DELAYED PHOTOIONIZATION FEEDBACK IN A SUPER STAR CLUSTER IN SBS 0335–052E

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ABSTRACT

SBS 0335–052 is a well-studied blue compact dwarf galaxy with one of the lowest metallicities of any known galaxy. It also contains six previously identified super star clusters. We combine archival HST NICMOS images in the Paβ line and the 1.6 μm continuum of the eastern component, SBS 0335–052E, with other space- and ground-based data to perform a multiwavelength analysis of the super star clusters. We concentrate on the southernmost clusters, designated S1 and S2, which appear to be the youngest clusters and are the strongest emitters of Paβ, radio, and X-ray flux. Our analysis leads to a possible model for S1 and perhaps S2 as a cluster of very young, massive stars with strong stellar winds. The wind density can be high enough to absorb the majority of ionizing photons within less than 1000 AU of the stars, creating very compact H ii regions that emit optically thick radiation at radio wavelengths. These winds would then effectively quench the photoionizing flux very close to the stars. This can delay the onset of negative feedback by photoionization and photodissociation on star formation in the clusters. This is significant since SBS 0335–052E resembles the conditions that were probably common for high-redshift star formation in galaxies near the epoch of reionization.

Subject headings: galaxies: dwarf — galaxies: individual (SBS 0335–052E) — galaxies: starburst — galaxies: star clusters

1. INTRODUCTION

Many present-day simulations of galaxy formation predict a much larger fraction of baryons that eventually become stars than the observed fraction of 5%–10% (Cole et al. 2001). At the baryon densities favored by cosmic microwave background (CMB) measurements the luminosity function is overpredicted at both high and low luminosities (Benson et al. 2003). Introduction of negative feedback by supernovae has not eliminated the problem. Negative feedback from the processes of star formation may offer the solution. SBS 0335–052E, found in the Second Byurakan Survey (Markarian et al. 1983), offers a unique opportunity to observe star formation and feedback in conditions similar to primordial star formation but in a relatively nearby (53 Mpc) galaxy. SBS 0335–052E resembles our current expectations for very early galaxy formation in that it has a very low metallicity, Z/0.4/0 (Izotov et al. 1990, 1992) and a very high gas-to-stellar mass ratio, ~25:1, based on the stellar content visible in optical light (Pustilnik et al. 2001; Papaderos et al. 1998). Observations with WFPC2 on the Hubble Space Telescope (HST) by Thuan et al. (1997) revealed six pointlike sources (see Fig. 1, left, for the source numbers and contour plots), superposed on diffuse emission. They deemed the six sources, which are within 500 pc of each other, to be super star clusters (SSCs) with current star formation.

Infrared Space Observatory (ISO) observations by Thuan et al. (1999) found strong dust emission from the region of the sources. These observations were supplemented by Dale et al. (2001) at 12.5 μm and other wavelengths and by Hunt et al. (2001) at 4 μm. Recent Spitzer observations (Houck et al. 2004) measured the spectrum of the infrared emission and found it quite different than other starburst galaxies and devoid of any PAH emission features as was noted by Thuan et al. (1999). Additional Spitzer IRAC and MIPS data have also been recently acquired by Engelbracht et al. (2005). Nonthermal radio emission with a possible optically thick thermal component (Hunt et al. 2004) has been found to come from the region of the sources S1 and S2. The resolution of the radio observations is not high enough to spatially separate the two sources; however, very recent radio observations by Johnson (2005) resolve the two sources. Sources S1 and S2 are the southernmost sources of the six SSCs that are bounded in the north by a supernova bubble, which has led to speculation of a sequence of star formation propagating from north to south (Thuan et al. 1997).

