How old are the HII Galaxies?

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ABSTRACT

Using a novel approach we have reanalyzed the question of whether the extreme star forming galaxies known as HII galaxies are truly young or rejuvenated old systems.

We first present a method of inversion that applies to any monotonic function of time describing the evolution of independent events. We show that, apart from a normalization constant, the “true” time dependence can be recovered from the inversion of its probability density function.

We applied the inversion method to the observed equivalent width of H\textbeta (EW(H\textbeta)) distribution for objects in the Terlevich and collaborators Spectrophotometric Catalogue of HII galaxies and found that their global history of star formation behaves much closer to the expectations of a continuous star formation model than to an instantaneous one. On the other hand, when the inversion method is applied to samples within a restricted metallicity range we find that their history of star formation behaves much closer to what the instantaneous model predicts.

Our main conclusion is that, globally, the evolution of HII galaxies seems consistent with a succession of short starbursts separated by quiescent periods and that, while the emission lines trace the properties of the present burst, the underlying stellar continuum traces the whole star formation history of the galaxy. Thus, observables like the EW(H\textbeta) that combine an emission line flux, i.e. a parameter pertaining to the present burst, with the continuum flux, i.e. a parameter that traces the whole history of star formation, should not be used alone to characterize the present burst.

Key words:

1 INTRODUCTION

HII galaxies are dwarf emission line galaxies undergoing a burst of star formation. They are characterized by strong and narrow emission lines originated in a giant star forming region which dominate their observable properties at optical wavelengths. Most HII galaxies are in fact Blue Compact Galaxies (BCG’s), but to the different selection criteria only a small percentage of BCG’s, i.e. those with the largest emission line equivalent widths, are HII galaxies. We will stick to the name “HII galaxies” to refer to the star forming systems selected from objective prism surveys and having strong narrow emission lines.

Various studies of the spectroscopic properties of HII galaxies in optical wavelengths revealed systems of very low heavy element abundances and high rates of star formation. Earlier morphological studies have suggested that a large proportion of the sample of HII galaxies observed are compact and isolated (Melnick 1987). This, together with the spectroscopic properties indicating low to very low metallicity plus a very young stellar content, led workers in the field ever since their discovery, to question whether these systems are truly young galaxies or made up by a few bursts separated by long quiescent periods in the lifetime of the galaxy. Reviews of the general properties of HII galaxies can be found in Melnick (1987), Terlevich (1988), the “Spectrophotometric Catalogue of HII Galaxies ” (hereafter SCHG, Terlevich et al. 1991), Stasińska & Leitherer (1996), Telles & Terlevich (1993; 1995; 1997), Telles, Melnick & Terlevich (1997), and more recently in the excellent review by Kunth & Östlin (2000).

More than 20 years ago Dottori (1981) suggested the use of the EW(H\textbeta) to detect differences in age among HII regions. Dottori & Bica (1981) applied the EW(H\textbeta) method to 31 LMC and SMC HII regions and found an uneven distribution of ages with most HII regions clustering at an EW(H\textbeta) of about 70Å and only 5 HII regions with EW(H\textbeta) >120 Å.

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This result led them to suggest that a galaxy-wide burst of star formation did occur 6 to 7 Myr ago in the Magellanic clouds.

The SCHG compiles, among other parameters, line ratios and equivalent widths for several hundred HII galaxies, and gives the opportunity of investigating the ages of actively star forming galaxies to find whether there is among them a truly young system. The SCHG is particularly appropriate for this task because, due to the selection criterion used to find them, the HII galaxies in the SCHG are probably the youngest systems that can be studied in any detail. This is due to the fact that the SCHG samples the narrow emission line galaxies with the highest equivalent width in their emission lines, and is particularly biased in the local universe (at z < 0.04) towards strong and compact emission in [OII] 5007Å. This bias is introduced by the technique used in all the 3 sources of data, the Cambridge, Tololo and University of Michigan surveys, that searched for strong emission using a Schmidt camera (either the UK or the Tololo Schmidt at the AAT and CTIO respectively) equipped with low dispersion objective prisms and IIIaJ emulsion, a combination that produces a sensitivity range from 3500˚A to 5300˚A.

