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ON THE EARLY EVOLUTION OF YOUNG STARBURSTS

D. Rosa González,[1] H. Schmitt,[2] E. Terlevich,[1] and R. Terlevich[1]

RESUMEN

En este trabajo estudiamos las propiedades de la emisión en radio de un conjunto de galaxias HII, con el propósito de detectar regiones de formación estelar jóvenes, en las cuales las primeras explosiones de supernova están teniendo lugar. Las distribuciones espectrales de energía observadas tienen tres comportamientos diferentes: (1) hay galaxias con una distribución de energía del tipo sincrotrón, (2) galaxias con espectro térmico y (3) galaxias que presentan absorción libre-libre a longitudes de onda larga. Este último caso es un indicador de la presencia de un cúmulo estelar masivo que se encuentra aún dentro de la nube molecular progenitora. Comparando las tasas de formación estelar (SFR) determinadas a partir de líneas de recombinación con las tasas determinadas a partir de las observaciones de radio encontramos que el SFR(Hα) es en promedio 5 veces mayor que el SFR(1.4 GHz). Estos resultados sugieren que la emisión de estas galaxias está dominada por un episodio de formación estelar reciente y masivo en el cual las primeras supernovas están empezando a explotar. Concluimos que el déficit de emisión sincrotrón en aquellas galaxias con los mayores anchos equivalentes de Hβ, solamente puede ser explicado si estas galaxias son extremadamente jóvenes con edades menores que 3.5 millones de años de forma que aún no han explotado las primeras supernovas de tipo II.

ABSTRACT

We studied the radio properties of very young massive regions of star formation in HII galaxies, with the aim of detecting episodes of recent star formation in an early phase of evolution where the first supernovae start to appear. The observed radio spectral energy distribution (SED) covers a behaviour range: (1) there are galaxies where the SED is characterized by a synchrotron-type slope; (2) galaxies with a thermal slope; and (3) galaxies with possible free-free absorption at long wavelengths. The latter SED represents a signature of massive star clusters that are still well inside the progenitor molecular cloud. Based on the comparison of the star formation rates (SFR) determined from the recombination lines and those determined from the radio emission we find that SFR(Hα) is on average five times higher than SFR(1.4 GHz). These results suggest that the emission of these galaxies is dominated by a recent and massive star formation event in which the first supernovae (SN) just started to explode. We conclude that the systematic lack of synchrotron emission in those systems with the largest equivalent width of Hβ can only be explained if those are young starbursts of less than 3.5Myr of age, i.e. before the first type II SNe emerge.

Key Words: galaxies: evolution — radio continuum: galaxies

1. INTRODUCTION

Thanks to their proximity and the posibillity of observing them in almost all the electromagnetic range, nearby galaxies are unique laboratories to study galaxy evolution. This contribution focus on the study of early stage of stelar evolution when most of the new formed stars remain deep inside the progenitor molecular cloud. In fact, during the early stages of evolution, very young star clusters should either lack or have a deficit of synchrotron emission, being dominated by free-free radio emission. Given that the synchrotron emission observed in starbursts is due to supernova activity, it is a direct tracer of the end of the evolution of massive stars ($M \geq 8\ M_{\odot}$). In the case of a coeval star formation burst, the first type II SNe appear after only 3.5 Myr and last until the 8 $M_{\odot}$ stars explode at around 40 Myr. Consequently, the lack of synchrotron emission in presently starforming regions is a good indicator of very young clusters. HII galaxies are low mass objects whose emission and thus most observables are dominated by a massive burst of star formation. Their optical spectrum is identical to that observed in giant HII regions like 30-Doradus in the LMC. These properties make these galaxies ideal targets for a study of integrated properties in search for features related to massive star clusters. Selected sources can then

[1]Instituto Nacional de Astrofísica Óptica y Electrónica, Luis Enrique Erro 1, Tonantzintla, Puebla, C.P. 72840, Mexico (danrosa@inaoep.mx).

