The stellar population and the evolutionary state of HII regions and starburst galaxies

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Abstract

RH IIs and starbursts are both powered by massive stars. They are the main contributors to the heating of the ISM via radiative and mechanical energy. Techniques to derive the stellar content and the evolutionary state of RH IIs and starbursts from their ultraviolet and optical integrated light are reviewed. A prototypical RH II (NGC 604) and nuclear starburst (NGC 7714) are discussed in more detail. The results reveal the necessity of multiwavelength analyses of these objects to estimate their stellar content and their evolutionary state in a consistent way.

Key words: ISM: HII regions - galaxies: starburst - galaxies: stellar content - galaxies: evolution.

1 RH IIs and starbursts: Definition and common characteristics.

Giant extragalactic H II regions (RH IIs) are amongst the brightest objects in galaxies. They have been studied extensively because they are the best indicators of the conditions that lead to massive star formation, and they show the cloud properties inmediately after the moment when stars form. RH IIs are characterized to have a size larger than 100 pc and Hα luminosity brighter than 10^{39} erg s^{-1} [19]. Thus, the nebula requires an ionizing photon luminosity $\geq 10^{51}$ ph s^{-1}; this is provided by a stellar cluster that contains more than 100 young massive stars. These characteristics are very similar to those of starburst galaxies. However, they are less luminous than prototypical starbursts, and thus, they can be referred to as mini-starbursts [37].

Starburst galaxies are objects in which the total energetics are dominated by star formation and associated phenomena [39]. They are characterized to have a size between 100 pc and 1000 pc, and Hα luminosity that ranges between 10^{40} erg s^{-1} and 10^{42} erg s^{-1}. Therefore, the nebula requires an ionizing photon luminosity that ranges between 10^{52} ph s^{-1} and 10^{54} ph s^{-1}; this is provided by a stellar cluster that contains several thousands of young massive stars. This definition covers galaxies with a very wide range of properties such as: blue compact dwarfs, H II galaxies, nuclear starbursts and ultraluminous IRAS starbursts. Typical bolometric luminosities range from 10^7 to 10^{12} L$\odot$, corresponding the lowest limit to the luminosity of super-star-clusters and the highest limit to infrared-luminous galaxies [22]. The star formation rate is so high (10–100 M$\odot$ yr^{-1} and in some ultraluminous infrared galaxies can be up to 1000 M$\odot$ yr^{-1}) that the existing gas supply can feed the starburst only for a small fraction of the age of the universe (few 10^8 yr).

One common definition to RH IIs and starbursts is: *brief intense star formation episodes that are taking place in small regions.* The main difference between both is that the luminosity of these episodes of star formation dominate the overall luminosity of the starburst galaxy ($L_{burst} \sim L_{galaxy}$), in contrast in RH IIs is significant smaller ($L_{burst} \ll L_{galaxy}$) [36].

A common characteristic to both is their ultraviolet and optical spectral morphology. RH IIs and starbursts are powered by massive stars. O stars emit photons with energies of tens of eVs that are absorbed and re-emitted in their stellar winds, producing ultraviolet resonance transitions. These wind lines are blueshifted by 2000–3000 km s^{-1} and/or show a P-Cygni profile [16]. The shape of the profiles reflect the stellar mass-loss rates which are a strong function of the stellar luminosity [3]. Therefore, the ultraviolet spectrum of RH IIs and starbursts is dominated by absorption lines formed in the wind of massive stars [30,20]. However, it can also show weak absorption lines formed in the photosphere of O and B stars [5], and strong absorption lines formed in the interstellar medium of the galaxy [17,13]. In contrast, the optical spectrum is dominated by nebular emission lines. The stellar wind is optically thin to most of the ultraviolet photons, that can travel tens of parsecs from the star before they are absorbed and photoionize the surrounding interstellar medium. Subsequently, this ionized gas cools down via an emission line spectrum. However, at optical wavelengths, the starbursts and some RH IIs show stellar features formed in the photosphere of early type stars (e.g. the higher order Balmer series and HeI lines) [35,34]. Other stellar lines detected in starburst are at near-infrared. The stronger one are the CaII triplet at 8600 Å and the CO bands at 2.2 μ [29]. These lines forme in the photosphere of giant and supergiant stars. However, these lines, that are detected in most of the starbursts, are very difficult to detect in RH IIs, probably because they have very little red-supergiant stars (see e.g. [35] and [6]).

