ON THE ORIGIN OF THE RED EXCESS IN VERY YOUNG SUPER STAR CLUSTERS: THE CASE OF SBS 0335-052E

A. Adamo1, E. Zackrisson1, G. Östlin1, and M. Hayes2

1 Department of Astronomy, Stockholm University, Oscar Klein Center, AlbaNova, Stockholm SE-106 91, Sweden; adamo@astro.su.se
2 Observatoire Astronomique de l’Université de Genève, 51, ch des Maillettes, CH-1290 Sauverny, Switzerland

Received 2010 July 13; accepted 2010 October 18; published 2010 November 30

Abstract

The spectral energy distribution analysis of very young unresolved star clusters challenges our understanding of the cluster formation process. Studies of resolved massive clusters in the Milky Way and in the nearby Magellanic Clouds show us that the contribution from photoionized gas is very important during the first Myr of cluster evolution. We present our models which include both a self-consistent treatment of the photoionized gas and the stellar continuum and quantify the impact of such a nebular component on the total flux of young unresolved star clusters. A comparison with other available models is considered. The very young star clusters in the SBS 0335-052E dwarf starburst galaxy are used as a test for our models. Due to the low metallicity of the galactic medium our models predict a longer lasted nebular phase which contributes between 10% and 40% of the total near-infrared (NIR) fluxes at around 10 Myr. We thus propose a possible solution for the observed flux excess in the six bright super star clusters (SSCs) of SBS 0335-052E. Reines et al. showed that the observed cluster fluxes, in the red-optical and NIR range, sit irreconcilably above the stellar continuum models provided. We find that in the age range estimated from the Hα emission we can explain the red excess in all six SSCs as due to nebular emission, which at cluster ages around 10 Myr still affects the NIR wavebands substantially.

Key words: galaxies: dwarf – galaxies: individual (SBS 0335-052E) – galaxies: starburst – galaxies: star clusters: general

Online-only material: color figures

1. INTRODUCTION

SBS 0335-052E, at a distance of 54 Mpc (according to NED), is one of the least chemically evolved galaxies in the local universe (Z = 1/40 Z⊙; Izotov et al. 1990, 1997; Kunth & Östlin 2000; Papaderos et al. 2006). In the 1990s, the first Hubble Space Telescope (HST) images of this irregular dwarf galaxy (Thuan et al. 1997) revealed that the main starburst region was dominated by six young super star clusters (SSCs). In Figure 1, we show the positions of the clusters as identified by Thuan et al. (1997) using the nomenclature of Reines et al. (2008b, hereafter R08). The clusters are located around a supernova cavity which has probably caused their formation, with star formation propagating from north to south (Izotov et al. 1997).

Thompson et al. (2009, hereafter T09) observed bright Paα emission in the galaxy and identified three new and actively star-forming regions, S3-Paα, S7, and S8 (indicated in the continuum-subtracted Hα image in Figure 1). These new areas were presented as places of less clustered star formation, where young stars are ionizing the gas in situ. Similar star-forming regions were also observed around SSC1 and SSC2.

Vanzi et al. (2000) found that a hot dust component is needed to explain the red H – K color observed globally in the galaxy. However, the very low visual extinction across the SSCs, which show prominent Brγ emission, implies that the clusters are quite dust free. Interestingly, Hunt et al. (2001), using imaging and spectroscopy data at 2–4 μm, found evidence of a deeply embedded cluster with a visual extinction AV ≥ 15 mag in the line of sight of the two young SSCs 1 and 2. They excluded that the IR flux was produced by the two optically bright SSCs because of the high discrepancy between the extinctions derived from the IR and from the optical data (AV ∼ 0.55 from the optical line ratios).

A different scenario was presented by R08 and Johnson et al. (2009) to reconcile the apparently discrepant extinction estimates in the knot containing SSCs 1 and 2. R08 inferred ~40% of Lyman continuum photon leakage from the two clusters which is ionizing the extended Hα-bright region around the knot. This could be possible if the medium surrounding the two clusters is clumpy. In this case the optical light would come through the “holes” suffering only low extinction, while in the NIR would transmit also the signal produced by the dense dust clumps, heavily extinguished.

Using Hα equivalent width, EW(Hα), measurements, R08 derived cluster ages between 3 and 15 Myr. The six SSCs also displayed a flux excess at wavelengths larger than 8000 Å, impossible to reconcile with the stellar continuum models used to fit the cluster spectral energy distribution (SED). R08 explored several possibilities to explain the origin of the red excess. The excess at ~0.8 μm was explained as the dust photoluminescence phenomenon commonly referred to as extended red emission (ERE; see Witt & Vijh 2004). The ERE has been observed in star-forming regions like 30 Doradus (Darbon et al. 1998) and in H II regions of local galaxies like NGC 4826 (Pierini et al. 2002), and is characterized by an extended emission feature between 7000 and 9000 Å. R08 attributed the flux excess at wavebands between 1.6 and 2.1 μm to two different mechanisms. For the youngest clusters SSC1 and SSC2, hot dust (~800 K) emission was advocated to explain the rise of the IR continuum. The remaining older clusters showed infrared colors consistent with those of red super giants (RSGs). In fact, if the models do not contain a reliable treatment of the RSGs (Laçon et al. 2008 and references therein) this could produce an apparent NIR excess in the observed SEDs at cluster ages around 10 Myr.

