The history of star formation of starburst galaxies

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Received ; accepted

Abstract. In this paper, we use different luminosity ratios to trace the histories of star formation of two different kinds of starburst galaxies: HII galaxies and starburst nucleus galaxies (SBNGs). The mean star formation rates (SFRs) for these galaxies is comparable, and compatible with a near constant star formation over a few Gyr period. We have also found an interesting difference between the burst stellar population of the SBNGs and the HII galaxies: SBNGs have an excess of intermediate-mass stars as compared to HII galaxies. We interpreted this difference as a sign that SBNGs have experienced a higher frequency of bursts of star formation than the HII galaxies. This interpretation is qualitatively consistent with the Stochastic Self Propagation of Star Formation (SSPSF) theory, which suggests that the starburst phenomenon depends on internal processes, regulated by the evolution of massive stars.

Key words: galaxies: Starbursts – infrared: galaxies – galaxies: stellar content – galaxies: evolution.

1. Introduction

Peculiar galaxies with unusual level of star formation are commonly known as starburst galaxies. The definition of a starburst galaxy is however rather vague, and mostly model dependent. The “standard” model proposes that the typical time scale of the starburst phenomenon is of the order of $10^7$ to $10^8$ years. Short time scales are assumed because young massive stars, which dominate the optical spectrum of a starburst galaxy, cannot live very long, and high star formation rates will theoretically exhaust any available gas reservoir very rapidly. Short time scales correspond well also to typical time scales of interacting galaxies, which is the favored scenario to explain the origin of the starburst.

On observing ground, the standard model is far from being conclusive. For example, a short time scale for the bursts implies that we should see a lot of post-burst galaxies, that is galaxies with E+A spectral type. But, those are rarely found (Norman 1991). The standard model do not explain also the variety of starburst galaxies observed (Salzer et al. 1989; Campos-Aguilar & Moles 1991). In particular, it does not explain what could be the difference between the two main groups of starburst galaxies: the HII galaxies (Terlevich et al. 1991) and the Starburst Nucleus Galaxies (SBNGs; Balzano 1983; Coziol et al. 1994). HII galaxies are usually located in small, metal poor galaxies, with low dust content (Peña et al. 1991; Coziol et al. 1994; Masegosa et al. 1994). By comparison, SBNGs are located in more chemically evolved and massive galaxies, with a large population of old or evolved stars and a huge quantity of dust (Mirabel & Duc 1993; Coziol et al. 1994; Coziol et al. 1995a). In general, HII galaxies are either irregular galaxies or blue compact dwarfs (BCDs), while SBNGs are more numerous among early-type galaxies (Sb and earlier; Coziol et al. 1995a). The standard model of starburst is furthermore inconclusive because the interaction hypothesis is not always confirmed. In fact, for a great number of starburst galaxies direct signs of interaction are either missing or the galaxies are simply isolated (Taylor et al. 1993; Telles & Terlevich 1995; Barth et al. 1995; Coziol et al. 1995b).

The goal of this paper is to gain a wider view of the starburst phenomenon based on their histories of star formation. To do that, we compare different luminosity ratios which are taken as tracers of star formation rates (SFRs) over different periods of time (Kennicutt 1983; Gallagher et al. 1984; Thronson & Telesco 1986). By comparing large and different samples of galaxies, we can both develop a coherent view of the evolution of the star formation in galaxies and arrive to a better definition of the starburst phenomenon.

2. The different types of starburst galaxies

In Fig. 1, we compare different samples of galaxies by the mean of the diagnostic diagram of [NII]λ6584/Hα against [OIII]λ5007/Hβ (Baldwin et al. 1981; Veilleux & Osterbrock 1987). In this figure, the sample of IRAS galaxies
Fig. 1. Diagnostic diagram of the different kind of starburst galaxies: the high–excitation HII galaxies and the low–excitation SBNGs. The frontier between the two starburst types is placed at $\log([\text{OIII}]/H\beta) \geq 0.4$. Compared to HII regions models, the different starbursts trace a quasi continuous sequence in metallicities.

comes from Allen et al. (1991), the sample of HII galaxies from Peña et al. (1991), and the SBNGs from the Montreal Blue Galaxy (MBG) survey (Coziol et al. 1993; Coziol et al. 1994). In this diagram, the continuous curved marked AGNs is the empirical separation between galaxies where the gas is assumed to be ionized by stars, and galaxies where the main ionizing source is a power law (Veilleux & Osterbrock 1987). The curve marked HII regions is the model of disk HII regions developed by Evans & Dopita (1985).

The main feature of this diagram is that the two types of starburst galaxies can be distinguished based on their level of excitation: the HII galaxies show high–excitation spectra and the SBNGs show low–excitation spectra. The frontier between the two groups is situated at $\log([\text{OIII}]/H\beta) \geq 0.4$. This limit is almost the same as the one, proposed by Shuder & Osterbrock (1981), to separate AGNs from LINERs (that is $\log([\text{OIII}]/H\beta \geq 3$).