The spectral morphology of RH IIs and starbursts at the ultraviolet and optical wavelengths allow to derive the stellar content and the evolutionary state of the cluster in a self-consistent way by doing multiwavelength analysis of these objects. In this paper I will give an overview of different techniques to date

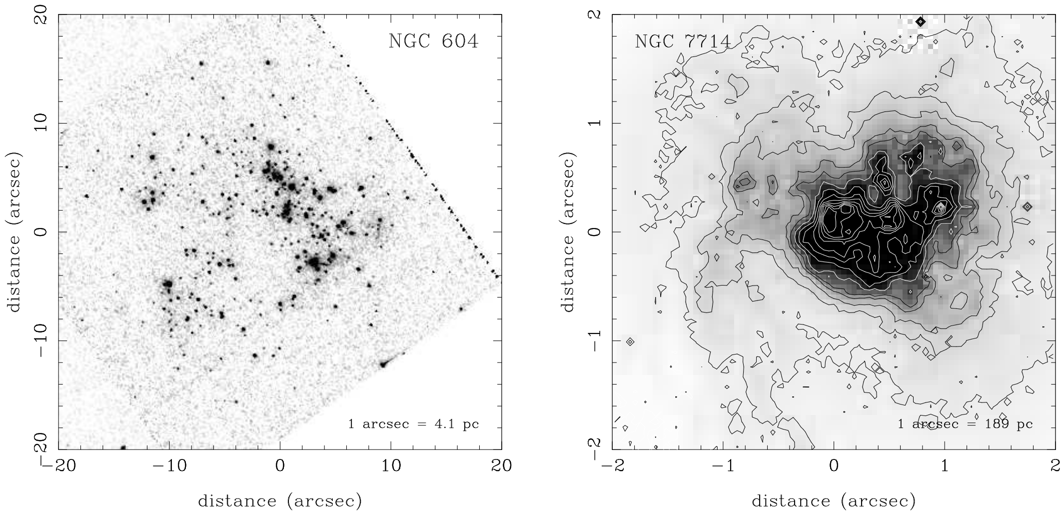

Fig. 1. *HST*+WFPC2 image of central stellar cluster of NGC 604 at 1700 Å (left) and the nucleus of NGC 7714 at U band (right).

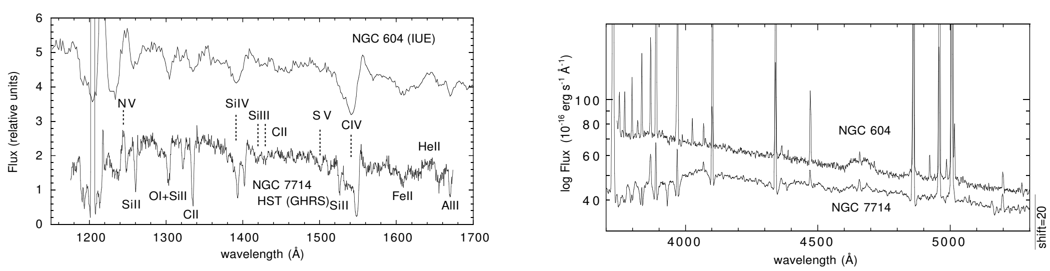

Fig. 2. Ultraviolet (left) and optical (right) spectra of NGC 604 and of the nucleus of NGC 7714. The spectra show the dichotomy picture characteristic of starbursts and RH IIs: The UV wavelengths dominated by absorption lines and the optical wavelengths by nebular emission lines. Broad HeII λ4686 emission is detected in the optical spectra of both objects.

RH IIs and starbursts and to estimate their stellar content. For guiding the discussion I will apply these techniques to the prototypical nuclear starburst NGC 7714 and the prototypical RH II NGC 604. The ultraviolet and optical apperance of these objects are shown in Figures 1 and 2. However, first I will discuss the effect that extiction has on the ultraviolet emission.