The clusters are very young (3–15 Myr). This age range is quite complex, due to the rapid dynamical evolution that the
clusters experience (see Portegies Zwart et al. 2010 for a review). At such young stages, the contribution from photoionized gas in the broadband integrated fluxes can be substantial (Bergvall & Östlin 2002; Anders & Fritze-Alvensleben 2003; Zackrisson et al. 2008; Reines et al. 2010). In the starburst galaxy Haro 11, we found a peak of cluster formation only 3.5 Myr old (Adamo et al. 2010). The analysis of such young clusters requires models that include both the stellar continuum and photoionized gas emission contributions (see Zackrisson et al. 2001; Adamo et al. 2010). However, we also found that a subsample of clusters in Haro 11 displays a flux excess above models including photoionized gas emission at wavelengths longward of 8000 Å. The observed discrepancies could be explained if other mechanisms, not included in the models and related to the young ages of the clusters, are contributing at redder wavebands. Hot dust, a considerable fraction of pre-main-sequence (PMS) stars, and young stellar objects (YSOs) are possible mechanisms causing the red excess in Haro 11.

Previous cases of NIR excess observed in still embedded star clusters of dwarf starburst galaxies were explained by several authors as caused by hot dust (Cresci et al. 2005; Cabanac et al. 2005). Observations of very young star clusters in the Small Magellanic Clouds have revealed not only complex environments composed of bright main-sequence stars, but also PMS objects and YSOs only observable in the NIR (Carlson et al. 2007; Gouliermis et al. 2010). A significant fraction of YSOs was suggested as the origin of the red excess in the starburst galaxy NGC 253 (Fernández-Ontiveros et al. 2009).

The NIR excess in young star clusters has been observed in several nearby starburst galaxies. Here, we explore to what extent the red excess reported in SBS 0335-052E by R08 can be explained by nebular emission, or whether other mechanisms are needed.

In Sections 2 and 3, we present the photometric data and our synthetic evolutionary models which we use to perform new fits to the cluster SEDs as described in Section 4. In this section, we also test the validity of our fits and attempt an estimation of the sizes of the emitting $\text{H}_\alpha$ regions. In Section 5, we compare our results with previous studies of the galaxy. Our conclusions are summarized in Section 6.

2. DATA SAMPLE

The data reduction and photometry were carried out and described in detail in Section 3 of R08. In the present work we will use their photometry (published in their Table 1) to test our models and investigate the origin of the red excess in SBS 0335-052E.

In Figure 1 we show two of the science frames of SBS 0335-052E, previously published by Östlin et al. (2009). We illustrate the positions of the clusters as in R08 and the star-forming regions identified by T09. The photometric annuli around the clusters have a radius of 0.15′′ (∼40 pc at the adopted distance). This corresponds to the size set by R08 to perform aperture photometry. The six SSCs are bright and visible in all the UV, optical, and IR $\text{HST}$ frames. The continuum frame in Figure 1 shows that the positions of the compact clusters are clearly defined and that the aperture size used is suitable to avoid contamination from the neighboring diffuse regions. On the other hand, in the right frame, we see that $\text{H}_\alpha$ emission is quite strong at the locations of SSC1 and SSC2 which makes it difficult to distinguish between the compact and the less clustered surrounding regions. The remaining four star clusters do not show $\text{H}_\alpha$ fluxes as strong as the ones produced in the nearby very young active star-forming regions.

2.1. New Estimation of the $\text{EW}(\text{H}_\alpha)$ in the Clusters

The use of local sky annuli, like the ones used by R08, could oversubtract flux from the sources, producing an underestimation of the final $\text{EW}(\text{H}_\alpha)$. Due to the complexity of the environment around the clusters, we decided to re-estimate the $\text{EW}(\text{H}_\alpha)$ across the clusters using the same aperture radius as R08, but a constant value for the background as explained below.

The reduction of science frames shown in Figure 1 and software are described in more detail in Hayes et al. (2009); here, we briefly summarize the procedure. The continuum subtraction
of the Hα frame (FR656N) is non-standard, and utilizes custom software. This software performs spatially resolved, pixel-by-pixel SED fitting using five HST broadband filters between the FUV and optical domains, all of which were expressly chosen to be free from contamination by nebular lines. From the best-fitting synthetic stellar population, the software computes the expected flux due to continuum processes in the FR656N narrowband filter. This is then subtracted from the observation itself, and maps of the pure 6563 Å continuum and continuum-subtracted Hα are output.