In Fig. 1, the relative scarcity of starburst galaxies in the transition region $-0.9 < \log([\text{NII}/Ha]) < -0.6$ can be explained in part by the observational biases of the different surveys. Objective-prism surveys are biased against low-excitation galaxies (Masegosa et al. 1994), while color surveys, like the MBG survey, are biased against high-excitation galaxies (Coziol et al. 1994). Similarly, very few IRAS galaxies are detected in the transition region because HII galaxies have a lower dust content than SBNGs. Therefore, there may be a continuous sequence of excitation of starburst galaxies. Theoretically, such con-
Table 1. Two component models for the far far-infrared radiation

|               | HII galaxies | SBNGs | late-type | early-type |
|---------------|--------------|-------|-----------|------------|
| Number        | 143          | 94    | 79        | 124        |
| $< f_{60}/f_{100} >$ | 0.57 ± 0.21  | 0.52 ± 0.18 | 0.38 ± 0.11 | 0.29 ± 0.40 |

tinuous sequence of excitation could be explained by HII regions photoionization models (McCall et al. 1985; Evans & Dopita 1985; Campbell 1988; Peña et al. 1991; McGaugh 1991). Following these authors, the most important parameter is the abundance of elements: metal poor galaxies produce higher excitation than metal rich galaxies. On this matter, it is not clear that the small number of galaxies with Log([NII]/H$\alpha$) $< -1.8$ can be explained by a detection bias effect (McGaugh 1991; Masegosa et al. 1994). In fact, this phenomenon more probably reflects the rarity of galaxies with very low metallicities (Campbell 1988; Peña et al. 1991). In this sense, galaxies resembling IIZW40 should be consider rather special.

The fact that HII galaxies are less chemically evolved than SBNGs are usually interpreted as a consequence of different types of phenomena. Among several hypotheses, HII galaxies could be either young galaxies (Terlevich et al. 1991) or galaxies with retarded star formation (Searle & Sargent 1972; Taylor et al. 1993), whereas SBNGs are considered as old galaxies, which were rejuvenated by a recent infall of matter (Huchra 1977). Following these hypotheses, it is not obvious why we should see a continuous sequence of metallicity of the different starburst galaxies. Different phenomena should also imply different histories of star formation.

3. The different tracers of star formation rates

We can follow the history of star formation of galaxies by tracing their SFRs on two different time scales (Kennicutt 1983, Gallagher et al. 1984, Thronson & Telesco 1986). The first tracer of star formation is the H$\alpha$ luminosity ($L_{H\alpha}$). $L_{H\alpha}$ is related to massive OB stars and therefore reflects the recent SFR, with time scale of $10^6$–$10^7$ yrs. The second tracer of star formation is the B luminosity ($L_B$). $L_B$ traces the SFR on time scale of $4 \times 10^8$ to $6 \times 10^9$ yrs, when stars of masses between 1 and 3 $M_\odot$ dominate the main sequence (Larson & Tinsley 1978; Gallagher et al. 1984).

There is two problems with $L_{H\alpha}$. The first one is that $L_{H\alpha}$ is sensitive to dust extinction, which effects are still poorly understood in external galaxies. The second problem is that there still are very few galaxies with H$\alpha$ fluxes measured. For these reasons, but also because of the of the IRAS survey, it was proposed to use the far–infrared luminosity ($L_{IR}$) as a tracer of recent SFR (Thronson & Telesco 1986). The idea is that active star forming regions are associated to a large quantity of dust which is predominantly heated by the massive young stars. Unfortunately, there is also a controversy on this matter and some authors have warned against the generalized use of $L_{IR}$ as a tracer of recent SFR (Sauvage & Thuan 1992). One of the problems is that we do not know what is the contribution of older population stars in heating the dust. However, we think it is well demonstrated that in active star forming galaxies the contribution of young massive stars dominates in the far–infrared (Helou 1986; Sekiguchi 1987).

As a further test, we can compare the two IRAS flux at 60 $\mu$m and 100 $\mu$m ($f_{60}/f_{100}$). Following Mazzarella et al. (1991) this ratio is a good indicator of the nature of the dust heating sources in galaxies. It provides a direct in-
In Fig. 2, we compare the distribution of the interstellar radiation field produce by OB stars as compared to the cooler cirruslike component due to old stars. In this paper, we use the $f_{60}/f_{100}$ ratio for the SBNGs and the HII galaxies with those of two samples of NGC normal field galaxies. The early-type galaxies are from Hogg et al. (1993). This last sample was chosen because it represents a group of galaxies with low SFRs (Hogg et al. 1993). The sample of late-type galaxies are from Kennicutt (1983). This sample is composed mostly of late-type spiral galaxies. It represents normal star formation in the disk of galaxies. Mean values of the $f_{60}/f_{100}$ ratios for the different types of galaxies are reported in Table 1. In Fig. 2 it can be seen that the HII galaxies and the SBNGs have similar distributions. Both starburst galaxies have comparable mean $f_{60}/f_{100}$ ratios (see Table 1). Furthermore, the mean ratios for both types of starburst galaxies are clearly higher than the mean ratio for the late-type spirals. Therefore in starburst galaxies the far-infrared luminosity is mostly related to the young massive stars.

From Fig. 2, we can see that the distribution of the $f_{60}/f_{100}$ for the NGC field galaxies follow the well known variation of star formation along the Hubble types: the SFRs in late-type galaxies are higher than in early-type galaxies. In Fig. 2, the increases of the SFRs along the Hubble sequence is also correlated in the far-infrared to an increases of the mean ratio of $f_{60}/f_{100}$. Note that from the original sample of 279 early-type galaxies considered above, only 44% were detected by IRAS. By comparison, 79% of the sample of the late-type galaxies were detected. This phenomenon reflects the fact that the most active star forming galaxies are also the dust richest. If we consider those galaxies as closed systems, the amount of dust a galaxy contain should be related in some way to its history of star formation. Whence, the low dust content of early-type galaxies is also correlated to their present low star formation rates.

