al. 1986) Luminous and Ultra luminous Infrared galaxies (LIRGs and ULIRGs) are the most luminous objects in the local Universe. Highly extinguished and strong IR emitters, ULIRGs are considered to be the local analogues of the newly discovered high-z IR luminous galaxies. Recent optical spectroscopic surveys (Wu et al. 1998, Poggianti and Wu 2000) reveal that
the spectra of a large fraction of (U)LIRGs display a peculiar combination of spectral features in the optical: a strong Hδ line in absorption (EW > 4 Å) and a moderate [OII] emission (EW < 40 Å). Galaxies with this type of spectra were named “e(a)” galaxies and were found to be quite numerous in the cluster and field environments at z = 0.4 – 0.5 (Poggianti et al. 1999). The equivalent width of their Hδ line exceeds that of typical, quiescent spirals at low-z and their low [OII]/Hα ratios are consistent with the emission line fluxes being highly extincted by dust. Until recently, such a combination of moderate [OII] emission and strong Balmer absorption, was thought to be associated with post-starburst galaxies, with little or no star-formation. Such a claim was mostly based on dust-free models. Poggianti et al. 1999 however, proposed that this peculiar spectral signature corresponds in fact to highly obscured starburst galaxies. Clearly, one still needs to investigate the exact origin of these spectra, namely, the nature of the star formation as well as the properties of the dust. A possible explanation for this unusual combination of emission/absorption features is selective extinction (Poggianti and Wu 2000). In such a scenario, HII regions (where the [OII] emission originates) are highly embedded and thus are affected by more extinction compared to the older stellar population which is responsible for the Balmer absorption.

Surprisingly enough, the combination of moderate emission lines and strong Balmer absorption has been also detected in the spectra of high-z IR luminous ISO galaxies (e.g. Flores et al. 1999). A recent near-IR survey of the same population revealed that the ISO galaxies are in fact actively starbursting but highly obscured objects, based on the strength of the Hα emission line and high equivalent width (Rigopoulou et al. 2000). Differential extinction is again at the heart of this spectral behaviour. Rigopoulou et al. (2000) have estimated the extinction in their sample of ISO galaxies based on optical colours and found it to be A_v ~3. After correcting the Hα line flux using optical indicators of extinction, the inferred Star Formation Rates (SFR) fall significantly below the proper SFR estimated from the far-Infrared flux. This implies that optical extinction is significant, and requires additional information for a more reliable evaluation.

Poggianti, Bressan and Franceschini (2001) have recently investigated in some detail the optical spectra of LIRG and ULIRG galaxies, to constrain the recent history of star-formation and the dust extinction characteristic of various stellar populations. By examining different star formation patterns they concluded that only a starburst, selective extinction scenario could explain the e(a) spectra. In this scenario the extinction is larger in the younger populations, a fact that mimics the
progressive escape of young stars from their parental molecular clouds, as they age. The observed FIR/V luminosity ratio could be explained only by models where a significant fraction of the FIR luminosity originates in regions that are practically obscured at optical wavelengths. Unfortunately this hinders any quantitative estimate of the duration and intensity of the burst and/or of the wavelength dependence of the extinction. Thus the optical-near UV spectrum by itself, even complemented with the information on the far-IR flux, are not enough to identify univocal modellistic solutions. One chance to reduce these uncertainties is provided by the extension of the spectral analyses to the near-IR regime (eg. Murphy et al. 1999).

2. Models in the near IR

In order to highlight the advantages of investigating over a wider wavelength range, we have followed the same methodology described in Poggianti, Bressan & Franceschini (2001). The integrated model spectrum, from the far UV to the near IR, has been generated as a combination of 10 stellar populations of different ages, computed with a Salpeter IMF between 0.15 and 120 $M_\odot$. The stellar SEDs have been obtained by extending the Pickles spectral library below 1000 Å and above 24000 Å with the Kurucz (1993) models. The composite (stars+gas) spectrum of each single generation has been then produced by one of us (AB) with the help of the photo-ionization code CLOUDY (Ferland, 1990). The ages of the 10 populations have been chosen considering the evolutionary time scales associated with the observational constraints: the youngest generations ($10^6, 3 \cdot 10^6, 8 \cdot 10^6, 10^7$ yr) are responsible for the ionizing photons that produce the emission lines; the intermediate populations ($5 \cdot 10^7, 10^8, 3 \cdot 10^8, 5 \cdot 10^8, 10^9$ yr) are those with the strongest Balmer lines in absorption, while older generations of stars have been modelled as a constant star formation rate (SFR) between 2 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.