[2]Remote Sensing Division, Code 7210, Naval Research Laboratory, 4555 Overlook Avenue, Washington, DC 20375, USA.

be studied in more detail with higher resolution observations. In this sense HII galaxies are considered "young". In fact they are probably the youngest stellar systems that can be studied in any detail. The youth scenario is supported not only by the strong emission lines from ionized gas, but also by their underlying stellar continuum properties, i.e. no stellar absorptions are detected in those HII galaxies with the strongest emission lines (EW(Hβ) > 150 Å) and only weak hydrogen and helium and some very weak metal lines are detected on those more evolved HII galaxies (EW(Hβ) < 50 Å). The lack of detection of stellar absorptions in the extreme HII galaxies is due to the fact that the optical spectrum of very young clusters is dominated by the light of massive blue supergiants close to the main sequence turn-off. The spectrum of these stars shows narrow and relatively weak absorptions of hydrogen and helium plus extremely weak metal lines. In the case of HII galaxies (and also HII regions) the weak and narrow stellar absorptions are filled with strong emission from the ionized gas of the associated HII region making it impossible to detect directly their presence.

Here we present the results of a study of integrated radio spectral energy distributions (SEDs) of nascent starburst candidates. We find several galaxies with flat spectra, typical of thermal emission, or even with inverted spectra, indicating the presence of heavily embedded star clusters. With the data at hand we compare the radio and emission line properties of these galaxies and propose a qualitative evolutionary model.

The long term objetives of this project includes not only to find and study the youngest bursts in the nearby Universe (Rosa-González et al. 2007a) but also to understand the transition between the dusty obscured (z between 2 and 3) to the optically bright ($z \sim 1$) Universe and the potential use of HII galaxies as standard candles (Melnick et al. 2000).

2. FIRST EVIDENCE OF DEALING WITH NASCENT GALAXIES

Our sample selection was based on the expectation that in young starforming galaxies their most massive stars did not have enough time to evolve and explode as supernovae. In a situation like this, these galaxies should have very little synchrotron emission (Bressan et al. 2002). Consequently, their radio luminosities should be smaller than what one would expect to find based on the SFR measured from other indicators, like Hα.

For the current study we selected a sample from the catalog of HII galaxies by Terlevich et al. (1991). Based on the reddening corrected Hα fluxes of the galaxies in this catalog, we estimate their Star Formation Rates (SFR) using the relation given by Rosa-González et al. (2002),

$$\mathrm{SFR}[M_\odot\,\mathrm{year}^{-1}] = 1.1 \times 10^{-41} \times \mathrm{L(H}\alpha) \,, \qquad (1)$$

where the L(Hα) is given in erg s^{-1}. These SFRs were then converted into radio 1.4 GHz fluxes, using the relation given by Schmitt et al. (2006). Comparing the predicted 1.4 GHz fluxes with values obtained from the NRAO/VLA Sky Survey (NVSS) catalog, we selected those galaxies which were not detected at the NVSS 5σ limit (2.5 mJy), or have an observed flux smaller than the predicted one. This deficit of 1.4GHz emission can be quantified in terms of the ratio between the observed 1.4 GHz flux and the expected flux based on the SFR calculated using the optical emission lines. For simplicity we denoted this ratio as the d-parameter.

The EW(Hβ) has long been used to estimate the age of a stellar burst (e.g. Dottori 1981; Luridiana & Peimbert 2001). However, the EW(Hβ) indicator which consists of the relation between the continuum flux which depends on the whole star formation history of the galaxy and the strength of the emission line which depends on the recent ($\sim 5 \times 10^6$ years) star formation activity can be significantly lower than the age of the current burst. This problem has been noticed in the analysis of the most extreme HII galaxies by Terlevich et al. (2004). To illustrate this problem, we plot in Figure 1 the evolution of the EW(Hβ) for the case of an instantaneous burst and for continuous star formation. Both models were calculated using the SB99 code for the case of a Salpeter initial mass function and masses between 0.1 and 100 $M_\odot$. In both modes the EW(Hβ) decreases with time but due to the formation of new massive stars in the continuous mode, the EW(Hβ) remains larger as time increases. These star forming histories mark the two extrema and the age of a galaxy with a given EW(Hβ) must lie between the limits shown in Figure 1. In the case of the existence of an old population, the observed EW(Hβ) is reduced even more –in comparison with the continuous case– due to the integrated light of the galaxy and the absence of massive stars responsible for the recombination lines. Interesting enough is the fact that there are no galaxies known to have EW(Hβ) greater than about 350 Å.