One of the early surprising results of the SCHG was that even in this strong emission line biased sample, there are less than 10% of the systems with EW(Hβ) > 150 Å (Fig. 1, left). In contrast, as shown in Fig. 1, right, a quick star formation proceeds uniformly with time, about half of which are less than 10% of the systems with EW(Hβ) > 150 Å. This result led them to suggest that a galaxy-wide burst of star formation occurred 6 to 7 Myr ago in the Magellanic Clouds. This is due to the fact that the SCHG samples the narrow emission line galaxies with the highest equivalent width in their emission lines, and is particularly biased in the local universe (at z < 0.04) towards strong and compact emission in [OII] 5007 Å. This bias is introduced by the technique used in all the 3 sources of data, the Cambridge, Tololo and University of Michigan surveys, that searched for strong emission using a Schmidt camera (either the UK or the Tololo Schmidt at the AAT and CTIO respectively) equipped with low dispersion objective prisms and IIIaJ emulsion, a combination that produces a sensitivity range from 3500˚A to 5300˚A.

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Many explanations have been put forward for the lack of systems with high EW(Hβ). Chiefly among them, time dependent escape of ionizing photons, dust affecting either the ionizing radiation or the visibility occurring preferentially during the first 3 Myrs, the presence of an underlying old population, uncertainties with the models, etc. The wide variety of possibilities has had the negative effect of almost halting the research in this important area.

We decided to take a fresh and different approach based as much as possible on unsupervised analysis of samples. We describe here a new method that, under the assumption that the catalogue samples a population of starforming galaxies at different ages, allows the reconstruction of the time evolution of the burst Balmer emission lines equivalent width, from their observed distribution.

2 THE METHOD

2.1 Brief description

In this section we present our probability density distribution inversion method. In contrast with other methods, we need only to assume that the birth rate of starbursts in the sample is random, i.e. there is no relation in the occurrence of starbursts in different galaxies, and that the time evolution of the observed parameter is monotonic.

In fact, starbursts have a variety of ages, and hence a range of equivalent widths of the emission lines. Two limiting cases are commonly used to describe their time evolution. They are the coeval starburst (SB) case, which assumes that all stars are formed simultaneously in an instantaneous SB episode, where the characteristic time $\tau_{SB}$ is short compared to the age of the galaxy ($\tau_{SB} \ll t$), and the continuous star formation case, which assumes the star formation rate to be constant in time. The first case is widely applied for individual, moderate mass star clusters, whereas the second one is assumed to be an average characteristic of the massive star forming systems. In both cases the evolution of the EW(Hβ) is a monotonically declining function of time. The continuous star formation could also be approximated as a sequence of small “mini-bursts” localized within a rather small region in space and separated by short time intervals (see, e.g. Sillich et al. 2002).

If the starbursts birth rate, $R(t)$, and the evolution of an individual starburst emission lines equivalent width are known, then the probability distribution of starbursts with equivalent width is given by (e.g. Scalo & Wheeler, 2001)

$$\rho_w(EW) = \frac{1}{N_0} \frac{dR[t(EW)]}{dEW},$$

where $N_0$ is the total number of objects in the sample, and the function $t(EW)$ describes the time evolution of the EW and is defined by the star formation mode.

Assuming a constant rate of star formation across the volume of the catalogue,

$$R(t) = \frac{N_0}{t_{SF}} = \text{Const}$$

one can obtain the normalized probability density as,

$$\rho_w(EW) = -\frac{1}{t_{SF}} \frac{dt(EW)}{dEW},$$

where $t_{SF}$ is the total evolutionary time to be considered.

For the case of a monotonic time dependence the inverse transformation of the EW distribution into a function $EW(t)$ is, from the relation (2):

$$t(EW) = - \sum_{i} t_{SF} \rho_i(EW) \Delta EW = \frac{t_{SF}}{N_0} \sum_{i} \Delta N_i,$$

where the limits $i$ and $i_{max}$ correspond to the bins with equivalent width EW and $EW_{max}$ respectively.