Chandra X-ray observations (Thuan et al. 2004) detect a point source at a position consistent with source 2 and possibly source 1. Thuan et al. (2004) conclude that the source is consistent with a compact group of high-mass X-ray binaries or an intermediate-mass black hole. Pustilnik et al. (2004) have analyzed the optical colors and Hα emission in SBS 0335–052E to determine the maximum age of the underlying low surface brightness (LSB) component of the galaxy. They find ages of ~≤(100, 400) Myr for (instantaneous, constant) star formation models with the instantaneous model providing the best fit; however, previous work by Östlin & Kunth (2001) has provided caveats to the age determination in SBS 0335–052.
The SSCs of SBS 0335–052E lie in the eastern component of the SBS 0335–052E/W complex. Radio H\textsc{i} observations by Pustilnik et al. (2001) find that both components are part of a large neutral hydrogen cloud of about $2 \times 10^9 \, M_\odot$, with a significantly larger spatial extent than most blue compact dwarfs (BCDs). Pustilnik et al. (2001) also determine a dynamical mass of $9 \times 10^9 \, M_\odot$ for the system, most of which must be dark matter. They also note the presence of NGC 1376 at a projected distance of 150 kpc with a radial velocity about 100 km s$^{-1}$ greater than the SBS 0335–052E system and a mass of $(0.5 \pm 1.0) \times 10^{12} \, M_\odot$. Figure 2 shows the spatial relationship of NGC 1376 and SBS 0335–052E. Interaction with NGC 1376 may be the trigger that initiated the current star formation episode in the SSCs (Pustilnik et al. 2001) and in SBS 0335–052W, which new work by Izotov et al. (2005) has found to have the lowest metallicity yet found for any galaxy.

The first \textit{HST} UV spectra were presented by Thuan & Izotov (1997), which showed Ly$\alpha$ in absorption, consistent with the large neutral hydrogen cloud observed at radio wavelengths. They also found UV metal lines with P Cygni profiles that are most likely associated with the UV-bright sources S4 and S5. \textit{HST} ACS UV images of SBS 0335–052E (Fig. 1, right), using the solar blind channel by Kunth et al. (2003), found very little, if any, Ly$\alpha$ emission escaping from the SSCs. They also revealed that S3 is double with a separation of only 26 pc projected on the sky. \textit{HST} UV spectra with the Space Telescope Imaging Spectrograph (STIS; Kunth et al. 2004) also show strong absorption in Ly$\alpha$ consistent with previous observations. Thuan & Izotov (1997) calculate a column density of neutral hydrogen of $7 \times 10^{21} \, \text{cm}^{-2}$, again consistent with the large H\textsc{i} mass determined from the radio observations. UV spectroscopy with \textit{FUSE} (Thuan et al. 2005) confirms this result and measures a low metal abundance in the neutral gas that is similar to the ionized gas, in contrast with earlier results (Thuan & Izotov 1997). They note that their spectrum does not show any H$_2$ absorption lines. The near-infrared H$_2$ emission spectrum observed by Vanzi et al. (2000) contains both thermal
shock and fluorescent excitation components, indicating a mixture of the two excitation mechanisms. Since the FUSE observations encompass the entire set of SSCs, the primary line of sight probed by the observations is that toward S4 and S5, which are the brightest sources in the UV continuum. The neutral gas metal measurements are therefore dominated by the gas along those sight lines. If the $H_2$ emission is primarily associated with the more obscured S1 and S2, and the lack of UV $H_2$ absorption lines quoted by Thuan et al. (2005) can easily be explained.

The general picture of SBS 0335−052E is a low-metallicity, gas-rich system with ongoing star formation in SSCs. The bulk of the underlying stellar population appears to be less than at most 400 Myr, indicating that most of the stars in SBS 0335−052E are the result of recent star formation. The metals that do exist in SBS 0335−052E may be a remnant of a much earlier episode of star formation or the result of an initial seeding of the intergalactic medium from the Population III stars that reionized the universe. We examine SBS 0335−052 as a local example of star formation processes that must have been common in the early universe. If SBS 0335−052 eventually becomes part of NGC 1376, it will be an example of a minor merger in the hierarchical process of galaxy assembly. In the following we concentrate on the southernmost sources, S1 and S2, which appear to be the youngest of the SSCs and the major source of the X-ray, $\text{Pa}_\alpha$, and radio emission. The $\text{Pa}_\alpha$ and radio fluxes, plus the ground-based–determined near-IR extinction, are the keys to building a consistent picture of S1 and S2 and judging the feedback effect of star formation in the sources. In this paper the primary question is not the age of the underlying stellar population but rather what is the effect of the current star formation on the immediate environment.

