ON THE RECENT HISTORY OF STAR FORMATION IN THE BLUE COMPACT DWARF
GALAXY VII Zw 403

S. Silich,1,2 G. Tenorio-Tagle,1,3 C. Muñoz-Tuñón,4 and L. M. Cairo5

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ABSTRACT

Here we attempt to infer the recent history of star formation in the BCD galaxy VII Zw 403, based on an analysis that accounts for the dynamics of the remnant generated either by an instantaneous burst or by a continuous star formation event. The models are restricted by the size of the diffuse X-ray-emitting region, the Hα luminosity from the star-forming region, and the superbubble diffuse X-ray luminosity. We have reobserved VII Zw 403 with a better sensitivity corresponding to the threshold Hα flux $8.15 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$. The total Hα luminosity derived from our data is much larger than reported before and presents a variety of ionized filaments and incomplete shells superimposed on the diffuse Hα emission. This result has a profound impact on the predicted properties of the starburst-blown superbubble. Numerical calculations based on the Hubble Space Telescope Hα data predict two different scenarios of star formation able to match simultaneously all observed parameters. These are an instantaneous burst of star formation with a total mass of $5 \times 10^7 M_\odot$ and a star-forming event with a constant star formation rate SFR = $4 \times 10^{-3} M_\odot$ yr$^{-1}$, which lasts for 35 Myr. The numerical calculations based on the energy input rate derived from our observations predict a short episode of star formation lasting less than 10 Myr with a total star cluster mass of $(1-3) \times 10^6 M_\odot$. However, the five main star-forming knots are sufficiently distant to form a coherent shell in a short timescale and still keep their energies blocked within local, spatially separated bubbles. The X-ray luminosities of these are here shown to be consistent with the ROSAT PSPC diffuse X-ray emission.

Key words: galaxies: dwarf — galaxies: individual (VII Zw 403) — galaxies: starburst — ISM: abundances — ISM: bubbles

1. INTRODUCTION

It has recently been recognized that the star formation activity in galaxies is very irregular in time, and many examples of major burst episodes exhibit an extremely high star formation rate (SFR) concentrated in well-localized space regions (Terlevich 1996). It is also now well known that starbursts (SBs) cause an emission that dominates the entire host galaxy luminosity and their mechanical energy input rate is expected to cause major structural changes in the surrounding interstellar medium (ISM). In this respect it has become of great interest to study the properties of the resultant large-scale expanding superbubbles that, powered by the violently injected newly processed matter, establish the timescale for mixing with the ISM (Tenorio-Tagle 1996; Silich et al. 2001). In extreme cases, the superbubbles are thought to break out of the galactic disks leading to an effective mass and energy transport into the low-density halos or even into the intergalactic medium via a superwind (Heckman, Armus, & Miley 1990).

SBs in the local universe are also assumed to be good representatives of the star-forming activity at high redshifts. This concept defines their cosmological interest as key laboratories for studying the ISM, the transport of supernova-processed metals, and the chemical evolution of galaxies and of the intergalactic medium. The resulting structure in the ISM due to mechanical energy injected by SBs is very similar to the interstellar wind-blown bubbles around single massive stars (see Weaver et al. 1977 for their four-zone model), although the much larger energy input rate in SBs leads rapidly to much larger scales. Hydrodynamical simulations (see Tenorio-Tagle & Bodenheimer 1988; Bisnovatyi-Kogan & Silich 1995 and references therein; Suchkov et al. 1994; Silich & Tenorio-Tagle 1998; D’Ercole & Brighenti 1999; Strickland & Stevens 2000) currently include differential galactic rotation, radiative cooling, and strong density gradients between the disk and the halo and thus are able to follow the moment of breakout, as well as the fragmentation of the expanding outer shell via Rayleigh-Taylor instabilities and the venting of the superbubble hot interior gas, either into the intergalactic space or into the host galaxy halo (the blowout phenomenon).

Most of the up-to-date simulations have been performed under the assumption of a constant energy deposition rate, as expected from an instantaneous burst model. However, studies of the stellar population in OB associations related to young ($\tau_{OB} < 10$ Myr) Large Magellanic Cloud (LMC) bubbles (see Oey & Smedley 1998 and references therein) have demonstrated that “realistic” energy input rates are very different from the assumed constant energy input rates used in numerical simulations. Thus, the instantaneous burst assumptions may not be applicable to all cases. Here we attempt to establish a method of comparison between the theory of superbubbles and the observations of remnants produced by massive star formation in galaxies. Two possible modes of star formation, instantaneous and extended bursts, are taken into consideration. For both cases the mechanical luminosity, ultraviolet photon output, mass returned to the ISM, and the fraction of each in met-
als, all as a function of time, are estimated. On the other hand, we have the observed parameters: the H\(\alpha\) or H\(\beta\) luminosity, which can be directly related to the SFR under the assumption that all photons are used up in the ionized region. One can also estimate the size and luminosity of the X-ray remnant. In some cases the remnants may have slowed down sufficiently to display their outer expanding shells, either in the optical or in H\(\text{I}\) observations, or both, giving further information about the size, expansion speed, and mass behind the outer shock. A comparison with the theory also requires some preconception of the galaxy’s ISM, which can as a first approximation be derived from H\(\text{I}\) observations and the inferred dynamical mass. However, one also needs to make an assumption about the fraction of this gas locked up in dense clouds and immersed into a less dense ISM background.

With the aim of establishing a method to confront theory with observations that may lead us to infer the recent star formation history of galaxies, the blue compact dwarf (BCD) VII Zw 403 is thoroughly analyzed. In § 2 we derive the main properties of coeval and extended star formation modes. In § 3 we summarize the main observational properties of our target. In § 4 we present a summary of the hydrodynamical calculations aimed at matching the observed properties. The results of the calculations and our main findings are discussed in § 5.

2. STAR FORMATION

Following the observational evidence in support of the concept of a continuous star formation spread over 10–20 Myr or more (Herbst & Miller 1982; Stahler 1985; Coziol, Doyon, & Demers 2001), Shull & Saken (1995) have discussed five possible tracks of the SFR time evolution, including both the time span of star formation and possible time variations in the initial mass function (IMF). Here we examine one of their cases: a constant SFR spread over a finite time interval \(\tau\). We compare its intrinsic properties with the standard instantaneous model. The simple model discussed below can be generalized to more sophisticated cases with a time-dependent SFR and a variable IMF.