Figure 2 shows the EW(Hβ) against the d-parameter expressed in percentage. Notice that most of our galaxies lie in a region where the observed flux is less than 50% of the expected value, showing

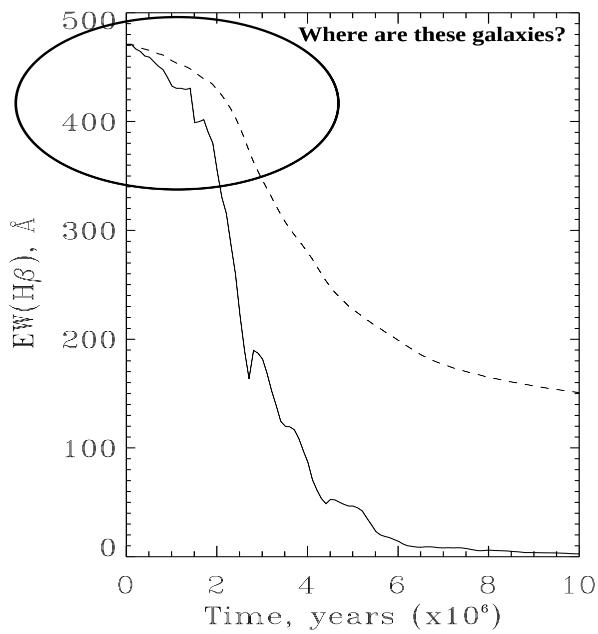

Fig. 1. Evolution of the EW(Hβ) for an instantaneous burst, solid line, and for continuous star formation, dashed line.

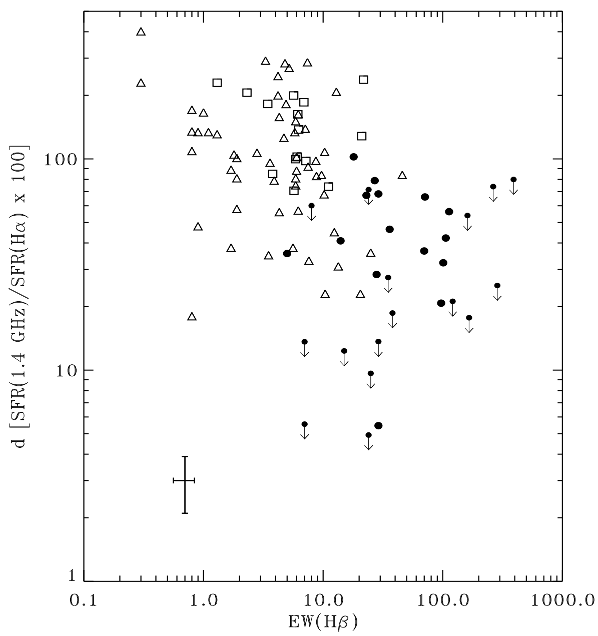

Fig. 2. Hβ equivalent width against the d parameter defined as the ratio between the observed and the expected 1.4 GHz flux (see text for further details). Circles are the sample HII galaxies and open symbols represent the control sample from Jansen et al. (2000) (triangles) and from Ho et al. (1997) (squares).

that indeed our sample has a deficit of synchrotron radiation. Five galaxies (Tol 116-325, MRK 1315, Tol 1303-281, Tol 1304-386 and Tol 1358-328) are extreme cases with the highest EW(Hβ) and just upper limits in the observed 1.4 GHz fluxes. Notice that, based on the EW(Hβ), these galaxies have ages of less than 10^7 years even in the case of continuous star formation (see Figure 1).