### 3.1. Relations between the different luminosities

In order to convince ourselves of the validity of our different tracers of star formation, we now compare $L_{Hα}$ with $L_{IR}$ (Fig. 3) and $L_B$ (Fig. 4). Table 2 gives a summary of the different relations found by comparing the luminosities. Five different types of galaxies are considered. The HII galaxies are composed of galaxies from the UM survey (Salzer et al. 1989) and the Calan-Tololo survey (Peña et al. 1991). The SBNGs are taken from the Balzano’s sample (1983) and from the MBG survey (Coziol et al. 1993; Coziol et al. 1994). The sample of NGC late-type spirals are from Kennicutt (1983). The fourth sample is the HII nucleus galaxies. Those are defined as galaxies with HII regions in their nucleus (Kennicutt et al. 1989). Together with LINERs galaxies, the HII nucleus galaxies are the most frequent types of galaxies found in spectroscopic surveys (French 1980; Heckman 1980; Stauffer 1983). In terms of star formation, the HII nucleus galaxies could represent the low-luminosity end of SBNGs. The last sample is composed of the early-type galaxies from Hogg et al. (1993).

The different luminosities were evaluated using heliocentric velocity ($V_h$) corrected for the motion of the sun according to $V_o = V_h + 250 \sin(l) \cos(b)$, where $l$ and $b$ are the galactic longitude and latitude of the objects. In this paper, we use $H_\alpha = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The $H_\alpha$ fluxes were taken from the original articles, and are uncorrected for intrinsic extinction. Unfortunately, no $H_α$ fluxes are available for the early-type galaxies.
Fig. 3. Relation between $L_{H\alpha}$ and $L_{IR}$. In the active star–forming galaxies the far–infrared luminosity is correlated to the H$\alpha$ luminosity. For the SBNGs, the slope of the linear relation is the same as for the HII galaxies, but the intercept is different.

The coordinates, the redshifts, the B magnitudes and the IRAS fluxes were all taken from the NASA/IPAC Extragalactic Database (NED). The B luminosity were corrected for Galactic extinction, as found in NED. The far–infrared luminosity is given by $\log(L_{IR}) = \log(F_{IR}) + 2 \log[z(z+1)] + 57.28$, where $z$ is the redshift and $F_{IR} = 1.26 \times 10^{-11}(2.58f_{60} + f_{100})$ erg cm$^{-2}$ s$^{-1}$ (Londsdale et al. 1985).

Fig. 3 suggests that in the HII galaxies, the SBNGs and the late-type spirals, $L_{H\alpha}$ is linearly correlated to $L_{IR}$. This relation is lost for the HII nucleus galaxies. On the other hand, Fig. 4 suggests a poorer correlation between $L_{H\alpha}$ and $L_B$. Consistency with our interpretation of the luminosities in terms of different tracers of star formation: the far–infrared luminosity, like the H$\alpha$ luminosity, is mostly related to the young stellar population, while the B luminosity is mostly related to intermediate-mass stars.

3.2. Size effect and the role of dust in luminosity–luminosity diagrams

In Fig. 3, the fact that $L_{H\alpha}$ increases with $L_B$ suggests that the different correlations found between the luminosities are affected by a “size effect. To take into account this effect, we have compared the ratios $L_{H\alpha}/L_B$ with $L_{IR}/L_B$, where $L_B$ is taken here as an estimator of the stellar mass of the galaxies. In Fig. 5, we can still see a linear increase of the far–infrared emission with the emission in H$\alpha$. These relations suggest that the amount of far–infrared emission per unit of stellar mass increases with the amount of ionized gas per unit of stellar mass.
Fig. 5. Normalized luminosity–luminosity diagram. Taking into account the size effect, active star–forming galaxies show a correlation of the far–infrared luminosity with the Hα luminosity. The SBNGs have lower ratios of ionized gas per unit of stellar mass. This cannot be explained by higher dust extinction, because the ratios of dust per unit of stellar mass are the same for all the active star–forming galaxies.

This behavior is a common characteristic of all the active star forming galaxies.

By comparing the luminosity ratios of the two different types of starburst galaxies, one interesting difference can be seen in all the figures: the SBNGs do not follow exactly the same relations as the HII galaxies. For the two types of starburst galaxies, the relations have the same slopes, but not the same intercept. In Fig. 5, this difference corresponds to a lower amount of ionized gas per unit of stellar mass in the SBNGs than in the HII galaxies. The simplest explanation for this phenomenon is to suppose an higher dust extinction in SBNGs. However, an higher extinction in SBNGs would also contribute to destroy any relation between the blue luminosity and the far–infrared luminosity, but in fact the correlation between these luminosities is better in SBNGs (see Table 2). Actually, if extinction was an important factor, one would have expected to see in SBNGs the far–infrared luminosity increasing faster than the Hα luminosity. The hypothesis of higher dust extinction in SBNGs seems also incoherent with the fact that both types of galaxies have the same mean far–infrared luminosities per unit of stellar mass, and the same mean dust temperature as determined by the comparable ratios of $f_{60}/f_{100}$.

In their study of starburst galaxies, Calzetti et al. (1995; hereafter CBKSH) have found a linear relation between the extinction in the optical, as extrapolated from the UV band, and the ratio $L_{IR}/L_B$. Following their interpretation, an increase of dust in a galaxy corresponds to a lower B luminosity and to a larger far–infrared emission. Applying their interpretation to Fig. 5, the amount of dust extinction in the optical increases from 0 at $\log(L_{IR}/L_B) = -1.0$ to 3 magnitudes at $\log(L_{IR}/L_B) = +1.0$. As one can see in Fig. 5, this interpretation cannot explained the differences between the two types of starbursts, because both span the same range of $L_{IR}/L_B$. Furthermore, the relation shown in Fig. 5, goes opposite to what we should expect from extinction effect: the slopes should be negatives. In Fig. 5, the behavior of $L_{IR}/L_B$ is better interpreted in terms of different SFRs: the SFR increases with
L_{IR}/L_B. The relation found by CBKSH between optical extinction and \( L_{IR}/L_B \) simply reflects the fact that the most active star forming galaxies are also the dustiest, as we have observed before. Therefore, the difference between SBNGs and HII galaxies must corresponds to another phenomenon. Fig. 5 furthermore suggests that this difference should vanish in the more active star forming galaxies.