2.1. The Properties of Starbursts

Let us assume an instantaneous burst characterized by an IMF with an exponent \(\alpha\),

\[
f(m) = \frac{(\alpha - 2)M_{\text{SB}}}{M_{\text{low}}^2 - M_{\text{up}}^2} m^{-\alpha},\]

where \(M_{\text{SB}}\) is the total mass of the SB cluster and \(M_{\text{low}}\) and \(M_{\text{up}}\) are the lower and upper cutoff masses, respectively. From this one can calculate the expected energy and mass input rates.

2.1.1. The Mechanical Energy Input Rate

The mechanical energy deposition from an SB should include the energy injection via stellar winds and from supernova explosions. Here the early mechanical energy injection (before the first supernova explosion at \(t = t_{SN}\)) has been approximated by a constant value \(L_w\), which adds the contribution of all individual massive stars in the cluster. This value can easily be scaled from the template of Leitherer & Heckman (1995, hereafter LH95) for an SB with a total mass of \(10^6 M_\odot\) within the mass range \(M_{\text{low}} = 1 M_\odot\) and \(M_{\text{up}} = 100 M_\odot\):

\[
L_{\text{SB}} = L_{\text{SN}} \frac{M_{\text{SB}}}{M_{\text{BH}}} = \text{const}, \quad t \leq t_{SN},
\]

where \(L_{\text{SB}}\) is the total stellar mass considered, \(M_{\text{BH}} = 10^6 M_\odot\), and \(L_{\text{SN}}\), following LH95, is set equal to \(10^{39} \text{ ergs s}^{-1}\).

After a time \(t > t_{SN}\) the energy released via supernova explosions dominates the SB mechanical energy deposition, and then the energy released by the SB as a function of time is defined by the expression

\[
E_{\text{SB}}(t) = \int_{M(t)}^{M_{\text{up}}} E_{\text{SN}} f(m) dm = \frac{\alpha - 2}{(\alpha - 1)} \frac{M_{\text{SB}} E_{\text{SN}}}{M_{\text{low}}^2 - M_{\text{up}}^2} \left[ M_{\text{low}}^{1-\alpha}(t) - M_{\text{up}}^{1-\alpha} \right],
\]

where \(M(t)\) is the mass of the stars exploding as supernovae after an evolutionary time \(t\). For simplicity, the energy released per supernova \(E_{\text{SN}}\) is assumed to be independent of the progenitor mass and equal to \(10^{51} \text{ ergs}\).

The energy input rate from the SB at the supernova-dominated stage is then

\[
L_{\text{SB}} = \frac{dE_{\text{SB}}(t)}{dt} = - \frac{\alpha - 2}{(\alpha - 1)} \frac{M_{\text{SB}} E_{\text{SN}} M_{\text{low}}^{-\alpha}(t)}{M_{\text{low}}^2 - M_{\text{up}}^2} \frac{dM}{dt}, \quad t > t_{SN}.
\]

The lifetime of the massive stars can be inferred from the approximations of Chiosi, Nasi, & Sreenivasan (1978) and Stothers (1972). Then the function \(M(t)\) has the form

\[
M(t) = \begin{cases} 
10 \left( \frac{9 \times 10^6}{t} \right)^2 M_\odot, & 30 \leq M \leq 100 M_\odot, \\
10 \left( \frac{3 \times 10^7}{t} \right)^{5/8} M_\odot, & 7 \leq M \leq 30 M_\odot.
\end{cases}
\]

Substituting the time derivative of \(M(t)\) into equation (4), one obtains

\[
L_{\text{SB}} = \frac{2(\alpha - 2)M_{\text{SB}} E_{\text{SN}} M_{\text{low}}^{1-\alpha}(t)}{M_{\text{low}}^2 - M_{\text{up}}^2} \frac{dM}{dt}, \quad t_{SN} \leq t \leq t_3,
\]

\[
\frac{5(\alpha - 2)M_{\text{SB}} E_{\text{SN}} M_{\text{low}}^{1-\alpha}(t)}{8M_{\text{low}}^2 - M_{\text{up}}^2} \frac{dM}{dt}, \quad t_3 \leq t \leq t_7,
\]

where \(t_3\) and \(t_7\) are the stellar lifetimes for a 30 and 7 \(M_\odot\) star, respectively.

2.1.2. Mass Deposition

Before the first supernova explosion, the mass injected by a star cluster results from individual stellar winds calculated as

\[
M(t) = \int_0^t \frac{2L_{\text{SN}}}{V_w^2} dt, \quad t \leq t_{SN},
\]

where the collective wind terminal velocity is assumed to be \(V_w = 2000 \text{ km s}^{-1}\). Afterward, the mass injection is dominated by supernovae and one can neglect the contribution from stellar winds. During the supernova-dominated stage, the total ejected mass as a function of time may be approxi-
mated by (see Silich et al. 2001)
\[ M_{ij}(t) = M_{SB}(t) \frac{M^2_{up} - M^2_{low}}{M_{up}^2 - M_{low}^2}, \quad t > t_{SN}. \]

Following Silich et al. (2001), we assume that the gas ejected by supernovae includes all the newly synthesized metals, and thus the mass in ejected metals as a function of time is
\[ M_{\text{metals}}(t) = \frac{(\alpha - 2)M_{SB}}{M_{up}^2 - M_{low}^2} \int_{M(t)}^{M_{up}} Y_{\text{metals}}(m)m^{-\alpha} dm, \]
where \( Y_{\text{metals}} \) is a particular element yield. One can then use, for example, oxygen as a tracer of the metallicity caused in the interior of superbubbles. In such a case the oxygen yield can be approximated by analytical fits to the stellar evolutionary tracks of Maeder (1992) and Woosley, Langer, & Weaver (1993), which account for the mass loss due to stellar winds (see Silich et al. 2001). The mean metallicity inside a supernova is then defined by the ratio of the wind- and supernova-ejected oxygen to the total mass within the supernova \( m_{\text{ej}} = M_{\text{ej}} + M_{\text{ev}} \), which includes also the mass thermally evaporated from a cold outer shell (\( M_{\text{ev}} \)):
\[ Z_{O} = \frac{M_{O}(O)/Z_{\odot}(O) + Z_{\text{ISM}}M_{\text{ev}}}{M_{\text{in}}} \]
where \( Z_{\text{ISM}} \) and \( Z_{\odot} \) are both in solar units, \( Z_{\odot}(O) = 0.0083 \) (Grevesse, Noels, & Sauval 1996).