Therefore, the shape of the time dependence of the equivalent width can be recovered from the observed distribution. On the other hand, the presence of an integration constant shows that the characteristic star formation time scale $t_{SF}$ cannot be obtained from the observed EW distribution alone.

2.2 Numerical simulations

We have run a number of tests on the analytical description above. Here we show the case for the evolution of the EW(Hβ) based on the expected evolution of an instantaneous burst.

We first generated a sample of random numbers homogeneously distributed in time, which we associate with the starburst birthrate. For each value the corresponding equivalent width was calculated using the predicted evolution from SB99 models. Panels a and b of figure 2 show the run of the...
**Figure 1.** The equivalent width distribution of HII galaxies from the SCHG is plotted on the left. Clearly, and contrary to model expectations, there are only a few systems with EW(Hβ) > 150 Å. The predicted time evolution of a coeval population for a Salpeter IMF with 100M⊙ and 0.1M⊙ upper and lower mass limit respectively is plotted on the right. For a random population with a constant production rate and considering that after 6.5 Myr a system will no longer be considered an HII galaxy, about equal number of systems with ages below and above 3.2 Myr are expected, i.e. about equal number of systems with EW(Hβ) above and below 150-200 Å.

**Figure 2.** Panel a shows the sample of random numbers homogeneously distributed in time, which we associate with the starburst birthrate. Panel b shows the adopted model, same as figure 1. Panel c shows the computed distribution function of equivalent widths. Panel d shows the inversion of panel c distribution function using equation 3. Note that the inversion closely reproduces the input model.
burst rate and the adopted evolution of the EW(H\(\beta\)) respectively. Panel c shows the resulting probability density distribution function of equivalent widths. This represents the distribution of EW(H\(\beta\)) in the homogeneously distributed instantaneous burst model catalogue. Using equation 3 we inverted the catalogue EW probability density distribution function shown in panel c and the reconstructed function is shown in panel d. As expected from the analysis above, the inverted distribution function reproduces remarkably well the shape of the input time evolution of the equivalent widths.

3 APPLICATION TO HII GALAXIES

We have applied the inversion method to several samples of HII galaxies and giant HII regions. We show here only the results for the SCHG that represents the more extreme case of bias towards strong line HII galaxies. The results for other samples will be published elsewhere but the main conclusions of the present paper are unchanged by the extended sample analysis.

The results of the inversion are shown with the thick line in figure 3 while the thin lines show the model predictions for the instantaneous burst (left panel) and for the continuous star formation (right panel) cases. It can be seen from figure 3 that the shape of the single burst model prediction is very different from that of the reconstructed evolution function of the EW(H\(\beta\)). The expected evolution of the EW(H\(\beta\)) will be different for different initial conditions in the models like the upper limit or slope of the IMF. We found that invariably all the predicted evolution curves have a convex shape (see figure 6 for different IMF values) while the inversion shows a concave shape. In what follows we will use as reference for the model corresponding to the instantaneous burst the prediction for \(M_{\text{up}} = 120\) M\(\odot\) and Salpeter slope. The reason being that the sample is strongly biased towards high excitation systems suggesting the need for a combination of relatively low metal content and a hot ionizing cluster to obtain it. This implies that stars more massive than 40-50 M\(\odot\) should be present at zero age.

On the right panel we can see that models with continuous star formation are in closer agreement with the shape of the time evolution of the EW(H\(\beta\)). This rather surprising result perhaps indicates that the presence of older stars is affecting the continuum luminosity, consistent with earlier suggestions from, e.g. Dufour et al. (1996), Garnett et al. (1997), Legrand et al. (2000).

3.1 Continuum colour and age.

To test on the somehow unexpected result of the previous section, we have analyzed other time dependent parameters that could provide independent information about the global age or evolutionary stage of HII galaxies.