2 Extinction

One way to derive the massive stellar content in RH IIs and starbursts is through the ultraviolet continuum emitted by these objects. However, due to the profound effect that dust has on the ultraviolet properties of starbursts, an estimation of the extinction needs to be done first. [31] have built the spectral energy distribution from X-ray to radio of a sample of ultraviolet local starbursts. They divided the sample in two classes, low-reddening (E(B-V)$\leq$ 0.4) and high-reddening (E(B-V)$\geq$ 0.4). Both have similar spectral energy distribution (SED) over the entire energy spectrum, peaking at the far-infrared. However, low-reddening starbursts have stronger ultraviolet emission than high-reddening starbursts, while in the far-infrared the opposite happens. This difference is due to the fact that the ultraviolet and visual radiation that is absorbed by dust is re-radiated in the far-infrared. This suggests that dust reddening is the likely cause for extinguished the ultraviolet spectra. Thus, the extinction has to be estimated in order to obtain the ultraviolet intrisic luminosity of the starburst. [2] show that in a sample of local starburst galaxies, the ultraviolet continuum can be paremetrized as F_λ= cte λ^β, with the spectral index β strongly correlating with the nebular extinction measured using the Balmer decrement. This spectral index also correlates with the ratio of the far-infrared to the ultraviolet flux, L_{IR}/L_{UV}, which is larger for β values [27]. [18] have also shown that β and L_{IR}/L_{UV} ratio correlate with the metallicity of the gas, the strength of the ultraviolet interstellar and wind absorption lines. These correlations point out that the more metal-rich starbursts are redder and more heavily extinguished in the ultraviolet.

Fortunately, β is independent of the IMF and the star formation history, and it ranges between -2.0 and -2.6, for ages appropriate for starbursts [23]. This allows to do an estimation of the extinction that affect the stellar cluster by comparing the observed ultraviolet continuum with the spectral energy distribution predicted by the evolutionary synthesis models. Then, the ultraviolet continuum is de-reddened to get the intrinsic ultraviolet luminosity and the massive stellar content. The color excess, E(B-V), derived in this way for local ultraviolet selected starburst galaxies is usually lower than 0.4 [26]. In particular, the values estimated for NGC 604 and NGC 7714 are 0.1 and 0.03, respectively. However, E(B-V) derived in this way is in many starbursts significantly smaller (by a factor 2) than that derived from the Balmer decrement [7,2]. This result, therefore, suggests that the ionized gas is associated to regions of higher dust content than the stars. The most probably explanation is that the dust has been swept away and/or destroyed from the site of star formation by the action of the stellar winds and supernova explosions. One important implication of this result is that the equivalent widths of the Balmer recombination lines are not free extinction quantities; thus, this limit their use as age diagnostic.

3 Evolutionary state of RH IIs and starbursts

One important question related with RH IIs and starbursts is whether the star formation proceeds in them in short (duration $\leq$ 10 Myr) or long lived bursts (duration $\geq$ 10 Myr). There are several different diagnostics that can be used to determine the evolutionary state of RH IIs and starbursts which are all based on their spectral morphology. Here, I give an overview of several techniques to date star forming systems which are based on the strength of the nebular emission lines, wind resonance ultraviolet lines, H Balmer series and HeI absorption lines, and the spectral energy distribution (SED) from the ultraviolet to the near infrared. I present the results of applying these techniques to NGC 604 and NGC 7714 (see [11] and [14] for more details).

3.1 Nebular emission lines

The emission line spectrum of an RH II and starburst depends on the radiation field from the ionizing stellar cluster, on the electron density and on the chemical composition of the gas. A photoionization code can take as input the spectral energy distribution of the cluster, and solve the ionization-recombination and heating-cooling balances to predict the ionization structure of the nebula, the electron density and the intensity of the emission lines. The star formation law, age and massive stellar content of the stellar clusters can be constrained by comparing the observed emission lines strengths with the predictions from the photoionization models, if the code uses as input the SED generated by a stellar evolutionary synthesis code. This technique has been used successfully to study the stellar content in starbursts and RH IIs (e.g. [9,32] and Stasińska this conference). However, the age range for which this technique is sensitive is restricted to the first 10 Myr, that is the evolutionary timescale of O stars. The thruthfulness of the results obtained with this technique depends strongly on the observational constraints used for the modeling. Important limitations to this technique comes from the effect of dust on the ionizing radiation field and of the geometric distribution of the gas on the ionizing structure of the nebula [33]. Thus, constraints on the spatial distribution of the ionized gas obtained from high resolution narrow-band images are very useful. The success of this technique relies on obtaining ages and information on the SED of the stellar cluster that are compatible with those resulting from other techniques like the modeling of the wind resonance ultraviolet lines.