2. OBSERVATIONS

The archival data analyzed here are from HST NICMOS images in F160W and $\text{Pa}_\alpha$ (GO-9360, PI: R. Kennicutt), which were taken as a component of the SIRTF (now Spitzer) Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003). All images are from the NICMOS camera 3, which has 0.2 pixels for a wide non–diffraction-limited field. The observations occurred on 2002 July 15. There are four 23.97 s integrations in the F160W filter, four 191.96 s integrations in the F187N filter, and four 159.96 s integrations in the F190N filter. This is the standard integration suite for the SINGS snapshot survey. The redshift of SBS 0335−052E puts the $\text{Pa}_\alpha$ line into the F190N filter rather than the rest-frame F187N $\text{Pa}_\alpha$ filter. In this case the F187N filter serves as the continuum filter. The narrowband integrations were both STEP32 with 14 reads in the F187N filter and 13 reads in the F190N filter. The F160W integrations were STEP8 with nine reads. The observations used a four-point spiral dither pattern with 0.9 spacing between the points. Integrations in each of the three filters were made at each dither position before moving to the next position. The integrations were carried out in a single orbit.

3. DATA REDUCTION

The NICMOS images were reduced in a standard manner (for a detailed description see Thompson et al. 2005). Although auxiliary observations were available for correction of South Atlantic Anomaly (SAA) passage persistence, they were not utilized as none of the images appeared to have suffered from the effect. The NICMOS data were then rebinned to the WFPC2 pixel size of 0.1 with the procedure IDP3 (Lytle et al. 1999). The images were aligned utilizing stars in the image, and the F187N image was subtracted from the F190N image to produce the $\text{Pa}_\alpha$ image. The NICMOS image was then aligned to the original WFPC2 images of Thuan et al. (1997), again using stars in the image. Initially this was done using only the brightest star in the image; however, this appeared to produce poor alignments. It was then discovered by aligning using the fainter stars in the field that the brightest star has significant proper motion and had moved by 0.18 between the NICMOS observations and the WFPC2 images taken in 1995 January. The alignment accuracy is better than 0.03.

The measured flux in $\text{Pa}_\alpha$ for S1 and S2 is $1.77 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$. The point-source limit for detection is about a factor of 100 below this number but varies across the image depending on the amount of diffuse emission in the region. The $1\sigma$ single pixel noise is 0.002 ADU s$^{-1}$, which is equivalent to $1.2 \times 10^{-18}$ ergs s$^{-1}$ cm$^{-2}$. The continuum subtraction is accurate to better than 5% based on the net residuals in the areas of the image that are devoid of sources. The F160W image has a $1\sigma$ single pixel noise of 0.01 ADU s$^{-1}$, while the S1+S2 source has a total signal of 62 ADU s$^{-1}$.

We also retrieved the archival ACS UV images from Proposal 9470 with Daniel Kunth as PI, which are described in Kunth et al. (2003). These were aligned with IDP3 and utilized to better understand the morphology of SBS 0335−052E at higher spatial resolution than the NICMOS images or the previous WFPC2 images. These images are in the continuum F140LP and Ly$\alpha$ F122M filters. The pixel size of the retrieved images is 0.025, which were subsequently rebinned to 0.1 to match the other images used in this investigation. The single pixel $1\sigma$ noise of the F140LP image is $4.0 \times 10^{-21}$ ergs s$^{-1}$ cm$^{-2}$. Since Ly$\alpha$ is in absorption, it is unclear how to interpret the F122M image; therefore, the F140LP image is the only ACS image used in this study. Using a point-spread function (PSF) determined from stars in the UV image away from the SSCs, we find that the SSC S1 is resolved with a radius of 3 pc assuming the 53 Mpc distance given in § 1.