Photometry was carried out in both frames, at the same position, using the same aperture radius (0′′15) as in R08. Because the Hα emission has a complex and extended morphology, we preferred to subtract a constant mean value of the sky background instead of a local sky annulus located around the position of the cluster, in both continuum and emission frames. The mean sky values were estimated in both frames, in the same position, and in a region that appeared free of Hα emission and continuum flux. No aperture corrections to the determined fluxes were applied since there are no point-like sources in the reduced frames and the one produced by a simple interpolation between the two nearest frames to Hα.

3. DESCRIPTION OF THE SPECTRAL EVOLUTIONARY MODELS

To produce self-consistent models which include the contributions from both stars and photoionized gas, we use the stellar population SEDs predicted by Starburst99 (Leitherer et al. 1999) as input to the Cloudy photoionization code (Ferland et al. 1998). The procedure closely follows that described by Zackrisson et al. (2001), in which Cloudy is called for every stellar population time step to ensure that the temporal evolution of the nebulae is treated self-consistently. This technique results in combined SEDs that are more realistic than the ones generated when using the nebular components produced by Starburst99 itself. The latter contain only nebular continuum (produced by free–free and free–bound emission), whereas the models we use include both nebular continuum and emission lines (produced by bound–bound mechanisms). In our models, the SB99 stellar population SEDs are produced using the Padova tracks (Bertelli et al. 1994) and assume a metallicity of Z = 0.0004, an instantaneous burst of star formation (resulting in a single-age population), and a stellar initial mass function with a double power law (dN/dM ∝ M−α, with α = 1.3 for M = 0.1–0.5 M⊙ and α = 2.3 for M = 0.5–100 M⊙). The nebular SED assumes a spherical, constant-density and ionization-bounded nebula with a gaseous metallicity identical to that of the stars. The gas filling factor f (which quantifies the porosity of the nebula), the hydrogen number density nH, and the gas covering factor c (which quantifies the amount of Lyman continuum leakage due to clumpiness in the medium or presence of dust) are all explored within reasonable boundaries. We generated a grid of models, with different combinations of values for f = [0.01, 0.001], nH = [10^2, 10^3] cm⁻³, and c = [0.1, 0.2, 0.3, 0.4, 0.5, 1.0] (c = 1 means that all the Lyman continuum photons ionize the gas; c = 0.1 means that only 10% of them photoionize the gas, i.e., that 90% of photons are leaking).

In Figure 2, we show how the integrated spectrum of a 10^6 M⊙ cluster changes as a function of the age during the first 15 Myr, using our models with f = 0.01, nH = 10^2 cm⁻³, and c = 1. For comparison we plot the corresponding Starburst99 stellar continuum spectrum (red dotted line) and the model with nebular continuum included (blue line). In the very early stages, around 3 Myr, the contribution from the photoionized gas is so strong that the whole spectral range from the near-UV to IR is affected. The stellar continuum is significantly below. The continua of the two models including the nebular contribution are in good agreement. However our models, implemented with Cloudy,
also include emission lines, very strong at this age. At 6 Myr, we observe that the stellar continuum and the spectrum of the model including both stellar and nebular components is similar in the near-UV and blue-optical range. The contribution from the line emission, however, is very important in the Balmer region. From the red-optical to the near-IR range the difference in fluxes between models with and without nebular treatment is still substantial. Around 10 Myr, fluxes at wavelengths longward of 1.0 \( \mu m \) still receive a non-negligible fraction of flux from the gas. This is evident using both SB99 (stellar and nebular continuum) and our models. At shorter wavelengths, only the integrated fluxes across the emission lines are affected. The nebular component is almost gone at around 15 Myr, with very small differences between the three spectra.

In Figure 3, we compare the fraction of nebular emission contributing to the total flux as estimated by our models and by the SB99 ones. We quantify these fractions as a function of the cluster age for the HST filters used in the analysis of SBS 0335-052E (R08). As already shown in the previous figure, the only significant difference between the two models is the presence/absence of emission lines. In the top panels, we clearly see the drop in the contribution of the photoionized gas already at 4–6 Myr in the NUV (ACS/F220W, U (ACS/F330W), B (ACS/F435W), and V (ACS/F550M) filters. In this age range, the difference between the two models is \( \leq 5\% \) and disappears at older ages if the filter does not transmit important lines (i.e., NUV, U, and V). On the other hand, the B filter in our models shows a significantly higher fraction of photoionized gas contribution due to the presence of the Balmer lines. Around 10 Myr the B band still transmits 10\% of the nebular flux which is mainly contained in the lines (see Figure 2 at \( \sim 0.4–0.45 \mu m \)). In the remaining UV and optical bands, only 5\% of the integrated flux is produced by the nebula. In the bottom panels we show the NIR filters. Again the discrepancy between our models and the SB99 ones is higher in filters which transmit strong lines (mainly in K). As already noticed before in the NIR range, at 10 Myr the nebula still supplies 10\% of the total flux in the optical I (WFPC2/F791W) band, 20\% in the H (NIC2/F160W) band and in the Pa\textsc{o} continuum narrow filter (NIC2/F187N), and up to 40\% in the K (NIC2/F205W) band. We also notice that at a given age the fraction of flux produced by the ionized gas increases as a function of the wavelength and shows a slower decline toward older ages.