The continuum colour is one of such age indicators. Particularly sensitive to early age are those colours that like Johnson's U-B, bridge the \(\lambda\lambda 3800 \text{\AA}\) to 4000\text{\AA} region. For this analysis, we selected those HII galaxies with the lowest dust reddening correction (about 220 HII galaxies) and compared them with SB99 estimates of the colours of an evolving stellar population.

In figure 4 we have plotted the EW(H\(\beta\)) and the \(\lambda\lambda 3730/5010\text{\AA}\) colour defined as the ratio of the intensities of the adjacent continua to the [OII]\(\lambda 3727\text{\AA}\) and [OIII]\(\lambda 5007\text{\AA}\) emission lines.

Figure 4 also shows in thick lines the evolution of the instantaneous and the continuous star formation models. The digits along the curves represent the age of the models in units of Myr.

If HII galaxies were truly evolving as continuous star forming systems, they will not depart much from the continuous star formation line. Furthermore we will expect a symmetric distribution with respect to the continuous star formation curve. This, however, is not the case for the sample of HII galaxies. Most of the observed values are above and/or to the left of the continuous star formation model predictions.

In Figure 4 we have also plotted the lines corresponding to multiple burst models. The thin solid lines represent the evolutionary sequence path for individual bursts from a sequence of identical instantaneous starbursts, separated by 50 Myr quiescent intervals. The lines correspond to the bursts starting at 50, 150, 350, and 750 Myr, respectively. The thin dashed lines show the evolution of a second burst which occurs 900 Myr after the initial one for a range of bursts mass ratios. The mass ratio of the second to the first starburst changes from the right top to the left bottom lines as \(10^{-2}, 5 \times 10^{-3}\) and \(10^{-3}\), respectively.

It is possible to see that both the position and the scatter of the points in the EW(H\(\beta\)) vs. colour diagram, are consistent with a population of galaxies undergoing multiple bursts of star formation during their cosmological evolution. It is interesting to note the almost complete absence of points to the right of the instantaneous case suggesting a good agreement between models and observation. Reassuringly, the highest observed EW(H\(\beta\)) is also consistent with the model predictions.

3.2 Metallicity and age.

Another parameter that is expected to change in galaxies with age is their metal content. In particular, Oxygen that represents more than 40 percent in mass of the metals, seems to be a good metallicity indicator given that is mostly produced in massive stars with little time delay (see, e.g. Pagel 1998).

To investigate the behaviour of the metallicity of HII galaxies versus their EW(H\(\beta\)) we have used the compilation of the best determinations of O/H in HII galaxies (Denicoló, Terlevich & Terlevich 2002). In figure 5 we have plotted metallicity and EW(H\(\beta\)) for the 183 star forming galaxies of the Denicoló et al. compilation. Figure 5 shows a clear relation with EW(H\(\beta\)) albeit with a lot of scatter. The tendency is in the sense that high metallicity HII galaxies show lower EW(H\(\beta\)) while low metallicity HII galaxies have invariably high EW(H\(\beta\)).

While a detailed analysis of the relation between metallicity and EW(H\(\beta\)) and its time evolution, requires galactic chemical evolution studies, outside the scope of this work and will be dealt with in a separate paper, the inspection of simple multiple burst models (Pilyugin & Edmunds 1996, Pilyugin 1999), nevertheless, allows as to predict that by selecting a sample within a narrow range of metallicities,
Figure 3. Application of the inversion method to the SCHG. The thick line shows the inversion results using equation 3 on the observed equivalent width distribution of HII galaxies (See left panel of Fig. 1). The thin line shows the model predictions for an instantaneous burst (left panel) and for continuous star formation (right panel).