4. THE VOLUME EMISSION MEASURE

The key elements to this study are the volume emission measure, $N_e^2 V$, and the nature of the thermal radio emission. Together they determine the nature of the stellar population and the state of the ionized gas in S1 and S2. In what follows we lump S1 and S2 together since they are unresolved in the NICMOS image. We assign half of the emission to each source, and hence half of the volume emission measure, although a radio image from Johnson (2005) indicates that S1 is the stronger radio source. The error is at most a factor of 2 and does not affect the major conclusions of the paper. The optical and near-infrared contour plots and the UV F140LP image are shown in Figure 1 in the orientation of the original WFPC2 images. The dominant $\text{Pa}_\alpha$ emission is clearly centered on S1 and S2 with some emission also at S3. The lack of emission at the other sources may be due to lack of integration time. The gradient in $\text{Pa}_\alpha$ emission is consistent with the propagation of star formation from the north to the south as discussed in § 1.

We next use the $\text{Pa}_\alpha$ image to determine the volume emission measure for S1 and S2, which in turn is a direct measure of the ionizing flux. Hunt et al. (2001) measured the Br$\gamma$ and Br$\delta$ flux in a 1.5" by 1.5" region centered on S1 and S2 that does not include any of the emission from S3. The measured $\text{Pa}_\alpha$ flux in this region is $1.77 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ after subtraction of flux from an aperture of equal area off the source to eliminate any contribution due to diffuse emission. The observed Br$\gamma$/Br$\delta$ ratio (Hunt et al. 2001) predicts an $A_V$ value of 12.1 ± 2 using the extinction law of Rieke & Lebofsky (1985), which is very similar to the value of 12.2 found by Hunt et al. (2001) using another extinction law. This in turn predicts an extinction of 1.64 mag at $\text{Pa}_\alpha$, which
gives an extinction-corrected Paα flux of $8.01 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ for the 1" by 1.5 region that contains S1 and S2. Here we have assumed that since S1+S2 is the brightest Paα emitter, it is also probably the brightest Brγ emitter as well and the measured extinction from Brγ/Brα is appropriate for correcting the Paα emission of S1+S2. Izotov et al. (1997) find that the optical emission lines are best matched with an ionized gas temperature of 20,000 K, which we use in the rest of the analysis. An important question is whether the observed Paα flux in this work is consistent with the Brγ measurements in the context of normal case B recombination theory. The extinction at Brγ from Rieke & Lebofsky (1985) is 0.57 mag, which gives an extinction-corrected Brγ flux of $1.52 \times 10^{-4}$ ergs s$^{-1}$ and a Paα-to-Brγ ratio of 5.26. The line ratios given in the Appendix of Hunt et al. (2004) show that the calculated ratio for 20,000 K is 4.22. Given the expected errors in fluxes and extinctions, this is considered in reasonable agreement. Note that if the Paα-to-Brγ ratio were affected by line optical depth effects, we would expect that the observed ratio would be less than the calculated ratio since the population of the $n = 3$ state of the hydrogen gas should be greater than the $n = 4$ state. The numbers in this calculation are listed in Table 1.

A caveat to the calculated extinction should be mentioned. If the extinction derived from the infrared lines is extrapolated to the ultraviolet wavelength of the ACS image, 1400 Å, it should be on the order of 24 mag. Comparison of the predicted flux at 1400 Å from the Starburst99 calculation described below indicates an extinction of approximately 8 mag. This, however, follows an already observed trend in SBS 0335–052E that the derived extinction decreases at shorter wavelengths (Hunt et al. 2001). The usual explanation is that only at longer wavelengths can you see into the regions of higher extinction. Since we are concerned with the true Paα flux, we use the extinction derived directly from the infrared lines, which is consistent in the ratios of Paα to Brγ and Brα. The radio images of Johnson (2005; slide 10) confirm that there are no hidden ionization regions off the observed sources that could be the source of additional Brα flux that might contaminate the measurement.