As a further test, in Figure 4 we plot the evolutionary tracks in different combinations of IR and optical colors. As already observed in Zackrisson et al. (2001), during the first 10 Myr the colors predicted by models which include a contribution from photoionized gas are quite different from the ones with only stellar continuum. We also plot, in the color diagram, the positions of the six SSCs of SBS 0335-052E. We clearly see that the cluster IR colors are much redder than the predictions provided by the stellar continuum only or by the stellar and nebular continuum tracks (SB99), but are in fairly good agreement with our models. The positions of the clusters in the bottom panel are shifted toward red \( F550M–F791W \) color (\( V–I > 0 \)). This displacement is due to a small flux excess in the I band, which is around 0.2–0.4 mag above the best-fitting models. This issue will be discussed in the following sections.

4. Constrain the Origin of the Red Excess

4.1. A New Cluster SED Fit from the NUV to the NIR

The SED fit made by R08 was limited to the near-UV and blue-optical filters (ACS/F220W, ACS/F330W, ACS/F435W, ACS/F550M). The Starburst99 spectral evolutionary models, including only the stellar continuum component, were used together with the LMC extinction curve (Misselt et al. 1999, and references therein) to estimate ages, masses, and extinctions of the clusters.

In Section 3, we argued that the photoionized gas is a crucial component for the models used to estimate the physical properties of the young clusters. In this section we explore the possibility to explain the red excess observed by R08 using these new models. The young clusters in SBS 0335-052E...
Relative contribution of the nebular emission as a function of the cluster age to the total flux transmitted in the HST filters used in this analysis. The SB99 models including stellar and nebular continuum are shown with a dash-dotted line. Our models are drawn by solid lines. The filters are indicated in the plots. A description of the models is given in Section 3.

are indeed in the age range where the contribution from the photoionized gas surrounding the clusters is expected to be important. The amount of flux produced by the gas and contributing to each of the cluster-integrated fluxes is a function of the total amount of ionizing UV flux produced by the massive stars in the cluster. The EW(Hα) is a direct measurement of the strength of the ionizing flux and is very sensitive to the rapid evolution of the massive stars during the first 15 Myr of the life of the cluster. R08 compared the measurement of the EW(Hα) with predictions made by SB99 to derive the ages of the clusters. We performed a similar estimation using the new measurements of EW(Hα) of each SSC and the predictions provided by Cloudy in our models. The ages constrained by R08 and our models are reported in Table 1 (fourth and fifth columns, respectively). The ages we derived are in good agreement with those already found by R08 and by Johnson et al. (2009) for the two bright radio sources SSC1 and SSC 2.

Keeping the age fixed, we produced a fit of the observed integrated fluxes of each cluster from UV to IR bands with the fluxes provided by our models at the corresponding ages. Our fit algorithm is described in detail in Adamo et al. (2010). Internal extinction was treated as a free parameter, and we used the Calzetti attenuation law (Calzetti et al. 2000), allowing extinction to vary from \( E(B-V) = 0.0 \) to 3.0 with a step of 0.01. In the previous fit, R08 used the LMC extinction law. We showed, however, in Adamo et al. (2010) that there are no substantial deviations in the estimated ages, masses, and number of clusters affected by a red excess when a Calzetti or an LMC law is used. The masses of the clusters were derived from the normalization between the best-fit model and observed data. The models that produce smaller residuals are the ones with \( f = 0.01, c = 1, \) and \( n_H = 10^4 \text{ cm}^{-3} \). The fits are shown in Figure 5, and the masses and \( A_V \) are given in Table 1. We notice, however, that the models with the same \( f \) and \( c \) values but lower hydrogen densities \( (n_H = 10^2 \text{ cm}^{-3}) \) produce fits with residuals only slightly bigger than the best models. The constrained extinction range is in good agreement with the values found using the optical to NIR line ratio (e.g., Vanzi et al. 2000). The values are also in agreement with the recovered extinction ranges in other starburst environments such as the Antennae system (Mengel et al. 2005) and M51 (Bastian et al. 2005). The estimated cluster masses for the two youngest clusters, SSC1 and SSC2. (A color version of this figure is available in the online journal.)
SSC2, are significantly lower than the ones determined by R08. They are instead, in agreement with the estimates by Johnson et al. (2009) derived from the thermal radio emission of the two young SSCs, under the assumption of no leakage of ionizing photons from the nebula surrounding the young cluster. The remaining clusters have estimated masses in agreement with the values previously obtained by R08. During the first few Myr, where the photoionized gas emission is dominant, we clearly see that the cluster mass can be overestimated by a factor of 2–3 if the models used do not include nebular contribution.