2.1.3. The UV Output

For a coeval star cluster, the UV photon production rate remains almost constant until the most massive star in the cluster begins to move away from the main sequence, soon becoming a supernova. From this moment onward, the UV flux rapidly decays (Beltrametti, Tenorio-Tagle, & Yorke 1982). We approximate this evolutionary track by the power function
\[ N_{UV}(t) = \begin{cases} N^0 \frac{M_{SB}}{M_{LH}} & 0 \leq t \leq t_{SN} \\ N^0 \frac{M_{SB}}{M_{LH}} \left( \frac{t_{SN}}{t} \right)^{5} & t > t_{SN}. \end{cases} \]
The initial flux \( (N^0) \) was normalized to the \( 10^6 M_{\odot} \) standard model of LH95 and was taken to be \( 9 \times 10^{52} \) photons s\(^{-1}\). If all UV photons are trapped within a star-forming region, then the \( H_{\alpha} \) expected luminosity \( L_{H\alpha} \) follows from a simple transformation (LH95): \( L_{H\alpha} = 1.36 \times 10^{-12} N_{UV} \) ergs s\(^{-1}\).

2.2. Continuous Star Formation

If the star formation process is not coeval but is instead spread over a time \( t_{SN} \), one can approximate it by a series of \( N_{\text{tot}} \) instantaneous sequential minibursts separated by \( \Delta t = t_{SN}/N_{\text{tot}} \). One can further assume that all minibursts would have the same mass \( M_{i} = M_{SB}/N_{\text{tot}} \) and IMFs and would evolve independently according to their own clocks set upon formation:
\[ t_{i} = t - (i - 1)\Delta t, \]
where \( t \) is an evolutionary time and \( i \) is the miniburst number. Then the number of minibursts at any given time \( t \) is
\[ n(t) = \begin{cases} \text{Int} \left( \frac{t}{\Delta t} \right) + 1 & \text{if } t \leq t_{SN} \\ N_{\text{tot}} & \text{if } t > t_{SN}. \end{cases} \]
The cumulative intrinsic properties (mechanical energy input rate, mass injection, and the number of UV photons or the \( H_{\alpha} \) luminosity) can be found by simply adding the miniburst parameters:
\[ L_{SB} = \sum_{i=1}^{n(t)} L_{i}, \]
\[ M_{ej} = \sum_{i=1}^{n(t)} M_{ej,i}, \]
\[ N_{UV} = \sum_{i=1}^{n(t)} N_{UV,i}. \]

Note that the input from each miniburst should be set to zero whenever their individual evolutionary time \( t \) exceeds the lifetime of the less massive star that can explode as a supernova, that is, once \( t \) becomes larger than their intrinsic \( t_{r} \).

The global energy properties of star formation events derived from this simple model are in a good agreement with the two extreme cases (instantaneous and continuous star formation) of LH95 and are presented in Figure 1. For comparison a value of \( \alpha = 2.35 \) has been assumed as well as a stellar range of masses between 1 and 100 \( M_{\odot} \).

Figure 1a compares the mechanical energy input rates derived for a \( 10^{6} M_{\odot} \) stellar cluster formed during \( t_{SN} = 1 \) (hereafter the instantaneous burst), 20, and 50 Myr. The solid line shows the rapid rise in the coeval case, which reaches a maximum immediately after the onset of supernova explosions and then drops to values \( \sim 10^{40.2} \) ergs s\(^{-1}\) to remain almost constant up to the end of the supernova activity (\( \sim 50 \) Myr). For the \( t_{SN} = 20 \) Myr event, the maximum energy deposition is delayed in time and converges with the 1 Myr values after approximately 25 Myr. The energy deposition rate for a \( \tau = 50 \) Myr star-forming episode suffers an even longer delay, to reach values similar to the maximum input from the previous two models, and then slowly decays without reaching a uniform value throughout the 100 Myr of its evolution.

The production rate of UV photons (see Fig. 1b) is highly dependent on the star formation time considered. For the 1 Myr SB the UV flux reaches its maximum value \( \sim 9 \times 10^{52} \) at \( t = t_{SN} \) and remains constant during the first 4 Myr. It then falls very steeply, reaching before 10 Myr of evolution values more than 2 orders of magnitude smaller than its maximum value. The 20 and 50 Myr clusters acquire their uniform constant value after 4 Myr of evolution, and then upon completion of their star formation phase, their UV photon output also rapidly decays with time.

The rate at which mass is ejected by the massive star cluster is shown in Figure 1c. The total ejected mass \( \sim 40\% \) of the star cluster mass and the total oxygen mass released by supernovae (about 2% of the total mass turned into stars) are clearly the same at the end of the evolution in the three cases considered. There are, however, substantial delays for larger values of \( t_{SN} \).
3. THE MAIN OBSERVATIONAL PROPERTIES OF VII Zw 403

VII Zw 403 is a BCD galaxy considered in recent years in many discussions related to star formation histories and possible impact of dwarf systems on the surrounding intergalactic medium. Although Tully et al. (1981) proposed that the galaxy might be a member of the M81 Group, more recent distance determinations (Lynds et al. 1998) locate it about 1.5 Mpc farther away at 4.5 Mpc distance. Therefore, it can be considered an isolated galaxy (Schulte-Ladbeck et al. 1999).

The X-ray observations (Papaderos et al. 1994; Fourniol 1997) added more interest to the system, as they revealed an extended kiloparsec-scale region of diffuse X-ray emission. These observations account for approximately 85% of the total X-ray luminosity ($L_{X,\text{total}} \approx 2.3 \times 10^{38}$ ergs s$^{-1}$) from the central unresolved core, while the remaining 15% is spread over the central kiloparsec-scale region. The high-resolution data reported by Lira, Lawrence, & Johnson (2000) revealed a strong point X-ray source displaced to the west with respect to the main H$\alpha$ emission. This is most probably a powerful ($L_{X} \sim 10^{38}$ ergs s$^{-1}$) binary system. However, the kiloparsec-scale diffuse component was not confirmed by these observations, possibly as a result of the low sensitivity of the HRI.