In order to investigate how our galaxies compare to normal, quiescent star forming galaxies in the $d-$parameter *vs* EW(Hβ) diagram, we obtained radio 1.4 GHz fluxes (from NVSS) for a sample of such galaxies from Jansen et al. (2000); Ho et al. (1997). We can see in Figure 2 that the normal galaxies have small EW(Hβ) and large d values, occupying a different region relative to the galaxies in our sample, again consistent with the interpretation that our galaxies are young and have a deficit of synchrotron radiation. A particularly interesting result from this figure is the fact that a significant portion of the normal galaxies, those with the smaller EW(Hβ), have $d >$100%. Although this result seems contradictory, since it implies a higher radio SFR than what is derived from Hα, it can be explained in view of the lifetime of these two indicators. For example, in the case of a single burst, the Hα emission lasts only 10 Myr, until all the ionizing photons die. The radio emission on the other hand will last much longer than that, because of the longer synchrotron emission life time and the fact that the stars that explode as SN last for $\sim$40 Myr.

3. RADIO SPECTRAL ENERGY DISTRIBUTION

The galaxies were observed with the VLA at 4.9 GHz (6 cm) and 8.4 GHz (3.5 cm) and we complemented the data set by including the 1.4 GHz data from the NVSS catalog. In Figure 3 we present the radio SEDs of three selected galaxies. Analyzing the spectral slopes of the galaxies detected at 1.4 GHz we find that they have spectral indices between those expected for thermal emission ($\alpha = -0.1$), and those characteristic of a source dominated by synchrotron radiation (typical value is around $\alpha = -0.8$, Condon (1992).

In Figure 4 we present the distribution of our galaxies in the F(1.4 GHz) *vs.* F(8.4 GHz) diagram. This figure also presents two lines indicating the location of thermal ($\alpha = -0.1$) and synchrotron ($\alpha = -0.8$) emission. In the case of more evolved star forming galaxies, where we find a mixture of these two components, the 1.4 GHz emission is dominated by synchrotron emission, while at 8.4 GHz both synchrotron and thermal emission produce similar con-