We also repeated the least-squares fit done by R08, excluding the I band and IR data (WFPC2/F791W, and NIC2 F160W, F187N, and F205W), and using models with only stellar continua. In this case, age was treated as a free parameter. The fits with the smallest residuals are shown in Figure 5 with red data points and red spectra. As already found by R08, the fit to the blue optical photometry using only stellar continua produced a quite evident displacement at wavelength longward of 8000 Å. Nevertheless, when nebular continuum and line emission are included in the models, we obtained a good fit for all the clusters and in all the passbands. Inside the photometric errors, the best-fitting model (black squares) is able to reproduce the SED shapes quite well. We notice, however, a persisting small excess (between 0.2 and 0.5 mag above the models) at 8000 Å (I band) which was observed in the bottom panel of Figure 4. We will discuss this feature in Section 5.

We produced, finally, a third set of fits from UV to IR, using our models with age as a free parameter. The two youngest SSC1 and SSC2 had a best-fitting age of 3 Myr, in perfect agreement with the EW(Hα) determination. SSC3, SSC4, SSC5, and SSC6 had best-fitting ages lower than the values determined using EW(Hα): 6, 9, 9, and 7 Myr, respectively. However,
investigating the 68.3% confidence levels, we constrained boundaries to the best-fitting ages (Table 2). We observe that inside the uncertainties produced by a free SED fit the solutions recovered using the observed EW(Hα) are in good agreement in all the cases except in SSC6 (marginally agreement). The estimated masses and extinction did not change significantly (see Table 2). Therefore, we do not discard either of the two results and consider the ages determined with the two methods as a valid range around the real age of the clusters.

4.2. Testing the Validity of the Models

Although our models can reproduce the shapes of the cluster SEDs, we need to test the consistency between the models and the physical conditions of the clusters. The models include the full amount of emission flux coming from the photoionized gas. This assumption implies that all the ionized gas (e.g., the H II region) around the cluster is spatially contained in the photometric aperture size used. Using the nebular properties produced by the best-fitting model, and cluster physical parameters published in previous works, we produced estimates of the radii of the H II regions around the clusters, as expected from the model. The radii were computed using the formula

\[ R_{\text{HII}} = \left( \frac{3Q_{\text{Hyc}}}{4\pi n_0^2 \alpha_B} \right)^{1/3} \]

(1)

under the assumption of a pure hydrogen cloud.

The \( Q_{\text{Hyc}} \) is the rate of ionizing Lyman continuum photons produced by very young stars and changes as a function of cluster age. If the medium around the stars is clumpy or dusty, it is possible that a fraction of the ionizing photons do not ionize the gas. R08 discussed the possibility of a clumpy medium around the two youngest SSCs 1 and 2, and estimated a leakage of ionizing photons of \( \sim 40\% \). Our best-fitting model had a covering factor \( c = 1 \), implying that all the Lyman continuum photons, produced by the young massive stars, ionize the gas. To verify this result we compared the \( Q_{\text{Hyc}} \) provided by the Starburst99 model with the values of \( Q_{\text{Hyc}} \) derived from the measured Hα fluxes (extinction-corrected). The observed \( Q_{\text{Hyc}} \) was estimated using Relation (1) in R08, which produces lower limits to the real values. The \( f(\text{H}\alpha) \) listed in our Table 1 were first corrected for the corresponding extinction values, and then converted into Hβ luminosities. The resulting \( Q_{\text{Hyc}} \) were scaled for the mass of the model (10^6 M⊙). We show the calculated values of the \( Q_{\text{Hyc}} \) for the six SSCs in Figure 6. For the two youngest clusters the estimated \( Q_{\text{Hyc}} \) values are in agreement with the model predictions, and do not show any significant leakage of ionizing photons. In the older clusters we observe a possible escaping fraction of 20%–30%, consistent with the more evolved phases the clusters are experiencing. In general, we consider the assumption of \( c = 1 \) a reasonable approximation.

To estimate the radii of the H II regions of each cluster we used the \( Q_{\text{Hyc}} \) predicted by the Starburst99 stellar continua, scaled for the mass of the cluster. In Table 1 we also show (in parentheses) the values of the radii if the estimated \( Q_{\text{Hyc}} \) from \( f(\text{H}\alpha) \) were used instead.

Studies of massive star-forming regions in our galaxy (Churchwell 2004; Conti & Blum 2002, among many others) have shown quite complex environments with density gradient going from \( n_H \approx 10^7 \text{ cm}^{-3} \) in pre-stellar cores to diffuse surrounding regions with \( n_H \approx 10^2 \text{ cm}^{-3} \), and ultracompact H II regions (\( n_H \approx 10^5 \text{ cm}^{-3} \)), all coexisting in the same system. Thompson et al. (2006) presented observational evidence of very compact H II regions in the positions of the two young SSC1 and SSC2. On the other hand, using two-dimensional spectroscopy, Izotov et al. (2006) found values of \( n_H \) across the SSCs of a few hundreds and EW(Hα) below 1500 Å even in the brightest Hα regions of the galaxy (SSC1+2). We notice, however, that the spectra are produced in regions approximately 10 times bigger (0′′52 or 0′′52) than the ones used here (radius of ∼0′′15), causing a smoothing of the values over low-density and diffuse regions around the clusters. Recently, using continuum radio data, Johnson et al. (2009) estimated an \( n_H \sim (4–7) \times 10^3 \text{ cm}^{-3} \) for SSC1 and SSC2, in agreement with the value of \( n_H \) = 104 cm^{-3} we derived from the fitting model.