The total dynamical mass of the galaxy is $2 \times 10^{8} M_{\odot}$, with approximately 20% or $4 \times 10^{7} M_{\odot}$ constituting the neutral hydrogen phase (Thuan & Martin 1981). VII Zw 403 does not exhibit a regular rotation but rather turbulent...
random motions of individual neutral hydrogen clumps with $\Delta V_t \approx 30$ km s$^{-1}$ (Thuan & Martin 1981). This value is taken as the velocity dispersion that supports the ISM against the self-gravity of the galaxy. The extension of the neutral hydrogen halo $R_{\text{ISM}}$ is not well known, but if the average ratio of the H I size to the optical size is accepted to be $f = 2.4$ (Thuan & Martin 1981), the H I halo radius $R_{\text{H I}}$ is about 1.9 kpc. A similar result is obtained if one assumes that the galaxy boundary occurs at the location where the escape velocity drops below the ISM random velocity $\Delta V_t$.

Lynds et al. (1998) showed that the stellar population of VII Zw 403 contains not only young blue main-sequence stars but also a much older evolved population that can be traced up to 1–2 Gyr back in time. They also studied the five centrally concentrated associations of young stars, with ages smaller than 10 Myr and which in H$\alpha$ emission appear to be surrounded by local small shells with radii $\sim 100$ pc. Schulte-Ladbeck et al. (1999) provided a near-infrared single-star photometry of the galaxy and confirmed that compact, young star-forming regions are embedded into a much older, low surface brightness halo.

### 3.1. New Observations

We present here new narrowband images of VII Zw 403 centered on the H$\alpha$ line and on the adjacent continuum (Fig. 2) that were taken in 1997 August at the 2.2 m telescope of the German-Spanish Astronomical Observatory at Calar Alto (Almería, Spain). The instrumentation consisted of the Calar Alto Faint Object Spectrograph (CAFOS) and a 2048 $\times$ 2048 SiTe CCD chip, with a pixel size of 0$''$.53 and an unvignetted circular field of view of about 11$''$.1 in diameter (14.4 kpc at the accepted distance to the galaxy of 4.5 Mpc). The averaged seeing was 1$''$.5.

The image reduction was conducted using standard procedures available in IRAF. Each image was corrected for bias using an average bias frame and was flattened by dividing by a mean twilight flat-field image. After, they were registered (for each filter we took a set of dithered exposures) and combined to obtain the final frame, with cosmic rays removed and bad pixels cleaned. The average sky level was estimated by computing the mean value within various boxes surrounding the object and subtracted out as a constant. Flux calibration was done through the observation of spectrophotometric stars from Oke (1990). For more details about data reduction and calibration refer to Cairo et al. (2001). We calculated the integrated H$\alpha$ flux out to the limiting isophote with a level equal to 2.5 times the rms of the background. In our case this threshold is $8.15 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. The H$\alpha$ flux was corrected for Galactic extinction following Burstein & Heiles (1984). No correction for internal extinction was performed.

Our H$\alpha$ image shown in Figure 2 displays a variety of shapes and structures that deserve discussion. Besides the SB knots, labeled 1–5 after Lynds et al. (1998), we detect a much fainter and extended well-structured diffuse emission. The largest obvious feature is a shell-like structure, 250 pc in radius, broken to the southwest, which we associate with knot 4. Knot 2 is almost overlapping in projection along its eastern rim.

On top of features and structures that appear to build a network of connecting knots, there is down to our limiting flux a diffuse-smooth emission that engulfs them all and most certainly results from photons leaking out of the main emitting knots.

The total H$\alpha$ luminosity is higher than reported previously. Clearly, our limiting flux is much lower than that of Lynds et al. (1998; their Fig. 2). Our data recover the low-intensity H$\alpha$ emission and thus provide a more precise estimate of the total H$\alpha$ luminosity.

The spatial resolution of the Hubble Space Telescope (HST) image (Lynds et al. 1998) also allows for the detection of a much smaller H$\alpha$ minibubble (cocoon), associated with knot 1. This bubble has similar energy to that inferred for the large superbubble reported above; however, it seems

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**Fig. 2.** Narrowband H$\alpha$ image of VII Zw 403. The left panel shows isocontours map of the continuum-subtracted H$\alpha$ image. The right panel presents a gray-scale map of H$\alpha$ emission in logarithmic scale. The lowest H$\alpha$ isocontour level corresponds to the threshold value $8.15 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$. Isocontours are equispaced in logarithmic scale.
much less evolved. The energy dumped by the cluster energizing knot 1 has not been able to sweep and displace so efficiently the surrounding ISM out of which it formed.

The above result has a profound impact on the modeling of SBs. Clearly, during the first few Myr of evolution every center of star formation disperses its high-density parental cloud. It is only after this task has been completed that the center of star formation disperses its high-density parental cloud. This has a major impact on the surrounding ISM and thus presents a number of loops or broken shells with radii \( R_t \approx 100 \) pc. Another important fact is that available observations display neither an H I nor an H II or X-ray large-scale shell surrounding the diffuse X-ray emission. This fact can be ascribed to a remnant evolving along its quasi-adiabatic phase or to a neutral hydrogen shell brightness that falls below the detection limit.

All considered models assume that the observed H I mass occupies a smooth low-density disk-halo distribution, although an important fraction of it (20% < \( f_c < 95\% \)) is in a dense cloud component. This has a major impact on the evolution of remnants as it affects both the time required to reach a given size and the resultant X-ray luminosity produced within the superbubble. Our models also assume that the ISM is supported in hydrostatic equilibrium in the galaxy gravitational field by the turbulent gas pressure produced by the random gas motions with an effective velocity dispersion \( \Delta V_i \) (see Tomisaka & Bregman 1993; Silich & Tenorio-Tagle 1998). An example of the resultant initial ISM smooth component density distribution is shown in Figure 3.