Using case B recombination theory

$$\int_{v_b}^{\infty} \frac{L_{\nu}}{h\nu} = Q(H^0) = N_e^2 V \alpha_B$$

and the Appendix from Hunt et al. (2004), the volume emission measure to total Paα power is given by

$$N_e^2 V = \frac{F_{\text{Paα}} (T/10^4 \text{ K})^{1.161}}{4.19 \times 10^{-28}},$$

where $F_{\text{Paα}}$ is in ergs s$^{-1}$. For a 20,000 K ionized gas the observed Paα for S1 only, assigning half of the S1+S2 emission to S1, requires a volume emission measure ($N_e^2 V$) of $7.2 \times 10^{65}$ cm$^{-3}$, which is equivalent to 16,000 O7 stars using the O7 star $N_e^2 V$ value of $4.43 \times 10^{61}$ from Sternberg et al. (2003).
5. RADIO COMPONENT

The optically thin free-free emission is directly proportional to the volume emission measure by the thermal bremsstrahlung equation

$$\frac{dP}{d\nu} = 6.8 \times 10^{-51} T^{-1/2} N_e^2 V g(\nu, T) \exp\left(-\frac{\nu}{kT}\right),$$  \hspace{1cm} (3)

where $dP/d\nu$ is in W m$^{-3}$ Hz$^{-1}$ and all units are in the mks system (Woan 2000). For radio frequencies the Gaunt factor $g(\nu, T)$ is given by

$$g(\nu, T) = 0.28 \left[ \ln\left(4.4 \times 10^{16} \nu^3 \nu^{-2}\right) - 0.76 \right].$$ \hspace{1cm} (4)

As in equation (3), the $Z$ dependence has been dropped since the majority of the gas is hydrogen. At a distance of 53 Mpc the value of the volume emission measure found in §4 from the Pa$\alpha$ flux of S1, converted to m$^{-3}$, predicts a thermal radio emission of 0.61 mJy at 10 GHz for an ionized gas temperature of 20,000 K, which is a factor of 4 above the flux observed by Johnson (2005; slide 8) of 0.15 mJy at 10 GHz for S1 only. The synchrotron flux observed by Hunt et al. (2004) for S1+2S is not present in the Johnson (2005) spectrum, indicating that it is probably associated with S2 or other regions outside S1.

Instead of the expected $\nu^{-0.1}$ decrease in radio flux with frequency spectrum of optically thin free-free emission, the observed radio spectrum has a roughly $\nu^{0.28}$ rising spectrum. This, coupled with the factor of 4 less emission than predicted from the emission measure, indicates that the radio emission has a significant optically thick component. The radio emission probably comes from a complex geometry of varying optical depths and perhaps temperatures, but observations of galactic H ii regions that surround the ionizing star (Simon et al. 1983) suggest a very simplified model of 7500 O stars with winds that produce H ii regions of high enough density that the Strömgren spheres are confined to areas close to the star. We can use the simplified models of Olnon (1975) as a guide.

Olnon (1975) showed that for a density structure of $(r/R)^{-q}$ around a star the frequency dependence of the optically thick radio emission is $\nu^q$, where $n = (2q - 3.1)/(q - 0.5)$. The unhindered free expansion wind with $q = 2$ gives a roughly $\nu^{0.28}$ spectrum. The value of $q$ for $n = 0.28$ is 1.72, which is appropriate for a wind that is not allowed to freely expand but is hindered by the surrounding medium. The flux at a frequency $\nu$ is given by

$$S_\nu = \frac{2\pi kT}{c^3 D^2} \nu^2 \left[ \tau_\nu(R) \right]^{2/(2q - 1)} \Gamma \left(\frac{2q - 3}{2q - 1}\right),$$ \hspace{1cm} (5)

where $D$ is the distance to the object and $R$ is the $R$ in the density equation. The optical depth $\tau_\nu(R)$ is given by

$$\tau_\nu(R) = \frac{(n_e)^2 \sqrt{\pi} R f(\nu, T) \Gamma(q - 1/2)}{\Gamma(q)},$$ \hspace{1cm} (6)

and the emissivity $f$ in cm$^2$ pc is given by

$$f(\nu, T) = 8.235 \times 10^{-2} \left(\frac{T}{k}\right)^{-1.35} \nu^{-2.1} \text{ (GHz)}$$ \hspace{1cm} (7)

for Olnon's model IV.