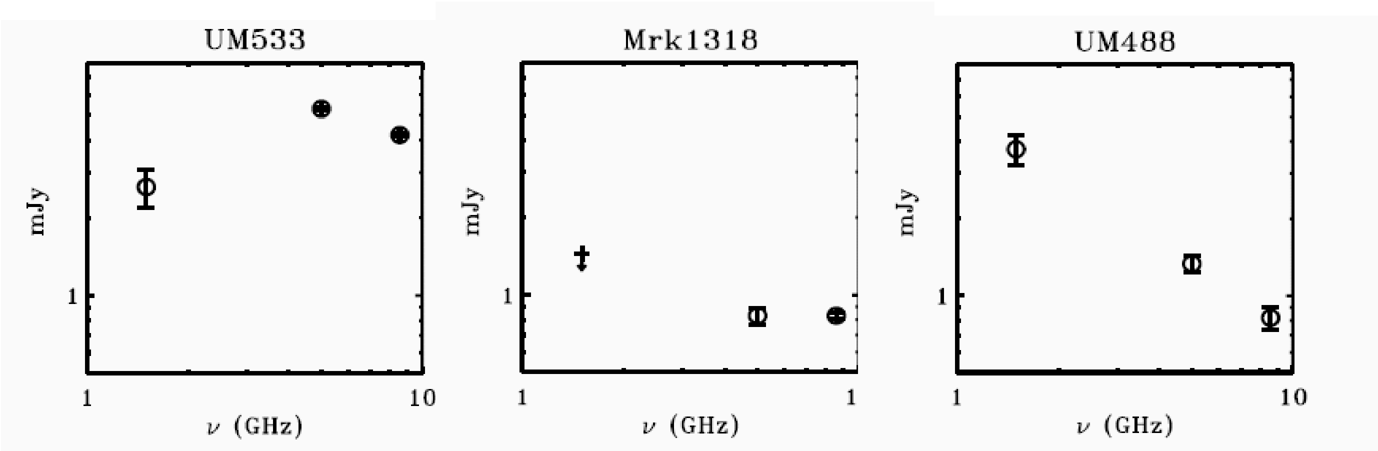

Fig. 3. Radio SED of three representative galaxies. The SED of UM533 shows the effect of the free-free absorption which have reduced significatively the flux at 1.4 GHz. Mrk1318 shows a typical, almost flat, spectrum of a thermal source. UM488 shows a steep spectrum consistent with being dominated by synchrotron emission.

tributions. Most of the galaxies in our sample lie in the region between these two lines, indicating that they are young objects still dominated by thermal emission.

It is obvious that Figure 4 represents an oversimplification, as the history of star formation is much more complicated and cannot be represented by either continuous or a single burst or even by a couple of bursts (e.g. Terlevich et al. 2004). Keeping this in mind we overplot two qualitative evolutionary tracks to the points in Figure 4. In the first case (solid thick line) we assumed that the galaxies start with only thermal emission from the OB associations, which are heavily absorbed at both 1.4 GHz and 8.4 GHz and can only be detected at the highest frequencies. In this phase the dense giant HII regions are characterized by optically thick free-free emission, which is observed as an inverted spectrum (thermal) radio source and it is commonly named ultradense HII region. Galaxies for which we only have upper limits at 1.4 GHz, seem to be consistent with that description.

Due to the effect of stellar winds, with typical velocities of 10^3 km s^{-1} and mass losses of about 3×10^{-5} $M_\odot$ year^{-1}, the absorbing material starts to blow away, the optical depth is reduced and a galaxy moves in this diagram towards the direction of UM 533 (4.2;2.6, in Figure 4). Once all the absorbing material is blown away, a galaxy moves up in this diagram, until it reaches the line where the radio emission is dominated by thermal radiation. As the galaxy continues to evolve, SNe explode producing copious amounts of synchrotron radiation and moving the galaxies to the top right portion of this diagram where the relation between radio and FIR is obtained (Yun et al. 2001). In this scenario we expect young galaxies to have $\alpha > -0.1$, with the younger objects having the larger slopes due to free-free absorption, evolving towards $\alpha = -0.8$.

In the second scenario we start with some synchrotron emission due to a previous generation of supernovae. If a new burst occurs a new generation of stars is produced, increasing the amount of ionizing photons, and moving the galaxy to the right towards the thermal relation (see dashed thick line in Figure 4). When the next generation of supernova explodes the galaxy starts to move up and right to the position of the non-thermal relation (dot-dashed line).

4. COMBINING OPTICAL AND RADIO MEASUREMENTS

In this section we combine the radio and optical data described in previous sections in order to test the evolutionary models outlined in § 3.

After an episode of star formation, the first SN explosion and consequently the first contribution to the synchrotron emission appears at about 3.5×10^6 years, which corresponds to an EW(Hβ) of about 120 Å for an instantaneous burst or 310 Å if star formation is continuous (Figure 1). Therefore objects with high EW(Hβ) and flat slopes are candidates to be galaxies dominated by very recent starburst episodes.

Massive stars within a young burst ionize the surrounding media producing free electrons and the presence of recombination lines. The intensity of the Hβ emission line is related to the free-free radiation