The calculations were carried out with our three-dimensional Lagrangian code, which accounts for the enrichment of the hot superbubble interior by the metals ejected via supernova explosions (Silich et al. 2001). Using oxygen as a tracer, we derived the time-dependent superbubble interior gas metallicity, which was then used in our calculations of

### TABLE 1

**VII Zw 403 Observational Properties**

| Parameter                              | Value   | Reference | Comments                       |
|----------------------------------------|---------|-----------|--------------------------------|
| Distance (Mpc)                         | 4.5     | 1         |                                |
| Galaxy total mass (\( M_* \))          | \( 2 \times 10^8 \) | 2         |                                |
| Galaxy ISM mass (\( M_* \))            | \( (4.7) \times 10^7 \) | 1, 2     | From H I observations          |
| Radius of the H I halo (kpc)           | \( \sim 1.9 \) | 1         |                                |
| ISM gas velocity dispersion (km s\(^{-1}\)) | \( \sim 30 \) | 2         |                                |
| ISM gas metallicity (\( Z_\odot \))   | 0.05-0.06 | 3         |                                |
| Total H\(\alpha\) flux (ergs cm\(^{-2}\)s\(^{-1}\)) | \( (195 \pm 4) \times 10^{-13} \) | 4         | Integrated out to the limiting isophote |
| Total H\(\alpha\) luminosity (ergs s\(^{-1}\)) | \( 1.8 \times 10^{39} \) | 1         |                                |
| \( H\alpha \) shell radii:             |         |           |                                |
| Large (pc)                             | \( \sim 250 \) | 4         | Around association 4           |
| Small (pc)                             | \( \sim 80 \) | 1         | Around association 1           |
| Diffuse X-ray emission (ergs s\(^{-1}\)) | \( (1.9-2.3) \times 10^{38} \) | 5, 6     | \textit{ROSAT}PSPC data        |
| Unresolved core (%)                    | \( \sim 85 \) |           | Not confirmed by \textit{ROSAT}HRI data |
| Extended diffuse emission (%)          | \( \sim 15 \) |           |                                |
| X-ray flux from the point source       | \( 9 \times 10^{-13} \) | 7         | \textit{ROSAT}HRI data         |

**References.**—(1) Lynds et al. 1998. (2) Thuan & Martin 1981. (3) Schulte-Ladbeck et al. 1999. (4) This paper. (5) Papaderos et al. 1994. (6) Fourniol 1997. (7) Lira et al. 2000.

![Fig. 3. — Gas density distribution for models assuming 90% of the ISM mass to be stored in clouds.](image-url)
the diffuse X-ray emission. As there are no firm observational restrictions on the VII Zw 403 star formation timescale, we have examined different scenarios of the recent star formation activity in this galaxy. Two sets of models have been considered: an instantaneous burst and an extended star formation episode. We have associated an instantaneous burst with the 1 Myr event and calculated the SB parameters for every model. The results of the calculations for instantaneous burst models are summarized in Table 2. The various models are labeled again with two separate indices that now represent the logarithm of the SB mass (also indicated in col. [2]) and the fraction of the ISM assumed to be in the smooth component, respectively. The preceding letter “I” indicates that all of these are instantaneous burst models. The second set of models assumes an extended phase of star formation. The results of the calculations for these models are summarized in Table 3. The various models are labeled again with two separate indices that now represent the star formation time \( \tau_{\text{SB}} \) (in Myr) and the fraction of the ISM in the smooth component. The letter “C” indicates the continuous star-forming mode, for which episodes lasting 5, 10, 20, and 40 Myr have been assumed. In all these models we assumed the same SFR \( 4 \times 10^{-3} \, M_\odot \, \text{yr}^{-1} \). Column (4) indicates the total stellar mass, and columns (3)–(8) list the same variables considered in Table 2. In all of these models we assumed that the photons currently produced by the stellar clusters are all used up in reestablishing the ionization of the central H II region. This fact is supported by the large H I mass present in VII Zw 403. The resulting H\( \alpha \) luminosity and the time-dependent mechanical energy input rate are shown in Figures 4a and 4b, respectively.

5. DISCUSSION

Table 2 shows that both low-mass \( 10^5 \, M_\odot \) and high-mass \( 10^7 \, M_\odot \) SB models are completely inconsistent with the VII Zw 403 parameters derived from Lynds et al. (1998) data. Indeed, the low-mass models lead to a very slow expansion speed, which makes them reach the 1 kpc size only after 10 Myr, even in the lowest density case with a cloud mass filling factor \( f_c = 90\% \) of the observed H I mass. After this time the most massive stars have left the main sequence and exploded as supernovae, causing a fast drop in the number of emitted UV photons and consequently in the H\( \alpha \) luminosity of the associated H II region. This luminosity in all low-mass SB cases is several orders of magnitude below the currently observed value. The high-mass models, on the other hand, are too energetic and produce an exceedingly high X-ray emission and an overwhelming UV photon flux when the superbubble radius reaches 1 kpc.