Distributing the observed flux equally among 7500 stars and matching the observed flux at 10 GHz gives the following parameters for the H ii regions around each star. The electron density at $R$ is $1.6 \times 10^6$, and $R$ is $2.1 \times 10^{-3}$ pc or 433 AU for a temperature of 20,000 K. The optical depth at $R$ is 9.7, justifying the assumption of optically thick emission. As is well known, Olnon's model IV is not valid for $q \leq 2$ since an integration of the density law leads to an infinite mass. The density law must be truncated at some radius as is done for $q = 2$ in Olnon's model V. The solutions are not given for other $q$-values, but the general nature is that they are basically model IV in the optically thick regions and the normal free-free spectrum in the optically thin regions; therefore, use of model IV in this frequency range is justified and real stars will have truncated flows when the pressure of the interstellar medium halts the wind. The parameters described above are typical of hypercompact H ii regions. If 2$R$ is taken as a characteristic size of the ionized regions, then the total volume occupied by the ionized gas is only $4.6 \times 10^{-3}$ pc$^3$, which is a filling factor of less than $10^{-4}$ for a 3 pc cluster radius. This is justification for our assumption that the H ii regions are confined to the stars themselves. The average distance between the 15,000 O stars in the cluster is about 0.1 pc, much greater than the size of the H ii regions. Note that integration of the density equation out to 1.9$R$ accounts for the volume emission measure calculated from the Pa$\alpha$ emission. In reality it is probable that although the majority of O stars may have confined H ii regions, some of the H ii regions have broken out and some ionizing UV emission is present throughout the cluster, producing a background optically thin component of emission. Obviously the stars in S1 will have differing density structures and the structure we have used here is a representative average. The variations in structure will produce bumps and wiggles in the radio spectrum as is observed in the spectrum of Johnson (2005). It also should be emphasized that the model developed here is not the only possible geometry of the ionized gas that will account for the line and radio emission. It is, however, motivated by observations in our own Galaxy of young stars with winds that limit the ionized area to a small region centered on the star.

5.1. Other Emission Components

Although not critical to our discussion of feedback in SBS 0335—052E, we address two other known emission components for completeness and to show that neither component has a significant effect on the galaxy at the present time. The X-ray emission component could conceivably have a significant role in the nature of the galaxy at a later time, however.

5.1.1. X-Ray Emission

The total X-ray luminosity for SBS 0335—052E is approximately $(3.0 \pm 0.5) \times 10^{39}$ erg s$^{-1}$ (Thuan et al. 2004) depending on the spectral model used to fit the data. The emission is primarily from a point source although Thuan et al. (2004) state that there is also evidence for faint extended emission with a luminosity of $6.4 \times 10^{37}$ ergs s$^{-1}$. The temperature of the X-ray-emitting gas is $kT = 2.7_{-1.3}^{+16.6}$ keV, which is much hotter than the 1 eV gas responsible for the nebular continuum. For this temperature gas the volume emission measure, $N_e^2 V$, required is $3 \times 10^{52}$ cm$^{-2}$, which is more than 1000 times less than is required for the nebular emission (see §4). This indicates that the hot X-ray-emitting gas is a minor component of the ionized gas in SBS 0335—052E. Thuan et al. (2004) indicate that the X-ray spectrum is relatively soft and consistent with either a cluster of high-mass X-ray binaries or an intermediate-mass black hole. The thermal bremsstrahlung from the X-ray-emitting gas is only $10^{-3}$ Jy at radio frequencies; therefore, it does not contribute to the observed radio flux.
5.1.2. Mid-Infrared Emission

One of the surprises of SBS 0335–052E was the discovery of strong mid-infrared emission from dust in a galaxy that has very low metallicity (Thuan et al. 1999; Plante & Sauvage 2002). Neither the ISO image nor the Spitzer peak-up image (Houck et al. 2004) has the spatial resolution to associate the infrared emission with a particular component or SSC, but it is consistent with being centered on S1–S2. The simplest explanation is that the infrared source is associated with S1 and S2. This is also consistent with the ground-based observations of Dale et al. (2001), which show that the Brγ emission and the 12.5 μm emission are coincident with an accuracy of 0.05″. The high emission measure of S1 and S2 indicates that they are young and still have dust nearby if not in the clusters themselves. Houck et al. (2004) comment that the mid-IR spectrum is consistent with very hot dust, which is another reason for associating the mid-IR emission with the young S1 and S2 SSCs. The intrinsic luminosity of $4.3 \times 10^9 L_\odot$ is sufficient to power the approximately $1.5 \times 10^9 L_\odot$ mid-infrared luminosity. In fact, with an $A_V$ value of 12 there should be a 3 times higher mid-infrared luminosity than that observed if the dust causing the extinction is located close to S1. Given our model of sources with strong winds, it is probable that the dust geometry is quite complex and that there may not be high dust obscuration over a full $4\pi$ sr, allowing a large fraction of luminosity to escape in directions other than along our line of sight to the sources. It is very probable that there is little, if any, dust in the strong-wind, ultracompact H ii regions surrounding the stars.