In order to estimate the radii of the H II regions for the two youngest clusters we used \( n_H = 10^4 \text{ cm}^{-3} \). In the previous section, the model with lower \( n_H \) also produced a good fit to the data. By keeping all the other parameters fixed, we checked whether a lower value of \( n_H = 100 \text{ cm}^{-3} \) produced very different flux values in the optical \( f \) band and in the NIR wavebands for ages between 6 and 15 Myr. We found that the difference between the two models was less than 1%. Finally, we decided to use \( n_H = 10^4 \text{ cm}^{-3} \) for SSC3, which has an intermediate age, and a density of a few hundreds for the oldest three SSCs.

The filling factor, \( f \), was fixed to 0.01. We set the recombination coefficient, \( \alpha_B \), for Case B recombination (Osterbrock...
& Ferland (2006) to 1.43 × 10^{-13} at an electron temperature of 20000 K (determined by Izotov et al. (1997) from optical emission lines of the galaxy).

The values we estimated are listed in Table 1. We derived quite small sizes for the H II regions of SSC1 and SSC2, due to the high value of n_H of the photoionized cloud surrounding the recently born clusters. The sizes increase for lower values of n_H. This behavior is expected since the ionizing photons travel farther in less dense environments. Nevertheless, we found consistency between the assumptions made in the models and the aperture used by R08 to make the photometric measurement.

5. DISCUSSION
5.1. The Origin of the IR Excess in the SSCs

R08 presented evidence of a flux excess in the red-optical and NIR wavebands. The excess at ~0.8 μm was attributed to the ERE phenomenon. The flux excess at wavebands between 1.6 and 2.1 μm was considered to have two different origins. For the youngest clusters SSC1 and SSC2, hot dust (~800 K) emission was advocated to explain the rise of the IR continuum. For the remaining SSC3, SSC4, SSC5, and SSC6, they showed that the IR colors were consistent with RSGs which mainly contribute to the NIR light at ages above 7 Myr.

We propose a new interpretation of the flux excess in the SBS 0335-052E SSCs. We have shown that the inclusion of the emission from photoionized gas in the models can well reproduce the colors (Figure 4) and the SED shape (Figure 5) of all the SSCs from UV to NIR. The ages found using the new estimated EW(Hα) are very similar to the one previously determined from R08 and confirm the general picture of the star formation propagating from north to south (Thompson et al. 2006; R08). Moreover, previous spectrophotometric studies of the galaxy from optical to infrared confirmed the presence of a dominant nebular contribution (Vanzi et al. 2000; Izotov et al. 2001). Vanzi et al. (2000) estimated that more than 45% of flux in the NIR spectra of the SSC1+2 and SSC4+5 regions are due to nebular continuum and emission. They also found, from the Hβ/Bry ratio, a visual extinction of AV ≈ 0.73, which is in good agreement with the values we found from the SED fits. Finally, they interpreted the red H−K color observed globally in the galaxy as due to a hot dust component (~670 K). However, due to the very bright Bry emission and low extinction observed across the two knots (SSC1+2 and SSC4+5), they concluded that even if there may be a large quantity of dust in the galaxy, it is not located inside the SSCs. The very young ages of SSC1 and SSC2, the absence of any treatment of the nebular emission, and the very high temperature of the dust advocated to explain the red excess in R08 make this explanation difficult to reconcile with the previously found observational properties. We showed that the integrated fluxes of these two clusters can easily be fitted from UV to NIR with self-consistent models including both stellar and nebular components.

For the remaining clusters R08 showed that the colors are compatible with the presence of RSGs, which are important in the NIR range at cluster ages around 7–10 Myr.

However, Papaderos et al. (2006) found for SSC3 evidence of Wolf−Rayet stars (W−Rs) in the optical spectrum. The presence of W−Rs is a very transient phenomenon and Starburst99 models predict that they last around 1 Myr at a cluster age of around 6 Myr. This age is in agreement with our estimate for SSC3. It is likely that SSC3 is still too young to show a contribution due to RSGs.

In the NIR spectrum of the knot SSC4+5, Vanzi et al. (2000) found no evidence of CO absorption typical of RSGs and important if the nebular emission does not contribute any longer (McCray et al. 2003). We have to mention that the regions where SSC4 and SSC5 are located are very complex due to the proximity of very young star-forming sources. It is possible that the spectra presented by Vanzi et al. (2000) are indeed dominated by these very young star-forming regions.