### Table 2

1 kpc Bubble Parameters for Instantaneous Burst Models

| Model       | \( M_{\text{SB}} \) (\( \times 10^5 \) \( M_\odot \)) | \( f_c \) (%) | \( \tau_{\text{dyn}} \) (Myr) | \( N_{\text{UV}} \) (photons s\(^{-1}\)) | \( L_{H\alpha} \) (10\(^{37} \) erg s\(^{-1}\)) | \( L_X \) (10\(^{37} \) ergs s\(^{-1}\)) | Shell State |
|-------------|---------------------------------------------------|---------------|----------------|-------------------------------------|---------------------------------|----------------|-------------|
| 15.0_10.....| 10^5                                               | 60            | 30             | 12.0                                | 7.4 \times 10^{46}              | 1.0 \times 10^{37}              | R            |
| 15.0_40.....| 10^5                                               | 60            | 30             | 12.0                                | 4.3 \times 10^{46}              | 5.8 \times 10^{35}              | R            |
| 15.0_70.....| 10^5                                               | 60            | 30             | 12.0                                | 8.7 \times 10^{46}              | 1.2 \times 10^{37}              | R            |
| 15.7_5.....  | 5 \times 10^5                                      | 95            | 6.7            | 9.5 \times 10^{35}                 | 1.3 \times 10^{37}              | 4.2 \times 10^{37}              | A            |
| 15.7_10.....| 5 \times 10^5                                      | 90            | 7.9            | 4.3 \times 10^{35}                 | 5.8 \times 10^{38}              | 1.6 \times 10^{38}              | A            |
| 15.7_40.....| 5 \times 10^5                                      | 60            | 12.0           | 4.5 \times 10^{35}                 | 6.1 \times 10^{37}              | 1.8 \times 10^{38}              | R            |
| 15.7_70.....| 5 \times 10^5                                      | 30            | 15.5           | 1.3 \times 10^{35}                 | 1.7 \times 10^{37}              | 2.3 \times 10^{38}              | R            |
| 16.0_5.....  | 10^6                                               | 95            | 6.0            | 3.5 \times 10^{35}                 | 4.8 \times 10^{39}              | 3.5 \times 10^{37}              | A            |
| 16.0_10.....| 10^6                                               | 90            | 6.8            | 2.0 \times 10^{35}                 | 2.7 \times 10^{39}              | 1.5 \times 10^{38}              | A            |
| 16.0_40.....| 10^6                                               | 60            | 9.8            | 2.7 \times 10^{35}                 | 3.7 \times 10^{38}              | 4.5 \times 10^{38}              | R            |
| 16.0_70.....| 10^6                                               | 30            | 12.0           | 9.1 \times 10^{35}                 | 1.1 \times 10^{38}              | 5.5 \times 10^{38}              | R            |
| 17.0_10.....| 10^7                                               | 90            | 4.7            | 1.5 \times 10^{35}                 | 2.0 \times 10^{41}              | 3.3 \times 10^{38}              | A            |
| 17.0_40.....| 10^7                                               | 60            | 5.8            | 4.4 \times 10^{35}                 | 5.9 \times 10^{40}              | 1.7 \times 10^{39}              | A            |
| 17.0_70.....| 10^7                                               | 30            | 6.3            | 3.0 \times 10^{35}                 | 4.1 \times 10^{40}              | 8.1 \times 10^{39}              | A            |
The intermediate-mass SBs ($5 \times 10^5$–$10^6 M_\odot$) are in better agreement with observations. However, for the emitted number of UV photons to be consistent with the value derived from the observed H$\alpha$ luminosity, the smooth component of the ISM has to contain only a small ($\sim 5\%$) fraction of the observed H$\alpha$ mass. The shock wave blown by coherent supernova explosions into this low-density medium remains adiabatic when it reaches a 1 kpc radius (see Table 2). Therefore, in these models (I5.7_5, I6.0_5) an essential fraction of the X-ray emission ($\sim 80\%$ in model I5.7_5 and $\sim 50\%$ in model I6.0_5) arises from the outer adiabatic shell of swept-up matter that should occupy the outer $\leq 20\%$ of the remnant volume. However, this is not resolved in the available X-ray maps. From the results in Table 3, it is clear that, for a reasonable agreement between the observed parameters of VII Zw 403 and a continuous star formation scenario, the episode of star formation should last no less than the dynamical time required for the superbubble to reach the 1 kpc radius.

### Table 3

| Model    | $M_{SB}$ ($M_\odot$) | $f_i$ (%) | $\tau_{SB}$ (Myr) | $N_{UV}$ (photons s$^{-1}$) | $L_{H\alpha}$ (ergs s$^{-1}$) | $L_X$ (ergs s$^{-1}$) | Shell State |
|----------|----------------------|-----------|-------------------|-----------------------------|-----------------------------|----------------------|-------------|
| C5_10... | $2.1 \times 10^4$    | 90        | 22.3              | $1.3 \times 10^{47}$        | $1.6 \times 10^{35}$        | $1.3 \times 10^{36}$  | R           |
| C5_40... | $2.1 \times 10^4$    | 60        | 50.5              | $1.5 \times 10^{45}$        | $2.1 \times 10^{33}$        | $1.3 \times 10^{36}$  | R           |
| C10_10...| $4.1 \times 10^4$    | 90        | 20.0              | $1.5 \times 10^{48}$        | $2.0 \times 10^{36}$        | $3.6 \times 10^{36}$  | R           |
| C10_40...| $4.1 \times 10^4$    | 60        | 34.5              | $4.0 \times 10^{46}$        | $5.4 \times 10^{34}$        | $6.6 \times 10^{36}$  | R           |
| C10_70...| $4.1 \times 10^4$    | 30        | 59.0              | $1.7 \times 10^{45}$        | $2.3 \times 10^{33}$        |                     | No          |
| C20_10...| $8.2 \times 10^4$    | 90        | 19.5              | $1.3 \times 10^{31}$        | $1.8 \times 10^{39}$        | $5.8 \times 10^{36}$  | R           |
| C20_40...| $8.2 \times 10^4$    | 60        | 29.4              | $1.7 \times 10^{48}$        | $2.3 \times 10^{36}$        | $1.6 \times 10^{37}$  | R           |
| C20_70...| $8.2 \times 10^4$    | 30        | 37.5              | $1.6 \times 10^{47}$        | $2.2 \times 10^{35}$        | $4.3 \times 10^{37}$  | R           |
| C40_10...| $1.6 \times 10^5$    | 90        | 19.5              | $1.3 \times 10^{31}$        | $1.8 \times 10^{39}$        | $6.3 \times 10^{36}$  | R           |
| C40_40...| $1.6 \times 10^5$    | 60        | 29.0              | $1.3 \times 10^{31}$        | $1.8 \times 10^{39}$        | $1.9 \times 10^{37}$  | R           |
| C40_70...| $1.6 \times 10^5$    | 30        | 35.1              | $1.3 \times 10^{31}$        | $1.8 \times 10^{39}$        | $3.2 \times 10^{37}$  | R           |

The best continuous star-forming model (C40_70), with SFR = $4 \times 10^{-3}$ $M_\odot$ yr$^{-1}$, $\tau_{SB} = 40$ Myr, and 30% of the total ISM mass in the dense cloud component, requires about 35 Myr for the outer shock to reach a radius of $\sim 1$ kpc. In this model an extended gaseous halo cannot completely prevent gas loss from the galaxy and allows a final shell speed slightly in excess of the escape velocity. The H$\alpha$ luminosity is not an issue in this case as it is exactly the amount used to derive the constant SFR. The time evolution of the superbubble diffuse X-ray emission is shown in Figure 5 for different ISM models. Initially the X-ray luminosity grows rapidly with time, following the energy input rate and mean hot gas metallicity time evolution. It reaches a maximum value after 10–20 Myr and then remains almost constant up to the end of the star-forming activity. The maximum X-ray luminosity is larger in models with a larger smooth ISM component and matches the value observed in VII Zw 403 when the smooth component of the ISM amounts to 70% of the observed H$\alpha$ mass. Note that we
stopped our calculations when the shock fronts reached the assumed galactic ISM cutoff position (1.9 kpc). This causes the breaks in the X-ray curves around 30 and 50 Myr for the \( f_c = 0.9 \) and 0.6 models, respectively.