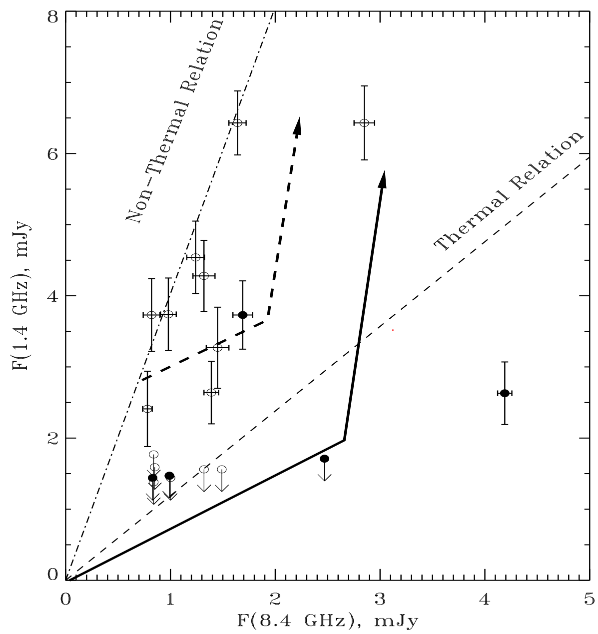

Fig. 4. Distribution of F(1.4 GHz) as a function of F(8.4 GHz) for the selected galaxies. The dashed thin line shows the expected position of galaxies dominated by thermal emission, while the dot-dashed line shows where galaxies dominated by non-thermal emission are located. Superimposed on this plot are solid-thick and dashed-thick lines indicating qualitative evolutionary tracks described in the text.

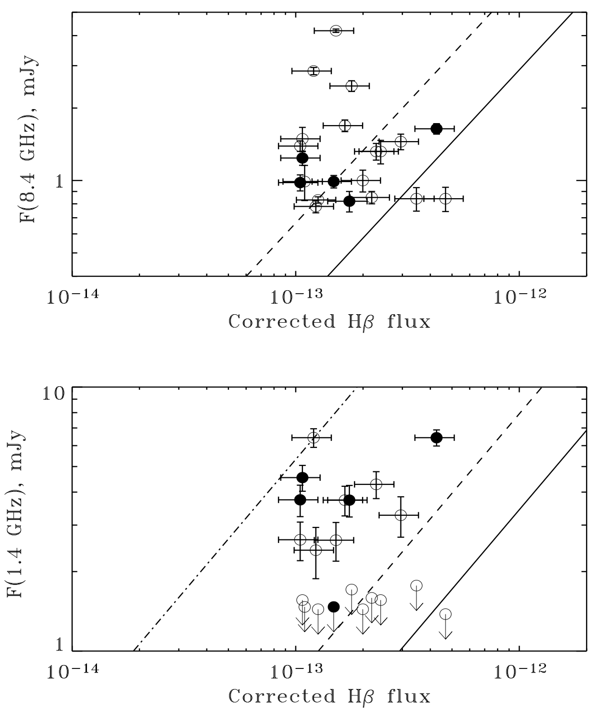

Fig. 5. Relation between the extinction corrected Hβ flux, the flux at 8.4 GHz (top panel) and the flux at 1.4 GHz (bottom panel). In both panels the solid line is the relation between the strength of the Hβ line and the corresponding radio flux for the case of thermal emission coming from a plasma with a temperature of 10^4K. The dashed lines correspond to a temperature of 5×10^4K. In the bottom panel we draw (dot-dashed-line) the relation given by Yun et al. (2001) which includes synchrotron emission. In both panels, the solid symbols are galaxies with $\alpha > -0.5$. Non detections are represented by the arrows (upper limits).

observed at radio wavelengths by (Condon 1992),

$$\mathrm{H}\beta\,(\mathrm{erg\,s^{-1}cm^{-2}}) = 2.8\times10^{-11}(\mathrm{Te}/10^4)^{-0.52}\nu^{0.1}\mathrm{F}_\nu, \quad (2)$$

where Te is the electron temperature of the plasma, ν is the frequency of the observation (expressed in GHz) and F_ν is the flux in mJy at the given frequency. For galaxies dominated by synchrotron radiation, the thermal emission is about 10 percent of the synchrotron radiation at 1.4GHz. However, due to the different behaviour and slopes of thermal and non-thermal emission, the thermal emission at 8.4GHz (3.5cm) could be about 50 percent of the synchrotron one or even more for those galaxies that are synchrotron deficient. Figure 5 (top panel) shows the extinction corrected Hβ flux against the flux at 8.4GHz. Most of the galaxies have fluxes which are consistent with thermal emission from plasmas with temperatures between 10^4K (solid line) and 5×10^4K (dashed line). However some galaxies have an excess of radio emission due to the presence of synchrotron emission.