However, we detect Hα emission at the locations of SSC3, SSC4, SSC5, and SSC6 which reveal that the emission from the photoionized gas is not yet gone. We have shown in Section 3 that the fraction of nebular emission contributing in the NIR filters (bottom panel of Figure 3) is still considerable and is strictly connected with the metallicity of the gas. The same models but at higher metallicity (i.e., solar metallicity) show that the nebular phase is over at around 6 Myr. Since SBS 0335-052E is among the lowest metallicity nearby galaxies known, we expect to see such prolonged contribution.

Both R08 and T09 analyzed the Paα NICMOS data available for SBS 0335-052E, reaching discordant results regarding the Paα emission in the SSC3, SSC4, SSC5, and SSC6. T09 reported a non-detection of Paα emission in these clusters, showing a dearth of ionized gas. On the other hand, the values reported by R08 (listed in their Table 3) are close to the ones predicted by the Hα/Paα ratio considering our derived extinction.

5.2. What is the Cause of the I-band Excess?

In the previous section, we noticed that the six clusters have observed fluxes in the I band (F791W) that sit above the best model predictions, with a discrepancy of 0.2–0.5 mag. It is likely that the flux excess in this filter is due to a mechanism other than photoionized gas. The presence of a strong UV radiation field fuelled by the very young massive stars and large quantities of dust distributed in the galaxy and close to the SSCs can originate the ERE phenomenon as already proposed by R08.

Another possible explanation for this small systematic offset could be related to the low-resolution power of the F791W data. The coarse pixel scale of the WFCPC/WF3 chip (0′′1) used to capture the F791W image and the small aperture radius used (0′′15) mean that the aperture correction is significantly more uncertain than for the remainder of the UV/optical data which were obtained with the ACS camera. A significant error in the F791W aperture correction would lead to the SSCs lying systematically above or below the best-fit models. The accuracy of the encircled energy distribution determination for a 0′′15 radius aperture is no better than 0.07 mag (Holtzman et al. 1995). While this is smaller than the observed excess (~0.3 mag) it cannot be excluded that an uncertainty in the aperture correction contributes to the apparent offsets. The clusters are poorly sampled in the image and this could produce higher uncertainties associated with the derived aperture correction.

6. CONCLUSIONS

We tested our models which include stellar continua and a self-consistent treatment of the photoionized gas to verify the impact of the nebular component on the total flux of the young star clusters. Using new measurements of the EW(α) we determined the ages of the six bright SSCs in SBS 0335-052E. The ages were used to produce new fits to the whole SED of the clusters using our custom-designed evolutionary models. With the contribution to the integrated fluxes from the photoionized gas, we can fairly reproduce the SED shape in all six clusters.
This new proposed explanation is also supported by previous numerous analysis of the starburst regions in the galaxy.

We verified whether the assumptions made by our models are in agreement with the observed physical properties of the clusters and of the starburst environment in general. We also tested the condition that the whole ionized region contributing to the total integrated fluxes is contained in the aperture size used to perform photometry. We found that the size of the emitting \( \text{H}\alpha \) regions around the clusters is reasonably smaller than the photometric radii.

We finally noticed a persistent flux excess at 0.8 \( \mu \text{m} \), impossible to reconcile with our spectral evolutionary models. We consider, in agreement with R08, the possibility that dust photoluminescence, typically observed in \( \text{H}\alpha \) regions around massive star-forming complexes, can contribute to the integrated flux transmitted by the \( WFPC2/F791W \) filter.

While nebular emission seems to be the origin of the red excess in the two dwarf galaxies SBS 0335-052E (this work) and NGC 4449 (Reines et al. 2010, 2008a), this is not the case for the red excess observed in the young star clusters of Haro 11 (Adamo et al. 2010), which remains unresolved. The access to X-shooter data for the SBS 0335-052E SSC1+2 and a few of the clusters with strong red excess in Haro 11 would represent a fundamental source of information to disentangle the different causes of the red excess and quantify the real amount of flux produced by nebular continuum and emission.

We thank Amy Reines for valuable discussions and suggestions made on this work. Nate Bastian, Brent Groves, and the anonymous referee are gratefully acknowledged for the useful comments made on this manuscript. A.A., G.Ö., and E.Z. acknowledge support from the Swedish Research Council. E.Z. acknowledges research grants from the Swedish Royal Academy of Sciences. G.Ö. is a Royal Swedish Academy of Sciences research fellow, supported from a grant from the Knut and Alice Wallenberg foundation. G.Ö. and E.Z. also acknowledge the Swedish National Space Board. M.H. acknowledges the support of the Swiss National Science Foundation. 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.