Note that for these moderate ISM densities and the relevant mechanical luminosities (see Fig. 4b), the shell of swept-up matter becomes radiative after a short time \( \tau_{\text{cool}} \approx 2.3 \times 10^3 n_{\text{ISM}}^{-0.71} L_{38}^{0.28} \text{ yr} \) (Mac Low & McCray 1988). However, this is not detected in the available H I maps. One can then claim that the large-scale shell is photoionized by radiation escaping the central H II region, and thus it should be most easily observed in H\(\alpha\) light. However, note that if \( \sim 80\% \) of the UV photon flux is being used to ionize gas around the central star clusters, as it is assumed to be for the totality of clusters 1 and 2 in VII Zw 403 (Lynds et al. 1998), then the rest of the photons (\( N_{\text{esc}} = 0.25 L_{17} / \left(3.16 \times 10^{-12} \text{ s}^{-1} \approx 3.25 \times 10^{50} \text{ s}^{-1} \right) \) would be free to ionize the outer ISM. If the number of UV photons trapped within the neutral smooth component is negligible, they will ionize the neutral outer shell. Such a shell would appear as a 1 kpc diffuse H\(\alpha\)-emitting feature with brightness

\[
B = \frac{1.36 \times 10^{-12} N_{\text{esc}}}{64 \pi R_{sh}^2} \theta^2 \approx 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2},
\]

where \( \theta = 1^\circ.5 \) is the averaged seeing. However, this is below our detection limit (8.15 \( \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \)), and thus the H\(\alpha\) emission excess expected at the bubble outer shell is unlikely to be detected. Approximately an order of magnitude better sensitivity has to be reached to confirm this possible model.

So far it appears that the remnants caused by the two completely different recent star-forming histories considered here are able to explain the observables in VII Zw 403. In all of our models, however, we have also calculated the time-dependent mixing of the metals freshly ejected by supernovae with the matter thermally evaporated from the outer shell. Figure 6 shows the time evolution of the mean inner gas metallicity (using oxygen as a tracer; see Silich et al. 2001) predicted for the superbubbles in the two extreme cases able to match the observations of VII Zw 403. Both cases show a superbubble interior metallicity largely different from that of the ISM detected in the optical regime (\( Z_{\text{ISM}} = 0.06 Z_\sun \); see Table 1). Enormous differences are found in the coeval case, which rapidly acquires several times \( Z_\sun \). On the other hand, the continuous star formation, although presenting high metallicity values, never surpasses \( Z_\sun \). This result could be used as a discriminator able to discard various possible recent histories of star formation in VII Zw 403. However, as it is likely that the swept-up matter in the shell preserves the same metallicity as the unperturbed ISM (see Tenorio-Tagle 1996), it will be difficult to distinguish between the metallicities of two overlaid X-ray components in the instantaneous burst case.

A close comparison of the \( HST \) observations and our data, however, has led us to realize that, although UV photons may escape their production centers and H II regions causing the extended diffuse ionized gas, the mechanical energy from the various star-forming centers has not had sufficient time to drive a large-scale remnant. This has not happened, despite the 5–10 Myr of evolution of the various subgroups in the galactic nucleus. It seems that the five star-forming centers are sufficiently distant from each other and that their mechanical energy is still currently being used to build up individual local shells. The largest H\(\alpha\) shell around star cluster 4 with a radius of \( \sim 250 \text{ pc} \) is not yet enclosing and not even in contact with the H II regions and smaller shells produced by the other star-forming centers present in the galaxy. This structure thus invalidates the assumption often made that a given mechanical luminosity derived from the H\(\alpha\) luminosity of a galaxy can be directly used in theoretical models as acting upon a smooth medium from the start of the calculation.
VII Zw 403 is clearly indicating that there may be an important leakage of UV photons out from the centers of star formation, causing an extended diffuse ionized region around an SB. However, for the mechanical energy of the various well-separated centers of star formation to start working together in the production of a large-scale remnant, a longer timescale is required. A sufficient period needs to allow for the multiple shock waves to merge and overlap with each other, clearly implying a longer time the larger the separation is between subgroups and the denser the ISM may be around the various star-forming centers.

This timescale is particularly relevant when one tries to match the remnants produced by the stellar activity in a badly (spatially) resolved or distant galaxy, for which one can nevertheless derive a good estimate of its Hα luminosity. If, for example, one will ignore the detailed structure of the ionized gas in VII Zw 403 and use the mechanical energy input rate derived directly from the total Hα luminosity, then little difference will be found between the coeval and the continuous star formation models. To fit simultaneously the larger Hα luminosity (4.7 × 10^{40} ergs s^{-1}) and the X-ray luminosity derived from the PSPC data, both models would require very similar star cluster masses [(1–3) × 10^6 M_⊙], a similar ISM structure with a large cloud mass filling factor (~95%), and a similar superbubble dynamical age (5–8 Myr). In both cases the expanding shell would remain adiabatic when the remnant reaches the 1 kpc radius. That is, if one takes the total Hα luminosity to derive the mechanical energy input rate and the bubble time evolution without knowing the ionized gas spatial distribution, one would predict a very powerful and young remnant. The delay caused by depositing the derived total mechanical luminosity locally into the different knots clearly changes the outcome.

Nevertheless, the high level of energy deposition (L_{SB} ≈ 2 × 10^{40} ergs s^{-1}) predicts (see Silich & Tenorio-Tagle 2001) that the ISM of VII Zw 403 will be blown away after a few tens of Myr.