To determine the evolutionary state of the prototypical RH II NGC 604 and nuclear starburst NGC 7714, the nebular lines were predicted by the photoionization code CLOUDY [8]. In these models the radiation field is the spectral energy distribution from the evolutionary synthesis code Starburst 99 [25] that is normalized to the ionizing photon luminosity derived from the total Hα flux of the nebula. The electron density and chemical composition of the gas are fixed to the values derived from the observations. The gas is distributed with constant density in a sphere with an inner radius of a few parcsecs and an outer radius that is determined by the ionizing front. The models assume that

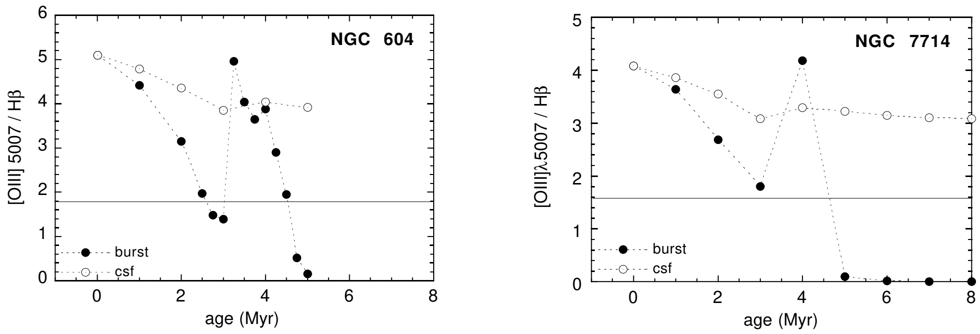

Fig. 3. Predicted [O III]/Hβ by CLOUDY using the SED from Starburst 99. The observed values are marked as horizontal lines. Models shown are those computed for ϕ= 0.1 (for NGC 604) and 0.001 (for NGC 7714). The electron density is 30 and 100 cm^{-3} for NGC 604 and NGC 7714, respectively. The chemical composition is Z$\odot$/2.

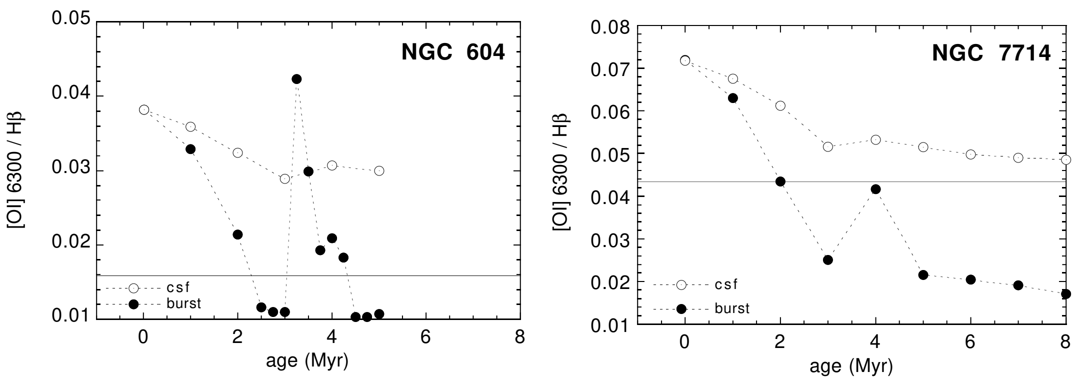

Fig. 4. As Figure 3 for the line ratio [O I]/Hβ.

the gas occupies only a fraction of the sphere; then, they are computed taking as a free parameter the filling factor, ϕ, that is related to the average ionization parameter U by U= $(\phi^2\ N_e\ Q)^{1/3}$. First, U is derived using the ratio [S II]6717+6732/Hβ that is a good calibrator of U [14]. The observed ratios indicate ϕ of 0.1 and 0.001 for NGC 604 and NGC 7714, respectively. These models predict a Strömgren radius of 110 pc and 185 pc for NGC 604 and NGC 7714, respectively. These values are in agreement with the nebular radius estimated from Hα images of these objects. Then, the strength of other emission lines are fitted. Line ratios indicative of the electron temperature and ionization structure suggest that the massive stellar population responsible for the photoionization of the gas has formed in an instantaneous burst 3 and 4.5 Myr ago in NGC 604 and NGC 7714, respectively (Figure 3 and 4).