From Table 2, we see that the correlation between \( L_{H\alpha} \) and \( L_{IR} \) is poorer in the late-type spirals. However, those galaxies have comparable SFRs as the SBNGs or the HII galaxies. The mean temperature of the dust is also lower in the late-type spirals than in the two type of starburst galaxies. One possible explanation is because the star formation in the late-type galaxies happens only in their spiral arms. Consequently, the active star forming regions are more dispersed and the contribution of older stellar population is more obvious in the B band and the far–infrared. This scenario is furthermore supported by the different slopes of the linear regressions, where we can see that both the B luminosity and the far–infrared luminosity increase faster than the H\( \alpha \) luminosity. In the case of the HII nucleus galaxies, the fact that we do not see any correlations between the luminosities, is clearly related to their low mean H\( \alpha \) luminosity. This could only mean that the SFRs on these galaxies is much lower than in the late-type spirals or that in the starburst galaxies. This interpretation is furthermore coherent with their mean ratio \( f_{\alpha}/f_{100} \), which is comparable to galaxies where the dust is mostly heated by old stars.

4. The history of star formation of starburst galaxies

Using \( L_{IR} \) and \( L_B \) as two tracers of SFRs on different time scales, we now proceed to compare the histories of star formation of the various types of star forming–galaxies. To quantify our luminosity–luminosity diagram in terms of SFRs, we have adopted the following model. We simplify the stellar formation process by separating it in two independent functions (Matteucci 1989): \( B(m, t) = \psi(t)\phi(t) \), where \( \psi(t) \) is the SFR and \( \phi(t) \) is the IMF. Parametrizing further the SFR as an exponential function: \( \psi(t) \propto \exp(-t/\tau) \), where \( \tau \) is the characteristic time scale of the star formation. Following this model, short time scales correspond to small values of \( \tau \), and a constant SFR corresponds to \( \tau \rightarrow \infty \). We use a Salpeter’s IMF with an upper mass limit of 100 M\(_{\odot} \) and a lower mass limit of 0.1 M\(_{\odot} \). Following this model, a mean constant SFR over the last 3 Gyr period should yield a ratio \( L_{IR}/L_B = 1 \) (Ghallager & Hunter 1987).

In Fig. 6, we test this model by comparing the sample of active spiral galaxies from Kennicutt (1983) with the sample of early-type galaxies from Hogg et al. (1993). Following Ghallager et al. (1984) and Kennicutt (1983), late-type spirals have produced new stars at roughly constant rates over the last 3 Gyr period (see also Kennicutt et al. 1994). While rapid star-formation has lead to early-type galaxies (Charlot & Bruzual 1991), which have now very low SFR compared to their past values. In Fig. 6, most of the late-type spirals are within a factor 3 of the constant SFR line, while most of the early-type galaxies are clearly below this line. In this paper, we will consider that in a galaxy with \( L_{IR}/L_B > 3 \) the SFR has probably increased by a substantial factor over its historical mean value, while in a galaxy with \( L_{IR}/L_B < 1/3 \) the present SFR has significantly declined.

In Fig. 6, we have also included the sample of Blue Compact Dwarfs (BCDs) and irregular galaxies (Irs) from Thronson & Telesco (1986), and a sample of starburst IRAS galaxies from Allen et al. (1991). Following the adopted model, most of the IRAS starburst lie in a present SFR much higher than their mean past value. The BCDs and Irs also seem to have higher SFR, although at a lower level than the IRAS starburst.

In Fig. 7, we compare the histories of star formation of the different types of starburst galaxies. The HII galaxies are from the UM survey (Salzer et al. 1989) and the Calan–toholo survey (Peña et al. 1991). The SBNGs are composed of the galaxies from the UM survey, the Balzano’s sample (1983) and from the MBG survey (Coziol et al. 1993; Coziol et al. 1994). The last sample is composed of the HII nucleus galaxies (French 1980; Heckman 1980; Stauffer 1983). Comparison of Fig. 6 with Fig. 7 shows that the HII galaxies, the BCDs and the Irs occupy the same region of the diagram. As we have stated earlier, they are of the same nature. As compared to the SBNGs, these samples of galaxies seem to contain a higher fraction of more active starburst galaxies. In part, this difference can be explained by the methods used to detect these objects: surveys based on the presence of lines are slightly biased toward higher active galaxies than surveys based on UV-bright excess. In the case of dwarf galaxies, it is even easier to pick out mostly bright galaxies, which turns out to be also the most active star forming galaxies of the population (Ferguson 1993; Melisse & Israel 1994).

In general, the HII galaxies trace a continuous sequence of luminosity with the SBNGs. This sequence can be interpreted as a sequence in stellar mass. The more massive galaxies (that is, galaxies with \( L_B > 10^9 L_\odot \)), seem to trace a continuous sequence of SFRs. The SFR increases from the HII nucleus galaxies to the SBNGs, and up to the IRAS starburst. Perhaps the most important feature of Fig. 7 is that most of the starburst galaxies are found in the region where the ratio \( L_{IR}/L_B \) is within a factor 3 of the line of constant SFR over a 3 Gyr period. There is very few ultra–luminous infrared galaxies (defined here as galaxies with a ratio \( L_{IR}/L_B > 10 \)).