This leads to another possible interpretation of the observed X-ray emission that is coming from the local bubbles generated by the various stellar subgroups. Take, for example, the OB associations 1 and 4 for which we know the total stellar mass, the ionizing flux, the age, and the local bubble radius. From these we have derived both analytic (Chu & Mac Low 1990) and numerical (Silich et al. 2001) estimates of the present bubble X-ray luminosity. Note that local bubble kinematic ages estimated from the Hα radii and expansion velocities (~1 Myr) are much smaller than the stellar cluster ages derived from the massive star isochrones, which are 4–6 Myr (Lynds et al. 1998). This discrepancy is often observed in the LMC bubbles (Oey & Smedley 1998) and most probably is related to the recent bubble blowout from the host molecular cloud (Silich & Franco 1999). We have assumed a mean stellar cluster age (5 Myr) as a better indicator of the bubble time evolution. One can then estimate the X-ray emission from the local bubbles if the energy input rate and the surrounding gas density \( n_e \) are known:

\[
L_X = 10^{36} ZI(\tau)c^{33/35} n_e^{17/35} t_\gamma^{19/35},
\]

where \( Z \) is the hot X-ray–emitting gas metallicity, \( I(\tau) \) is a dimensionless integral whose value is close to unity, and the energy input rate \( L_{SB} \) and the evolutionary time \( t_\gamma \) are measured in 10^{36} ergs s^{-1} and 10^7 yr units, respectively. We derive the appropriate star cluster mass and its mechanical luminosity from our SB model and use them to estimate the surrounding gas density from the standard (Weaver et al. 1977) bubble model:

\[
n_e = \left( \frac{267 \text{ pc}}{R_{sh}} \right)^5 L_{38} t_\gamma^3.
\]

These results were compared (see Table 4) with the numerical calculations assuming a time-dependent mechanical energy input rate and time-dependent hot gas metallicity. Note that the inferred X-ray luminosities show a good agreement with the observations. The large differences between the numerical and analytical estimations of the surrounding gas density result from the different mechanical energy input rates (a constant value for analytical models and increasing with time for numerical calculations).

### Table 4

| Parameter                      | Association 1 | Association 4 |
|-------------------------------|---------------|---------------|
| UV flux (s^{-1})              | 5 × 10^{50}   | 7 × 10^{50}   |
| Star cluster age (Myr)        | 5             | 5             |
| Star cluster mass (M_⊙)      | 4.7 × 10^4    | 6.6 × 10^4    |
| Shell radius (pc)             | 79            | 250           |

### Table 4

| Parameter                      | Analytic Model | Analytic Model |
|-------------------------------|----------------|----------------|
| ISM number density (cm^{-3})  | 1.1 × 10^5     | 4.9            |
| Bubble X-ray luminosity       | 3.5 × 10^{38}ZI(\tau) | 3.4 × 10^{37}ZI(\tau) |
| (ergs s^{-1})                 |                |                |
| Hot gas mean metallicity (Z_⊙)| Z_0 = 1.8      | Z_0 = 0.6      |

6. CONCLUSION

Here we have discussed the recent history of star formation and a possible nature of the diffuse X-ray emission in the nearby BCD galaxy VII Zw 403. Two possible scenarios of star formation have been considered: an instantaneous burst and an extended episode of star formation.

To construct the numerical model, we have provided new narrowband observations of VII Zw 403 centered on the Hα line with a long exposure time corresponding to the threshold Hα flux 8.15 × 10^{-17} ergs cm^{-2} s^{-1}. These observations reveal a variety of ionized filaments and incomplete shells superimposed on the diffuse Hα emission that most certainly result from the photons leaking out of the main star-forming centers. The largest feature is the 250 pc broken shell associated with stellar association 4. The total Hα luminosity derived from our observations, \( L_{H\alpha} = 4.7 \times 10^{40} \text{ ergs s}^{-1} \), is much larger than reported before. This has a profound impact on the predicted properties of the SB-blown superbubble.
The numerical models based on the HST Hα data require either an instantaneous burst of star formation with a total mass of $5 \times 10^5 M_\odot$ or a star formation episode with a constant SFR $= 4 \times 10^{-3} M_\odot$ yr$^{-1}$ lasting 35 Myr. The models, however, require radically different structures of the galactic ISM and imply very different properties of the resulting remnant.

The best coeval model assumes most of the ISM to be locked up within high-density clouds, and only ~5% of the observed neutral hydrogen mass is in the smooth component. The hydrodynamical calculations also predict the outer shell to be adiabatic after reaching a 1 kpc radius and to contribute 50%–80% of the observed diffuse X-ray emission. The bubble evolutionary time is estimated to be $\tau_{e} \approx 7$ Myr when its expansion speed is $\approx 200$ km s$^{-1}$.

The best continuous star formation model requires much higher density in the smooth ISM component, with only ~30% of the H I mass concentrated in dense clouds. This leads to a much smaller bubble expansion velocity ($V_{exp} \approx 35$ km s$^{-1}$), larger evolutionary time ($\tau_{e} \sim 35$ Myr), and a rapid cooling within the outer shell. That is, this model predicts a low brightness H I shell surrounding the diffuse 1 kpc X-ray region. This shell may also show up in Hα if exposed to the UV flux from the central cluster. The inner gas metallicities are also predicted to be very different in these two cases.

The numerical calculations based on the high energy input rate derived from our observations require an instantaneous burst or a short episode of star formation with SFR $\sim 0.1 M_\odot$ yr$^{-1}$ lasting less than 10 Myr with similar total stellar cluster masses ($1-3 \times 10^6 M_\odot$) and most of the ISM (~95%) locked up within high-density clouds. The comparison of the energy input rate derived from our Hα data with the theoretical limits implies that the entire ISM and metals produced by the current episode of star formation are going to be ejected from the galaxy after the coherent superbubble is formed.

It appears that the five main star-forming knots are sufficiently distant to form a coherent shell in a short timescale, while keeping their energies blocked within local, spatially separated bubbles. This provides a time delay that must be considered when developing a numerical model for the coherent superbubble driven by a number of young stellar clusters. Numerical calculations show that the X-ray luminosities from young local bubbles are in a good agreement with the ROSAT PSPC data. This agreement indicates that the observed diffuse component of the X-ray emission may be related to the small centrally concentrated bubbles, rather than to the coherent 1 kpc structure. Further observations with XMM-Newton are expected to be able to recover the real nature of the diffuse X-ray emission and the recent history of star formation in this galaxy.

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