Each simple population is assumed to be extincted by dust in a uniform screen according to the standard extinction law of the diffuse medium in our Galaxy ($R_V = A_V/E(B-V) = 3.1$, Cardelli et al. 1989). While a more complex picture of the extinction cannot be excluded, Poggianti et al. already have shown that the characteristics of the emerging spectrum require a significant amount of foreground dust (screen model). Indeed in the case of a uniform mixture of dust and stars, increasing the obscuration does not yield a corresponding increase in the reddening of
the spectrum: the latter saturates to a value (E(B-V) ~ 0.18)) which is too low to be able to account for the observed emission line ratios (see also Calzetti et al. 1994). In the model used here, 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.

Finally, the best-fit model, within a chosen star formation scenario, was obtained by minimizing the differences between selected features in the observed and model optical range: the equivalent width of four lines ([OII]λ3727, Hδ, Hβ and Hα) 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).

Figure 1. The observed average e(a) optical (3700 Å – 6900 Å) spectrum is compared with suitable models extended into the NIR region. All models reproduce well the shape of the observed continuum and equivalent widths of Hα (-62.48 ± 5.3), Hβ (0.68 ± 0.8), Hδ (5.64 ± 0.5) and [OII]3727 (-12.68 ± 2.1)(Poggianti et al 2001). The predicted EWs of selected lines in the NIR are shown. See text for more details.
3. Results

Fig. 1 depicts three particular cases that were successful in reproducing the optical spectral features of e(a) galaxies (Poggianti et al. 2001). Model A, the reference model, reproduces both the line strengths and the highly reddened continuum, but it can account for only 1/3 of the FIR emission, hence of the star formation rate. In this model the mass of young stars amounts to about 10% of the galaxy mass.

To solve the above discrepancy, some practically obscured regions were added in model B. As in model A, the starburst began $2 \cdot 10^8$ yr ago, but both the SFR during the burst and the extinction of the two youngest stellar generations are higher than in A. The recent SFR is about a factor of 10 larger than in model A and, for a standard Salpeter IMF in the range $0.1 - 100 M_\odot$, about 60% of the total mass in stars is formed during the burst. Thus the high ratio FIR/optical in this case, is indicative of a significant fraction of the galaxy mass being formed during the burst. It is worth noticing that assuming a top-heavy IMF during the burst 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. However different IMF with the same distribution of stars above say $1 M_\odot$, would essentially produce the same integrated spectrum, and would be practically indistinguishable. Finally, in model C the observed FIR/optical ratio is reproduced by adopting an extinction law with $R_V = A_V / E(B-V) = 5$, as observed towards some dense clouds in our Galaxy (Mathis 1990). In this case the recent SFR is only a factor of two larger than that of model A and the observed FIR/optical ratio is fully reproduced because, for a given E(B-V), the optical flux is much more extinguished. In spite of the different star formation histories, the shape of the continuum in the near infrared is fairly similar in the three cases. This is striking because the inspection of the models shows that, while in case A the near infrared continuum is contributed in almost equal parts by the young burst and the old disk, in case B it is dominated by the young burst while, in case C, it is due to the old disk.

Thus it appears that the degeneracy encountered at optical wavelengths would not be removed by the NIR photometry alone.

On the other hand the simulations clearly suggest different equivalent widths of the NIR hydrogen lines. In particular, in models B and C the line intensities are about twice as strong as in model A. In the case of model B, though the SFR is much higher than in the case A, the young populations are much more heavily obscured so that line intensities which are similar in the optical, are only a factor of two larger in
the NIR. A significant fraction of the SFR remains hidden even in the NIR. In the case of model C the intensity of the NIR lines simply reflects the larger SFR adopted. Finally, Table 1 shows the average E(B-V) re-

|       | Hβ/Hα | Paα/Brγ | Paβ/Brγ | Hβ/Brδ | Hα/Paα |
|-------|-------|---------|---------|--------|--------|
| A     | 0.96  | 0.20    | 1.15    | 1.08   | 1.19   |
| B     | 1.19  | 0.72    | 1.45    | 1.35   | 1.47   |
| C     | 0.90  | 1.37    | 1.98    | 1.38   | 1.67   |
| C*    | 0.71  | 0.70    | 1.01    | 0.90   | 0.98   |

* adopting an extinction law with R_V=5

covered with the ratios of the Hydrogen lines, in the optical and NIR spectral region, adopting the extinction law with R_V=3.1. We remind that, in the case of VLIRGs where the EW Hβ is almost null, the Balmer decrement is severely affected by the assumed equivalent width of the absorption component. On the other hand the NIR ratio Paα/Brγ is affected by too small a wavelength range. As for the other three line ratios, the Paβ/Brγ ought to be preferred because it is less affected by uncertainties in the old population and unaffected by [NII] emission.

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