For comparison, we have included in Fig. 7, some well known starburst from the literature. M82 is one of the most studied starburst galaxy. It is commonly know as the “typical starburst”. In Fig. 7, this galaxy looks more like an extreme case. II Zw 40 is another extreme case. In
Fig. 6. Calibration of the $L_{IR}$ vs. $L_B$ diagram in terms of SFRs. The diagonals correspond to different ratios of $L_{IR}/L_B$. Most of the late-type spirals have ratios $1/3 < L_{IR}/L_B < 3$. The galaxies in this region have a near constant star formation rate over a 3 Gyr period.

Fig. 7. The history of star formation of starburst galaxies. Very few starburst galaxies have $L_{IR}/L_B > 10$. In general, the HII galaxies have higher $L_{IR}/L_B$ ratios than the SBNGs. Most of the SBNGs have a ratio coherent with a near constant star formation rate over the last 3 Gyr.
Fig. 8. The luminosity-luminosity diagram for the AGNs. We discriminate two types of LINERs: the optical LINERs are located in spirals, with present low star formation rates, while the IRAS LINERs are in massive starbursts. The position of the ultra-luminous infrared galaxies (galaxies with $L_{IR}/L_B > 10$) as compared to the Seyfert galaxies suggest that they could be dust rich embedded AGNs associated to a strong starburst.

In our samples, this galaxy is one of the rare examples of a very active dwarf. On the other hand, NGC 7714 deserves its epithet of the archetype of the SBNGs (Weedman et al. 1981). Mrk 710 is one example of the variety of galaxies that are called starburst. This galaxy is directly on the line indicating constant SFR over a Gyr period.

Arp 220, NGC 6240, NGC 3690 and NGC 1614 are all examples of ultra-luminous infrared galaxies (Sanders et al. 1988; Armus et al. 1989). In Fig. 7, the position of the IRAS starbursts is similar to those of the ultra-luminous infrared galaxies, which suggests a similar nature. Actually, the origin of the activity in those galaxies is not very clear. In fact, some of the ultra-luminous infrared galaxies shows optical spectra similar to a Seyfert 2 or of a LINER. Therefore, if an AGN is also present in those galaxies, and contribute to heat the dust, the interpretation of the ratio $L_{IR}/L_B$ in terms of different SFRs is not totally correct. To examine this question further, we compare in Fig. 8 the luminosities of the IRAS starburst galaxies with those of a sample of Seyfert 2 galaxies (Bonatto & Pastoriza 1992), and of two different samples of LINERs: the original sample of LINERs detected in the optical by Heckman (Heckman 1980), and a sample of IRAS LINERs (Allen et al. 1991).

The position of the optical LINERs in Fig. 8 suggests that they reside in galaxies with declining SFRs. On the contrary, all the IRAS LINERs seem to be in a very strong starburst phase. This dichotomy between the two samples of LINERs suggests that we should be careful when we try to determine which phenomenon best explain the optical spectrum of a LINER, in particular, between photoionization of a nonstellar continuum or shock heating related to an ongoing starburst (Ho et al. 1993). By comparison, the Seyfert 2 galaxies have much lower ratios $L_{IR}/L_B$ than the IRAS starburst (note that in this kind of diagram, the Seyfert 1 galaxies are indistinguishable from the Seyfert 2). In Fig. 8, either the AGN do not contributes to heat the dust, and all the Seyfert 2 galaxies are also in a starburst phase, or the AGN contributes significantly and the Seyfert 2 reside in low-star forming galaxies. The problem is probably more complicated as it should also consider the amount of obscuring material collected in the nuclear region (Maiolino et al. 1995).

By comparing the IRAS starbursts with AGNs, we can conclude that the IRAS LINERs and the IRAS starburst galaxies could have a very special nature. Those galaxies could be dust rich embedded AGNs, associated with a strong starburst. Consequently, the HII galaxies and the SBNGs are probably more representative of the starburst phenomenon. Therefore, the most important characteristic of a starburst galaxy should be a mean constant SFR over a few Gyr period.
### Table 3. Massive stars characteristics

| Spectral type | Mass ($M_\odot$) | $L_{bol}$ ($L_\odot$) | $N_L$ (s$^{-1}$) | $L_{H\alpha}$ ($L_\odot$) | $L_{H\alpha}/L_{bol}$ |
|---------------|------------------|------------------------|-----------------|--------------------------|------------------------|
| O5            | 49               | $6.8 \times 10^5$      | $4.2 \times 10^{49}$ | $1.5 \times 10^4$       | $2.2 \times 10^{-2}$   |
| O9            | 22               | $4.6 \times 10^4$      | $1.2 \times 10^{48}$ | $4.3 \times 10^2$       | $9.3 \times 10^{-3}$   |
| B0            | 19               | $2.5 \times 10^4$      | $2.3 \times 10^{47}$ | $8.3 \times 10^1$       | $3.3 \times 10^{-3}$   |
| B0.5          | 15               | $1.1 \times 10^4$      | $1.7 \times 10^{46}$ | $6.1 \times 10^0$       | $5.5 \times 10^{-4}$   |
| B1            | 12               | $5.2 \times 10^3$      | $1.9 \times 10^{45}$ | $6.8 \times 10^{-1}$    | $1.3 \times 10^{-4}$   |

### 5. The difference between HII galaxies and SBNGs

Following our analysis, the principal difference between the HII galaxies and SBNGs resides in their mean ratios $L_{H\alpha}/L_B$ and $L_{H\alpha}/L_{IR}$. This difference of ratios explain why, in Fig. 3 and in Fig. 4, the SBNGs do not occupy the same region of the diagram as the HII galaxies and the disk HII regions. In SBNGs both ratios are near 1000 while in the HII galaxies and in the late-type spirals, the same ratios are near 100. We have also earlier that this phenomenon cannot be explained by a higher dust extinction in the SBNGs. In this section we explore further this problem by comparing the energy budget of the different starburst galaxies.