3.2 Ultraviolet stellar lines

Stellar winds are driven by radiation pressure [28]. Massive stars transform their radiative momentum into kinetic energy with an efficiency $\eta = (\dot{M}\ v_\infty)/(L/c) \sim 0.3$ for O stars of solar metallicity [21], where $\dot{M}$ is the mass loss rate, v_∞ the terminal velocity of the wind, L the luminosity of the star and c the light speed. This expression explains why the profile of the wind resonance ultraviolet lines contains information about the mass-loss rate and on the stellar luminosity. Since there is a well-defined stellar mass-luminosity relation, the profiles intimately deppend on the stellar content of the starburst and its evolutionary state. The most prominent wind lines in the spectra of RH II and starburst are those of N V λ1240, Si IV λ1400, C IV λ1550 and He II λ1640. C IV shows always a strong P-Cygni profile if O stars with zero-age-main-sequence masses above 30 $M_\odot$ are present. In contract, Si IV and He II forms if blue supergiant stars and stars with very dense wind (as Wolf-Rayet) are present in the cluster (respectively). Evolutionary synthesis models show that the profile of these lines depend on the IMF parameters and the evolutionary state of the starburst [23]. As the nebular emission lines, the age range for which this technique is sensitive is only the first 10 Myr. After this age, the cluster is dominated by B stars and photospheric lines of C and Si can be used to estimate the evolutionary state of the cluster [5]. One important limitation of this technique comes from the strong dependency that the stellar winds have with the metallicity and the difficulty to built a stellar library at sub-solar metallicity.

The strength of the wind lines in NGC 604 and NGC 7714 indicate that the stellar cluster formed in an instantaneous burst 3 Myr and 5 Myr ago, respectively (Figure 5). These ages are consistent with the presence of Wolf-Rayet stars, as indicated also by the wind lines He II λ1640 and λ4686 (see Figure 2). In both objects, stars more massive than 80 $M_\odot$ formed in the cluster and they follow a Salpeter IMF (or even flatter IMF in the case of NGC 604). This result is consistent with that obtained from the analysis of the nebular emission lines. Therefore, we conclude that the stellar cluster responsible of the photoionization of the interstellar gas and the ultraviolet continuum emission in these two prototypical objects formed in a short period of time a few Myr ago.

3.3 H Balmer and HeI photospheric lines

Evidence that other stellar populations contribute significantly to the optical and near-infrared wavelengths come from other diagnostics that are sensitive to the presence of B and A stars, as for example the H Balmer series and He I

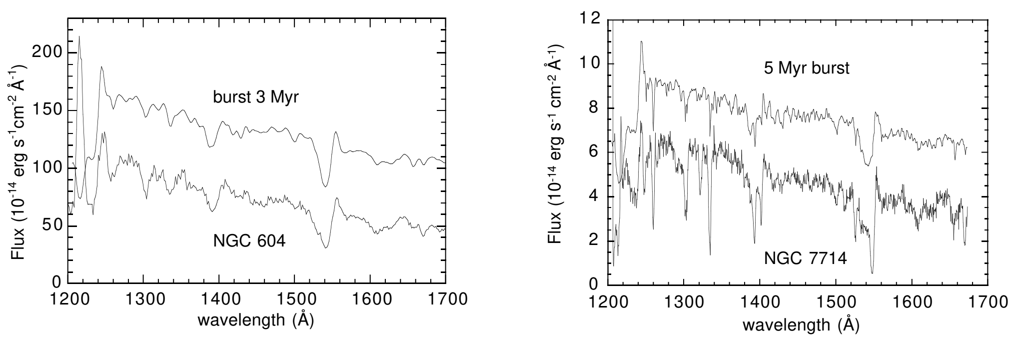

Fig. 5. De-reddened ultraviolet spectra of NGC 604 (left) and the nucleus of NGC 7714 (right) and the synthetic burst models (shifted in flux for clarity) that fit the wind stellar lines.