6. FEEDBACK ON THE GALAXY

One of the critical missing elements in our ability to model the formation, growth, and evolution of galaxies is a good understanding of how the initial star formation affects, or has feedback on, subsequent star formation. SBS 0335–052E affords an opportunity to observe the process at reasonably high resolution under conditions similar to star formation at very high redshift. There are several qualitative clues and a few quantitative ones that can be identified.

6.1. Qualitative Evidence

There is significant evidence, as discussed by Thuan et al. (1997) and now with the increase of Paα emission toward the southern clusters, that there is a progression of apparent ages, starting with the supernova cavity in the northeast and ending with the obviously young S1 and S2 in the southwest. This suggests that each episode of star formation has positive feedback on subsequent star formation. The lack of a significant population of stars in the supernova cavity suggests that the very first star formation episode ended very quickly, blowing out the area but producing compression of the gas that led to star formation at S6, S5, and S4. These then induced star formation at S3 and subsequently at S1 and S2. More qualitative evidence of positive, or at least nondestructive, feedback is the double source, S3. The two clusters are separated on the sky by only 26 pc and are therefore almost certainly associated. That two clusters can form stars in such close proximity is strong evidence that adjacent star-forming areas do not produce strong negative feedback. Although not as intense as S1+S2, S3 has detectable Paα emission, indicating current star formation. It is not possible to determine which of the clusters, or perhaps both, is the source of the star formation. The exact nature of the clusters is not critical, but rather that two clusters can form in close proximity, regardless of the sequence, is evidence that the presence of large-scale star formation does not necessarily terminate other star formation in the immediate environment. It is unfortunate that we cannot observe this system at much higher resolution to see the dynamical interaction between two closely paired clusters.

The simple existence of SSCs, which have thousands of O stars within a radius of only a few parsecs, sets severe limits on the negative feedback from massive star formation. The formation of the first massive stars does not prevent the subsequent formation of thousands of more massive stars at average distances of far less than a parsec from the first stars. In fact, this is a motivating consideration in the construction of our model system to see if there is a plausible model that matches the observed parameters and that allows the formation of such a cluster. Since a large fraction of stars may have formed in clusters, this has important implications on theories of galaxy evolution.

6.2. Quenched Photoionization Feedback

If our model of individual H ii regions surrounding the O stars is even approximately correct, it says that the volume of ionized gas in at least S1 is quite small compared to the volume of the cluster. This invokes a scenario that most of the luminous stars are losing mass through stellar winds and the ionizing photons of the stars are expended within a few hundred AU from the stars due to the high densities created by the winds. This quenches any negative feedback due to the photoionization of neutral gas. Other than through winds and gravity, these stars have very little effect on their environments outside of their H ii regions. As long as these winds continue, photoionization will not play a role in feedback on the galaxy as a whole. It is important to note here that the boundaries of the H ii regions are simply where the ionizing photons are depleted and do not necessarily mark any boundary for the gas outflow.

Although the effects of photoionization can be accurately mapped through emission-line images and radio emission maps, the effects of stellar winds are less easily measured. Work by Chevalier & Clegg (1985) indicated that massive and concentrated star clusters should produce a strong stationary superwind at all times in their evolution. This would remove gas from the cluster and affect the surrounding region through shocks and density enhancement. Recent work by Dopita et al. (2005), however, indicates that many outflows around H ii regions created by young stellar clusters are “stalled” by the ambient interstellar medium. In this case, however, the individual stellar H ii regions appear to be stalled by the intercluster gas. This may be a phase that further delays the onset of feedback at the cluster level. Dopita et al. (2005) note that it is mainly the pressure that controls the expansion of the H ii regions. The low stellar-to-gas mass ratio and the large gas mass of SBS 0335–052 may contribute to stalling out the expansion of the stellar H ii regions.