The energy budget of ionized regions can be checked by comparing the ratio of $L_{H\alpha}$ with $L_{IR}$. The idea behind this method is that the energy produced by a star to ionized the gas is also sufficient to heat the dust which emits in the far–infrared band (Devereux & Young 1990; Calzetti et al. 1995). Therefore, the different ratios $L_{H\alpha}/L_{IR}$ should be comparable to the ratio of the Hα luminosity to bolometric luminosity ($L_{bol}$) of ionizing stars of different spectral types (Devereux & Young 1990). Those ratios can be found in column 6 of table 3, together with the parameters used to evaluated them. In column 1, we have the spectral type of the stars. In column 2, the masses of the stars were calculated using the relation (Allen 1973): 

$$\log(L/L_\odot) = 3.45 \log(M/M_\odot).$$

Columns 3 and 4 gives respectively the bolometric luminosities and the number of ionizing photons, as calculated by Panagia (1973). The Hα luminosity in column 5 was calculated using the relation: 

$$N_L = 2.2 \times 10^{-12} L_{H\alpha} S^{-1}.$$

In Fig. 9, overplotted on the $L_{H\alpha}$, $L_{IR}$ diagram, we have reported the ratios from column 6 of table 3. Note that the different ratios produce lines, because they correspond in fact to cluster of stars. In Fig. 9, the $f$ vector is a correcting factor between the far–infrared luminosity and the bolometric luminosity (Devereux & Young 1990). In this figure, we give also the vector corresponding to a correction of 1 magnitude dust extinction. A 1 magnitude dust extinction is the mean value usually evaluated in starburst galaxies by the Balmer decrement (Balzano 1983; Peña et al 1991; Masegosa et al. 1994; Calzetti et al. 1995). As a byproduct, this kind of diagram could also indicates the equivalent spectral type of the ionizing stars.

![Fig. 9. The energy budget of starburst galaxies. The continuous lines give the ratios between the ionizing luminosity and the bolometric luminosity for stars of different spectral types. The vector R corresponds to the correction between the bolometric luminosity and the far–infrared luminosity ($f$), and the correction for an optical extinction $A_V = 1$ magnitude.](image)

Taken at face value, Fig. 9 suggests that the HII regions of SBNGs are dominated by B type stars.

In the literature, we can find similar reports of this phenomenon. For example, in their study of the UM galaxies, Salzer et al. (1989) have found that if we use the B luminosity to determine the number of O7 star present in the starburst galaxies, the ratio of massive stars decreases in the SBNGs as compared to the HII galaxies (see their
Fig. 10. The energy budget of the SBNGs considering the maximum number of corrections as suggested by CBKH (see details in the text). The starburst galaxies from CBJKH have been grouped following their level of extinction, as determined by the UV spectral index $\beta$. The position of a galaxy in this diagram does not depend on its level of extinction.

In their study of the Markarian SBNGs, Deutsch & Willner (1986) have also observed a better correlation between $L_B$ and $L_{IR}$, which they explained by a greater contribution of B type stars to heat the dust. Finally, by modeling the Bracket lines of a sample of starburst galaxies, Doyon et al. (1992) have found values suggesting a higher number of intermediate-mass stars, which they interpreted as a sign of a truncation of the IMF of starburst galaxies towards intermediate-mass stars (they proposed an upper-mass limit of, at most, 30 $M_\odot$, which is closer to an O9 star than an O7 star, see Table 3).

In their study of starburst galaxies, CBKSH have also determined the energy budget of their sample of starburst galaxies. One of their conclusions is that the stellar populations responsible for the observed UV and optical spectrum is sufficient to explain the far-infrared fluxes in the IRAS bands. However, they have determined that only 30% of the IRAS flux could be attributed to warm dust. To fit their model in the far-infrared, they had also to suppose that 30% of the warm dust was due to massive stars embedded in dusty regions, which were not manifest through UV or optical emission. In Fig. 10, we have applied all their corrections to our sample of SBNGs, as well as to the sample of starbursts of CBKSH. All the galaxies were also corrected for internal extinction, supposing a 1 magnitude extinction for the SBNGs. In Fig. 10, even with the corrections, we cannot change the observed ratios $L_{H\alpha}/L_{IR}$ to make them compatible with stars more massive than spectral type O5. The sample of galaxies of CBKSH seems to work better, because it is slightly biased towards more active galaxies (as judge from the mean far-infrared luminosity Log$_{10}L_{IR} = 10.2$). In Fig. 10, we have grouped the starburst of CBKSH following their level of extinction, as determined by the UV spectral index $\beta$. Increasing amount of dust obscuration corresponds to increasing values of $\beta$. As can be seen, the position of a galaxy in Fig. 10 does not depend on the amount of extinction.