At 20 cm (1.4GHz: bottom panel in Figure 5) the flux is clearly contaminated by the presence of synchrotron emission. As in the top panel the solid and dashed lines represent the thermal emission based on equation 2. All the galaxies detected at 20 cm have fluxes above the thermal limits, however the galaxies not detected at 20 cm (the upper limits) are close to the thermal region.

Due to the presence of massive stars in normal and starburst galaxies, there is a strong relation between the observed FIR and the flux at 1.4 GHz. This correlation, which covers several orders of magnitude in luminosities, is explained by the presence of massive stars which heat the dust producing the observed FIR radiation and, as a consequence of the short life time of these stars, they explode as SN producing the synchrotron emission observed at 1.4 GHz (Yun et al. 2001). Combining this strong correlation with the relation between the FIR luminosities and the current SFR from Kennicutt (1998), Yun and collaborators proposed a robust relation between the luminosities at 1.4 GHz and the SFR,

$$\mathrm{SFR}[M_\odot \ \mathrm{year}^{-1}] = 5.9 \times 10^{-29} \times \mathrm{L}_{1.4\mathrm{GHz}} \ , \qquad (3)$$

where the luminosities are expressed in units of erg s^{-1} Hz^{-1}. Notice that all SFR estimates have uncertainties, because each estimator traces different populations and depends on several assumptions, e.g. the initial mass function, or on the light attenuation which is a strong function of wavelength.

Comparing the SFR estimated by the 1.4 GHz luminosities with those given by the recombination lines we find that the optical SFR is on average 4 times higher than the SFR given by the radio luminosities. In the bottom panel of Figure 5 we plot a dot-dashed line where the optical SFR is equal to the radio SFR based on the Yun et al. (2001) relation. Only three galaxies are close to the dot-dashed line showing that most of the observed starbursts still are in the early stages of evolution, when not too many stars have become SN, and as a result the observed radio SED is dominated by thermal emission. The most extreme cases are those galaxies with non detection at 20 cm. The cases with clear signature of free-free absorption and those dominated exclusively by thermal emission are similar to regions detected in NGC 625, and in He2-10.

5. DISCUSSION AND CONCLUSIONS

We combined optical spectroscopy with radio continuum observations to detect systematically extremely young systems, before the first Type II SNe explode. The lack of these energetic events produce a deficit in the observed radio fluxes that was quantified introducing the d-parameter.

To fully explain the observed trends, a highly synchronized star formation is required, i.e. the massive star forming phase should be shorter than ∼3-4Myr in order to prevent the appearance of the first supernovae associated to the more massive stars and the consequent synchrotron emission. This also suggests that there has been no large star forming event in the previous 10^8yr. We just started to put the observational basis to understand the early evolution of massive stellar clusters and we proposed a simplified evolutionary scenario in line with previous theoretical studies.

The results summarized above have important implications for the understanding of the early stages of evolution of low mass galaxies as the ones described in this study and of young massive star clusters.

The extreme radio SEDs of these young systems must be included in the estimation of photometric redshifts of distant obscured galaxies that will be discover with the near future facilities (e.g. ALMA and LMT/GTM). In fact, high redshift (sub)mm-galaxies with extremely weak optical counterparts could be the analogous of the galaxies discussed in this talk (with a stellar mass ∼100 times higher !!!).

Because the high energy ($2 - 10$ keV) emission of star-forming galaxies is mainly due to HMXBs, for a given SFR, the lack of X-ray emission could be a sign of a young system in which the population of compact objects is not fully developed (Rosa-González et al. 2007b).

An extensive version of this work that includes details of the VLA observations, together with further discussions which incorporate among others the analysis of the FIR emission and the q-parameter has been presented in Rosa-González et al. (2007a).

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