absorption lines. The spectra of early type stars are characterized by strong H Balmer and He I absorption lines, with very weak metallic lines formed in the photosphere of O, B and A stars [38]. In the spectra of RH IIs and starbursts the H Balmer and He I recombination nebular emission lines are super-imposed on the corresponding photospheric lines. However, the higher order terms of the Balmer series and some of the He I lines can be detected in absorption or show absorption wings. These stellar lines can be detected easier in absorption than the lower terms of the Balmer series, as Hα, because the strength of the gaseous Balmer lines in emission decreases rapidly with decreasing wavelength, whereas the equivalent width of the stellar absorption lines is constant with wavelength [15]. These lines are very sensitive to the age if the burst is younger than a few Myrs and can be used to date starburst and post-starburst galaxies until 1 Gyr [15].

In very young stellar systems (few Myr old), these lines can also be detected in absorption in spectra where the continuum light is maximized with respect to the nebular contribution. For example, a spectrum corresponding to the central zone ($\sim$ 5$\times$5 arcsec) of NGC 604 can show the higher order terms of H Balmer series and He I lines in absorption because the core of the stellar cluster is in a hole of nebular emission. The age of the stellar population that dominates the optical light can be estimated comparing the strength of these lines with the prediction of the evolutionary synthesis models. For NGC 604, the shape of these lines is compatible with the profiles predicted by an instantaneous burst 3 Myr old (Figure 6). However, in NGC 7714 these lines are stronger and wider than those predicted by the instantaneous burst, 4-5 Myr, that fits the ultraviolet continuum and the nebular emission lines. An older population ($\sim$ 200 Myr old) contributes significantly to the optical light of the nuclear starburst of NGC 7714 (Figure 6).

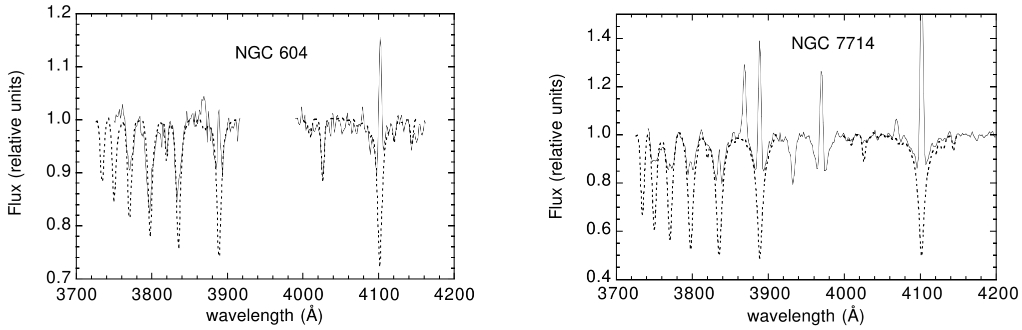

Fig. 6. Normalized optical spectrum of inner 1.2×4.6 arcsec of NGC 604 (left) fitted by a burst 3 Myr old (dotted line); and the nucleus of NGC 7714 (right) fitted by a composite model with contributions of burst of 5 Myr and 200 Myr old (dotted line).

3.4 SED from the ultraviolet to the near-infrared

Evidence that starbursts experience several recurrent bursts of star formation also comes from the analysis of the spectral energy distribution from the ultraviolet to the near-infrared. A composite ultraviolet-optical-near-infrared spectrum of the inner 2 arcsec ($\sim$ 380 pc) of the nucleus of NGC 7714 indicate that an instantaneous burst 4.5 Myr old that fits the ultraviolet light contributes less than 30% to the optical and less than 5% to the near-infrared light. As the strength of the Balmer absorption lines indicates an intermediate population, $\sim$ 200 Myr, contributes significantly to the optical light. However, these two populations can not account for the strong near-infrared continuum detected in NGC 7714. An additional population rich in red supergiant stars, $\sim$ 10 Myr, heavily obscured is needed to fit the near-infrared light; the ultraviolet flux produced by this population is totally hidden from view (Figure 7) [10]. This result is in the line of that found by [18] that a significant fraction of the stellar population of a starburst is obscured, because even after correcting by extinction the ultraviolet flux represent only 10% of the actual luminosity of the starburst. In contrast, the spectral energy distribution of NGC 604 is well fitted by an instantaneous burst 3 Myr old (Figure 7). Therefore, no evidence of recurrent star formation episodes is found in the inner 20×20 arcsec of NGC 604.