REFERENCES

Adamo, A., Östlin, G., Zackrisson, E., Hayes, M., Cumming, R., & Micheva, G. 2010, MNRAS, 407, 870
Anders, P., & Fritz-Alvensleben, U. 2003, A&A, 401, 1063
Bastian, N., Gieles, M., Lamers, H. J. G. L. M., Scheepmaker, R. A., & de Grijs, R. 2005, A&A, 431, 905
Bergvall, N., & Östlin, G. 2002, A&A, 390, 891
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Cabanc, R. A., Vanzi, L., & Sauvage, M. 2005, ApJ, 631, 252
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Carlson, L. R., et al. 2007, ApJ, 665, L109
Churchwell, E. 2004, in ASP Conf. Ser. 322, The Formation and Evolution of Massive Young Star Clusters, ed. H. J. G. L. M. Lamers, L. J. Smith, & A.Nota (San Francisco, CA: ASP), 329
Conti, P. S., & Blum, R. D. 2002, ApJ, 564, 827
Cresci, G., Vanzi, L., & Sauvage, M. 2005, A&A, 433, 447
Darbon, S., Perrin, J.-M., & Sivan, J.-P. 1998, A&A, 333, 264
Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, PASP, 110, 761
Fernández-Ontiveros, J. A., Prieto, M. A., & Acosta-Pulido, J. A. 2009, MNRAS, 392, L16
Gouliermis, D. A., Bestenlehner, J. M., Brandner, W., & Henning, T. 2010, A&A, 515, A56
Hayes, M., Östlin, G., Mas-Hesse, J. M., & Kunth, D. 2009, AJ, 138, 911
Holtzman, J. A., et al. 1995, PASP, 107, 156
Hunt, L. K., Vanzi, L., & Thuan, T. X. 2001, A&A, 377, 66
Izotov, I. I., Guseva, N. G., Lipovetskii, V. A., Kniazev, A. I., & Stepianian, J. A. 1990, Nature, 343, 238
Izotov, Y. I., Chaffee, F. H., & Schaerer, D. 2001, A&A, 378, L45
Izotov, Y. I., Lipovetskaya, V. A., Chaffee, F. H., Foltz, C. B., Guseva, N. G., & Kniazev, A. Y. 1997, ApJ, 476, 698
Izotov, Y. I., Schaerer, D., Blecha, A., Royer, F., Guseva, N. G., & North, P. 2006, A&A, 459, 71
Johnson, K. E., Hunt, L. K., & Reines, A. E. 2009, AJ, 137, 3788
Kunth, D., & Östlin, G. 2000, A&AR, 10, 1
Lançon, A., Gallagher, J. S., III, Mouchine, M., Smith, L. J., Ladjal, D., & de Grijs, R. 2008, A&A, 486, 165
Leitherer, C., et al. 1999, ApJS, 123, 3
McCrady, N., Gilbert, A. M., & Graham, J. R. 2003, ApJ, 596, 240
Mengel, S., Lehner, M. D., Hatte, N., & Genzel, R. 2005, A&A, 443, 41
Misselt, K. A., Clayton, G. C., & Gordon, K. D. 1999, ApJ, 515, 128
Osterbrock, D. E., & Ferland, G. J. 2006, in Astrophysics of Gaseous Nebulae and Active Galactic Nuclei, ed. D. E. Osterbrock & G. J. Ferland (2nd ed.; Sausalito, CA: Univ. Science Books), 2006
Östlin, G., Hayes, M., Kunth, D., Mas-Hesse, J. M., Leitherer, C., Petrosian, A., & Atek, H. 2009, AJ, 138, 923
Papaderos, P., Izotov, Y. I., Guseva, N. G., Thuan, T. X., & Frickey, K. J. 2006, A&A, 454, 119
Pierini, D., Majeed, A., Boroson, T. A., & Witt, A. N. 2002, ApJ, 569, 184
Portegies Zwart, S., McMillan, S., & Gieles, M. 2010, ARA&A, 48, 431
Reines, A. E., Johnson, K. E., & Goss, W. M. 2008a, AJ, 135, 2222
Reines, A. E., Johnson, K. E., & Hunt, L. K. 2008b, AJ, 136, 1415
Reines, A. E., Nidever, D. L., Whelan, D. G., & Johnson, K. E. 2010, ApJ, 708, 26
Thompson, R. I., Sauvage, M., Kennicutt, R. C., Jr., Engelbracht, C. W., & Vanzi, L. 2006, ApJ, 638, 176
Thompson, R. I., Sauvage, M., Kennicutt, R. C., Engelbracht, C. W., Vanzi, L., & Schneider, G. 2009, ApJ, 691, 1068
Thuan, T. X., Izotov, Y. I., & Lipovetskaya, V. A. 1997, ApJ, 477, 661
Vanzí, L., Hunt, L. K., Thuan, T. X., & Izotov, Y. I. 2000, A&A, 363, 493
Witt, A. N., & Víb, U. P. 2004, Astrophys. Dust, 309, 115
Zackrisson, E., Bergvall, N., Olofsson, K., & Siebert, A. 2001, A&A, 375, 814
Zackrisson, E., Bergvall, N., & Leitet, E. 2008, ApJ, 676, L9