To reproduce ratios $L_{H\alpha}/L_{IR}$ compatible with those of massive stars of spectral type O5 and earlier, we have to suppose a mean optical extinction of 3 magnitudes. This however is inconsistent with the mean extinction value, as estimated by the Balmer decrements or the UV spectral index (Balzano 1983; CBKSH). A mean correction of 3 magnitudes would also imply an even greater correction of the B luminosity (by about a factor 3), because the B band is more affected by extinction than the V band. The corrected bolometric luminosities of the SBNGs would then be much more higher than normal HII regions, and comparable to those of nearby AGNs. But, such luminous objects surely would give other signs of their high activity. In the case of SBNGs, we do not see these signs. In fact, the only possible case of extreme dust rich starburst galaxies in our samples are the IRAS starburst or the ultra-luminous infrared galaxies. But, all these galaxies produce far-infrared emission much higher than the SBNGs.

We can also suppose that in SBNGs less than 70% of the far-infrared emission comes from the hot dust. Sauvage & Thuan (1992) have determined that between 50% to 80% of the far-infrared emission is due to cool dust, depending on the morphology of the galaxy. Considering that the mean temperature of the dust in SBNGs is much higher than in the late-type galaxies (see Fig. 2), the value of 30%, as determined in the model of CBKSH, is probably the lowest limit possible for starburst galaxies. We could also suppose a higher ratio of non-ionizing stars. However, to make the SBNGs similar to the HII galaxies, we would have to suppose that as much as 90% of the stars are invisible in the optical and in the UV.

The main difference between the HII galaxies and the SBNGs could be a difference of stellar population. Supporting this interpretation, we show in Fig. 11, the distribution of the $H\alpha$ equivalent width ($W_\lambda(H\alpha)$) of the different types of starburst galaxies. The equivalent width of
the $H\alpha$ emission line is useful to estimate a relative population of massive to less-massive stars, because $H\alpha$ traces the highest mass stars and the continuum at the wavelength of $H\alpha$ traces lower mass stars. Despite strong dependences on the metallicity, the upper-mass limit or the slope of the IMF, the equivalent width is basically determined by the evolution of the HII regions (Copetti et al. 1986): it decreases with the age of the HII region. From Fig. 11, it is clear that the stellar population of the SBNGs is much different than from those of the HII galaxies. The dashed line in Fig. 11 corresponds to the median value for normal disk HII regions (Kennicutt et al. 1989). The equivalent width of the metal poor HII galaxies are comparable to those of normal disk HII regions. The equivalent width is 10 times lower in SBNGs, and almost a 100 times lower in the less active HII nucleus galaxies.

6. The regulating role of massive stars in the evolution of galaxies

We see two possibilities to explain the difference of stellar populations between SBNGs and HII galaxies. The first one is to suppose that in SBNGs the IMF is truncated towards intermediate-mass stars (Doyon et al. 1992). The second possibility is that the HII regions of SBNGs are more evolved on the average than in normal HII regions. Without further observations, we cannot discriminate what is the exact solution. The main reason is that we still do not know the details of how stars are formed, and in particular, if their formation implies a universal IMF. However, we believe that the actual observations, based on studies of molecular clouds and of star formation in external galaxies, are in better agreement with an universal IMF (Kennicutt et al. 1994). Furthermore, in luminous starburst it is more often proposed that the IMF is truncated toward massive stars (Rieke et al. 1980; Terlevich & Melnick 1985; Rieke 1991).

The alternative to a variation of IMF is to consider that the HII regions of SBNGs are more evolved than in HII galaxies. In SBNGs, this would implies burst stellar population older than $10^7$ yr. This scenario is however incompatible with a near constant SFRs on a time scale of 3 Gyrs. It is important to note that the method that we have used to determined the history of star formation of our galaxies is not sensitive to time scale shorter than 1 Gyr (Gallagher & Hunter 1987). Therefore, the SFR of the starburst galaxies could have changed on shorter time scales. In fact, it is possible to reproduce a mean constant star formation rate on a few Gyr scale by a sequence of short bursts (Coziol & Demers 1995). To be able to distinguish some evolution of the star forming regions, we would need bursts of star formation with $\tau$ of the order of $10^7$ or $10^8$ (Charlot & Bruzual 1991). The large population of intermediate-mass stars observed in SBNGs would therefore suggests that the SBNGs have experienced a succession of many short duration bursts.

Our observation are qualitatively consistent with the stochastic self propagation star formation theory (SSPSF), as proposed by Gerola et al. (1980). This theory was originally elaborated to explain the burst of star formation in HII galaxies. As a main feature, it predicts that the star formation in HII galaxies are happening in a sequence of bursts separated by long periods of time. The active agents are the massive stars: via supernovae explosion, star formation is propagated or stopped in the near neighborhood of an active region, depending on the matter available. The probability of propagation of the star formation increases with the mass of the galaxy. In small galaxies the frequency of the bursts will be low, while in more massive galaxies it will approach near constant star formation rates. Furthermore, the frequency of bursts could determined the level of chemical evolution of a starburst galaxy. Therefore, SBNGs galaxies are more
evolved than HII galaxies because they have experienced more bursts of star formation.

The SSPSF theory is also consistent with the luminosity biases observed between our different samples. In low-mass galaxies, the variation of luminosity between two bursts is very large, and could reach as much as a 7 magnitudes (Gerola et al. 1980). Therefore, it is more easy to detect an active HII galaxy than its non-active counterpart. On the contrary, the luminosity of massive galaxies with multiple bursts will reach a certain equilibrium, and the majority of SBNGs will be found with a luminosity value as predicted by near constant SFRs. Consequently, massive starbursts, with unusually high SFRs, are better detected in the far–infrared than in the blue.

7. Summary and conclusion

We have verified that the different luminosities of various star forming galaxies can be used to trace SFRs over different time scales. Consistent with this idea, the Hα emission is better correlated to the far–infrared emission than to the B emission. Furthermore, the amount of far–infrared emission per unit of stellar mass increases linearly with the amount of ionized gas per unit of stellar mass. Therefore, both $L_{H\alpha}$ and $L_{IR}$ are tracers of recent star formation rates on time scales of $10^7$ or $10^8$ yr, whereas $L_B$ is related to intermediate-mass stellar population, and traces SFRs on a time scale of a few Gyr.