Thus, the star formation in the prototypical starburst galaxy NGC 7714 proceeds in a very different way to that in the prototypical RH IIs NGC 604. Thus while, in the starburst the star formation is taking place for long period of time through several recurrent bursts, in more simple systems, as NGC 604, the star formation lasts for a very short period of time. However, evidence that multiple stage starburst occurs in other simple stellar systems exists. For example, in the RH II NGC 2363 two burst of less than 1 Myr and $\sim$ 3 Myr old

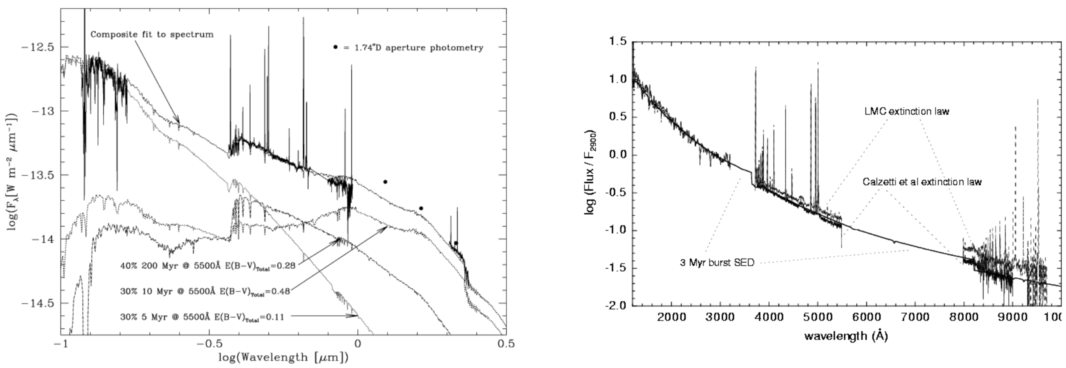

Fig. 7. SED of the nucleus of NGC 7714 (left), fitted by composite model with contributions of bursts 5 Myr, 10 Myr and 200 Myr old; and NGC 604 (right) fitted by a 3 Myr old burst.

is taking place over a linear scale of 100 pc [6]. Other good example is in the super star cluster A (SSC A) of NGC 1569. Its ground-based optical spectra show Wolf-Rayet features at 4686 Å and near-infrared CaII triplet at 8600 Å in absorption. Its spectral energy distribution is well fitted by two burst model, with the younger burst having an age of 3 Myr and the older having $\sim$ 10 Myr, to explain the simultaneous presence of hot massive stars and red supergiants [12]. This result is supported by HST optical images that reveal that SSC A is resolved in two subclusters separated by a projected distance of $\sim$ 2 pc ([4]). Even these two subclusters would not be connected, a comparison with the star formation scenario in 30 Doradous (the central cluster R136 is surrounded by filaments that form a very young complex with characteristics very similar to those of Orion [37,1]) suggests that the young cluster in SSC A could be initiated as a consequence of the energetic stellar activity of the older central cluster.

4 Summary

RH IIs and starbursts are objects in which the total energetics is dominated by star formation and associated phenomena. Their stellar content is responsible for their spectral morphology at ultraviolet and optical wavelengths. The ultraviolet is dominated by absorption lines formed in the stellar wind of massive stars, and the optical by nebular emission lines formed in the interstellar gas. However, at the Balmer jump, absorption (mainly H and HeI photospheric lines) and nebular lines happen together. These characteristics emphasize the necessity of doing a multiwavelength analysis of these objects to derive their stellar content and evolutionary state in a consistent way. In particular, the analysis of the wind stellar and the nebular emission lines indicates that the young stellar population in RH IIs and starbursts lasts for only a few

Myrs. However, starburst galaxies are more complex star forming systems than RH IIs because their optical and near-infrared continuum are mainly produced by an intermediate age population. This suggests that the star formation in starbursts is taking place via several recurrent bursts lasting for a few hundred Myrs.

Acknowledgement

I thank to my collaborators Marisa García Vargas, Jeff Goldader, Claus Leitherer and Enrique Pérez for their contributions to this work.

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