7. FUTURE EVOLUTION

The future evolution of the SSCs and of SBS 0335–052 itself is of great interest. SBS 0335–052W has an even lower metallicity than the eastern component, but with a higher X-ray luminosity (Thuan et al. 2005; Izotov et al. 2005). It appears that the western component has not yet had a major episode of star formation.

7.1. Evolution of SBS 0335–052

As suggested by Pustilnik et al. (2001), the star formation in the eastern component was probably triggered by interactions, either between the eastern and western component or with NGC 1376. Since the two components share a common H ii cloud, it appears likely that it was the interaction with NGC 1376 that
triggers the formation of the SSCs. The large amount of neutral gas, $2 \times 10^9 M_\odot$, shows that there is adequate mass for further star formation in both components. Based on only the radial component of the velocity difference between SBS 0335$-$052 and NGC 1376, they are gravitationally bound to each other. It would appear that the eventual fate of SBS 0335$-$052 is to merge with the much larger NGC 1376 in what in hierarchical galaxy assembly would be called a minor merger. In most galaxy merging simulations significant star formation occurs after the first encounter, which would mean that SBS 0335$-$052 has already had its first encounter with NGC 1376 and may have been significantly closer to it in the past.

7.2. Evolution of the SSCs

The current SSCs in SBS 0335$-$052E will evolve on a much shorter timescale than the SBS 0335$-$052/NGC 1376 system. According to the stellar populations calculated by Starburst99, there are more than 2500 stars in the S1 SSC with more than $30 M_\odot$. These stars should end up as black holes at the end of their evolution. Although many of the black holes may be ejected from the cluster due to supernova kicks, there exists the possibility of having several thousand black holes within the 3 pc radius of the cluster. This proximity may lead to mergers that could form an intermediate-mass black hole, consistent with the X-ray emission from the region. An alternative scenario is presented by Portegies Zwart et al. (2004), who modeled the cluster MGG 11 in M82. They calculated that the dynamical time for a 100 $M_\odot$ star to sink to the center of the cluster was 3 Myr, which led to several collisions and the formation of an 800–3000 $M_\odot$ star, which then led directly to the creation of an intermediate-mass black hole without significant mass loss. Although the radius of S1 is about twice that of MGG 11, it has about 10 times more mass, leading to a similar dynamical sink time from equation (1) of Portegies Zwart et al. (2004). In either scenario super star clusters may be the birthplace of intermediate-mass black holes that can be the seeds of the massive black holes that power AGNs. The lack of X-ray emission from the other sources in SBS 0335$-$052 indicates that this process did not occur in those sources; however, we do not currently have detailed information on their stellar density in the formation epoch equivalent to the current epoch of S1 and S2.

8. Conclusions

The Pa$_\alpha$ flux from the S1 SSC provides a determination of the volume emission measure that, when compared to the observed radio emission, indicates that much of the radio emission occurs at high to moderate optical depth and high density. A simple model that divides the volume emission measure equally among the 7500 O stars predicted from Starburst99 and using radio emission models of Olnon (1975) indicates a very low filling factor for the ionized gas, consistent with the assumption of individual H I regions. The confinement of the ionizing flux to regions of only a few hundred AU around individual stars limits and delays the effect of photoionization of neutral gas and molecular clouds. This provides a consistent picture of how several thousand O stars can form within a radius of 3 pc and may be indicative of star formation at early times in the universe. Although indicating very little negative feedback at the current time, SBS 0335$-$052 has a very low stellar-to-gas mass ratio. As that ratio increases and the gas mass decreases, the confining pressure of the interstellar medium may decrease to a level where the H I regions are no longer stalled at small radii and begin to produce negative star formation feedback on the galaxy as a whole. Finally, we address the evolution of both the complex and the SSCs, indicating that SBS 0335$-$052 may be part of a minor merger with NCC 1376 and speculating that S1 and SSCs in general may be the birthplace of intermediate-mass black holes.

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