Using $L_{IR}$ and $L_B$, and a simple model of star formation, we have compared the star formation histories of different samples of star forming galaxies. We have shown that our model is consistent within a factor 3 with the history of star formation of normal field galaxies. Applying this model to the two types of starburst galaxies, we have found that most of them have a ratio $L_{IR}/L_B$ compatible with a mean SFR near constant over a few Gyr period.

The HII galaxies have comparable ratios than the SBNGs, and trace a continuous sequence in mass with the SBNGs. The HII nucleus galaxies represent the low-luminosity end of the SBNGs. There are very few ultra-luminous infrared starburst galaxies. The nature of these galaxies is not well determined. In particular, the IRAS starburst and the IRAS LINERs could be dust–rich embedded AGNs with a very strong starburst.

Comparing the different linear relations for the HII galaxies and the SBNGs, we have found some interesting differences. The amount of ionized gas per unit of stellar mass is lower in the SBNGs than in the HII galaxies. Furthermore, the amount of far–infrared emission per unit of ionized gas is higher in the SBNGs than in the HII galaxies. We have verified that these effects cannot be explained by supposing higher dust extinction in the SBNGs. To examined further these differences, we have checked the energy budget of the different starbursts. Our analysis suggests that the burst populations of the SBNGs are dominated by B type stars. We see two possibilities to explain the difference of stellar populations between the SBNGs and the HII galaxies: either the IMF in SBNGs is truncated towards intermediate-mass stars, or the HII regions of SBNGs are more evolved than in the HII galaxies.

We argue that our observations are compatible with the idea of multiple bursts of star formation in the SBNGs. This would explain the great number of intermediate-mass stars in SBNGs. Our analysis is qualitatively consistent with the SSPSF theory, which predicts that the frequency of bursts increases with the mass of the galaxy. In more massive galaxies, this frequency approaches a near constant star formation rates. Following this theory, the frequency of bursts could also determined the level of chemical evolution of a starburst galaxy, which could explain why the SBNGs are more evolved than the HII galaxies. However, it still remains to understand the details of this mechanism, and to better determine the importance of the starburst phase in the evolution of these galaxies.

The possibility that the bursts are regulated by the evolution of massive stars and could be prolonged over longer periods of time could explain the many cases of relatively isolated starburst galaxies. Another possibility related to the prolonged starburst phase, is perhaps the chance to identify the initial event that gave birth to the nearby population of isolated starburst galaxies. For example, considering a redshift distribution $z < 0.03$ for the SBNGs, a crude calculation show that the time elapsed between this event and the interacting blue galaxies at $z = 0.2$ is only of the order of a few Gyrs. This is comparable to the prolonged time scale of the starburst galaxies. Therefore, the signs of past interacting events are not necessarily extinct, and the population of distant blue galaxies has not necessarily completely disappeared today.

Acknowledgements. I wish to thank Vicky Meadows for providing unpublished data on the IRAS galaxies, and Clarissa Barth for reading and commenting this work. I wish also to thank the referee, James Lequeux, for the comments and suggestions that greatly helped to improve this paper. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The financial support of the brazilian FAPESP (Fundaçao de Amparo à Pesquisa do Estado de São Paulo), under contracts 94/3005–0 is gratefully acknowledged.

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Log([NII]/Hα)

Fig.1
Fig. 2

Histograms showing the distribution of SBNGs, HIIGs, NGC late-type, and NGC early-type galaxies. The x-axis represents the ratio $f_{60}/f_{100}$, and the y-axis represents the number of galaxies N.
Fig. 3

Log (L_{\text{IR}}/L_\odot) vs. Log (L_{\text{H\alpha}}/L_\odot)

- + NGC late-type
- □ HII galaxies
- ● SBNGs
- × HII nucleus galaxies
Log(L_{IR}/L_B)

SBNGs

[HII] galaxies

+ NGC late-type

× HII nucleus galaxies

Log(L_{H\alpha}/L_B)
Fig. 7

- HII galaxies
- SBNGs
- Well known starbursts
- HII Nucleus galaxies

Log \( \frac{L_{\text{IR}}}{L_\odot} \)

Log \( \frac{L_{\text{B}}}{L_\odot} \)
Log($L_{IR}/L_\odot$) vs. Log($L_{B}/L_\odot$)

- Starbursts (IRAS)
- Seyfert 2
- LINERs (opt.)
- LINERs (IRAS)

Fig. 8
Fig. 9

- NGC late-type
- HII galaxies
- SBNGs
- HII nucleus galaxies

Log \( \frac{L_{\text{H}\alpha}}{L_\odot} \)

Log \( \frac{L_{\text{IR}}}{L_\odot} \)

Av = 1 mag
Log \( \frac{L_{\text{IR}}}{L_{\odot}} \)

\[ \text{SBNGs (corrected)} \]

- \( \beta > 0 \)
- \( 0 > \beta > -1.0 \)
- \(-1.0 > \beta > -2.0 \)
- \( \beta < -2.0 \)

Fig. 10
Fig. 11

The figure shows the distribution of $W_\lambda(H\alpha)$ for different types of galaxies:

- **HII Nucleus Galaxies**
- **SBNGs**
- **HII Galaxies**

The x-axis represents $\log W_\lambda(H\alpha)$, and the y-axis represents the number of galaxies ($N$) in each bin.