Figure 4. The colour vs. equivalent width plot for the models and the 217 HII galaxies from our sample. The numbers on the model tracks represent the star cluster age (from 1Myr to 9Myr and from 1Myr to 1000Myr for the instantaneous and continuous star forming models, respectively). The thin solid lines show the evolution of a system following a sequence of identical bursts separated by 50 Myr time intervals. For simplicity we plotted only 4 results, i.e. those starting at 50, 150, 350 and 750 Myr. Dashed lines display evolutionary trends for the secondary starbursts occurring 900 Myr after the initial instantaneous burst of star formation. The ratio of the secondary to the initial starburst mass drops from the right top to the left bottom like $10^{-2}$, $5 \times 10^{-3}$ and $10^{-3}$, respectively.
and under the assumption that in short time scales, i.e. less than 10 Myrs, very little (if any) contamination due to the present burst occurs (e.g. Roy and Kunth, 1995), we may be able to construct a sample with a narrow range in its chemical evolutionary age. If this is the case, the inversion of the EW(Hβ) distribution of a sample with a narrow metallicity range may recover a star formation history more closely related to a single event.

For this test, we have selected from Denicoló et al. (2002), the sub-sample of 70 galaxies covering the range 7.50 < 12 + log (O/H) < 8.25. The result of the inversion of the distribution for this sample restricted in O/H is shown in figure 6 together with the predictions from three SB99 models. Two of the models represented in the figure, correspond to a Salpeter slope IMF having upper mass limits of 100M⊙ and 30M⊙ respectively, the other corresponds to an upper mass of 120M⊙ and an IMF slope of 3.0, i.e. steeper than the Salpeter case.

Clearly, the inversion has yielded an evolution whose shape is very close to that of the instantaneous models; furthermore the inversion seems more in agreement with an IMF with Salpeter slope and an upper mass limit intermediate between 30M⊙ and 100M⊙, or with a steeper slope IMF.

The simplest interpretation consistent with our findings is that there are two different time scales for the evolution of HII galaxies on the metallicity - EW(Hβ) plane.

On a time scale of about 106 yr after any starburst, the evolution on the metallicity - EW(Hβ) plane proceeds vertically downwards as it is associated with a rapid decrease of the EW(Hβ) as shown, e.g. in figure (1, right) and with basically no change in the metal content of the ionized gas.

On time scales of order of 107 yr there is the secular or cosmological evolution of the ISM metal content which reflects on the stellar population build-up.

The superposition of these two time scales results in the dispersion observed in figures 4 and 5.

Our findings are also consistent with the idea that the observed value of the EW(Hβ) results from the emission produced in the present burst superposed on the continuum generated by the present burst PLUS all the previous star formation.

4 CONCLUSIONS

We have developed a simple inversion tool that allows to reconstruct from observed probability density distributions of some monotonical parameter, its time evolution.

We applied the inversion method to the EW(Hβ) distribution of a sample of 217 extreme star forming galaxies from the SCHG. We have shown that, considering the sample as a whole, its EW(Hβ) evolution is not well described by a coeval burst model, and that HII Galaxies seem to have a star formation history that is closer to that predicted by a continuous star formation model.

The simplest interpretation is that while the observed emission lines track the present burst, the underlying continuum contains the whole history of star formation of the HII galaxy.

Even though HII Galaxies are selected by their strong emission lines, they are not truly young galaxies. Most of them have undergone substantial star formation probably during the previous 100 - 1000 My to the present burst.

The situation changes when the analysis is restricted to a sub-sample covering a narrow range in metallicities (7.50 < 12 + log (O/H) < 8.25). In this case the EW(Hβ) evolution seems well described by a coeval burst model with an IMF having an upper mass limit around 80 M⊙.

Clearly it would be very interesting to extend the method to the analysis of larger samples of galaxies like, e.g., that one provided by the Sloan Digital Sky survey.

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Figure 5. Metallicity vs. EW(H$\beta$) from Denicoló et al. (2002) compilation. The rectangle isolates the selected restricted metallicity range used for the analysis (see text). It engulfs 70 objects.

Figure 6. The inversion of the time evolution of the EW(H$\beta$) for the restricted metallicity range subsample. The thick solid line represents the inversion, and the thin dashed and dotted lines represent model predictions (SB99) with three different upper mass values and two different slopes for the IMF, as labelled.
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