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THE DWARF IRREGULAR GALAXY SEXTANS A. II. RECENT STAR FORMATION HISTORY¹

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ABSTRACT

We have used the *Hubble Space Telescope* to obtain photometric data of the resolved stars in the nearby ($D = 1.4$ Mpc) dwarf irregular galaxy Sextans A (DDO 75, A 1008-04). The data consist of WFPC2 images in 3 bands: F439W (1 hour), F555W (30 minutes), and F814W (30 minutes). We constructed very accurate color-magnitude diagrams (CMDs) in V and I down to a limiting magnitude of 26 in V . The CMDs show several clearly separated populations that align well with stellar evolution model predictions for a low metallicity system. We use the MS stars to calculate the star formation history (SFH) over the past 100 Myr. We also present a method for extracting the SFH from a second population, the blue He-burning (HeB) stars, independent of the MS. These are stars in the bluest part of the so-called ‘‘blue-loop’’ phase. This is the first time these stars have been unambiguously identified in a low metallicity system. This method has the potential to determine the SFH over the past 1 Gyr, although photometric errors in the present data limit the range to 600 Myr. We have combined the spatial density distribution of the blue HeB stars with the star formation rate (SFR) calculations to determine the behavior of the star formation in both space and time. In the past 50 Myr, Sextans A has had an average SFR ($5000 \pm 1500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$ assuming a Salpeter IMF) that is ~ 20 times that of the average SFR over the history of the galaxy ($\sim 310 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$ assuming an 11 Gyr lifetime). This current activity is highly concentrated in a young region in the Southeast roughly 25 pc across. This coincides with the brightest H II regions and the highest column density of H I. This one region contains half of all the current star formation activity within our field of view. Between the ages of 100 and 600 Myr, the star formation is roughly constant at $\sim 2000 \pm 500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$, still well above the lifetime average for the galaxy. The fluctuations during this time are spatially correlated. There are regions with a factor of ~ 5 enhancement in SFR compared to the full field of view (25%–30%

¹Based on observations with the NASA/ESA *Hubble Space Telescope* obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, under NASA contract NAS 5-26555.

of the star formation at any given time) that come and go in different locations over time. These regions are 200–300 pc in diameter and last 100–200 Myr. We estimate the star formation efficiency of these regions to be $\sim 9\%$. There is an age progression of these regions, suggesting the star formation may be propagating through the galaxy. © 1997 American Astronomical Society. [S0004-6256(97)00712-7]

1. INTRODUCTION

Dwarf irregular (dI) galaxies are excellent laboratories for studying the star formation process. They are gas-rich, have low metallicity, show little differential rotation, and contain active star formation (see Gallagher & Hunter 1984). The simpler structures make them easier to study than larger spiral galaxies (but see Skillman 1996 for a counter argument). In addition, the stellar properties of these galaxies provide a test for the accuracy of modern stellar evolution models at very low metallicity. For these reasons, dI galaxies are powerful tools for revealing the physical processes of galaxy formation and evolution.

The star formation process is most directly probed by determining the star formation history (SFH) of the galaxy. Searle *et al.* (1973) described the history of dIs as a series of periodic bursts of star formation with long quiescent periods in between. This would explain the wide range in activity and surface brightness seen in dwarf galaxies. Davies & Phillips (1988) suggested that these bursts provide an evolutionary link between dIs and the gas-poor dwarf ellipticals (dEs). Through these intense bursts the gas would either be used up or ejected from the galaxy, thus converting a dI into a dE.

The episodic nature of star formation could result from the locally spontaneous conversion of gas clouds into stars, which may be coupled to properties of the host galaxy through global parameters such as the gravitational field or gas pressure (see Elmegreen 1992). Alternatively, global star formation rates can be highly variable as a result of feedback from previous generations of stars that directly influence future star formation processes, as in stochastic self-propagating star formation (SSPSF) models (see Seiden & Schulman 1990; Franco 1992). The SSPSF models naturally yield episodic star formation as a feature of small galaxies in which few “cells” are available to support star formation and there is little differential rotation. These models predict that most small galaxies will experience periods when waves of star formation cross the galaxy, interspersed with longer quiescent periods (e.g., Gerola *et al.* 1980; Comins 1983, 1984).

There have been many observational attempts to determine the SFH of dwarf galaxies. It is possible to infer the SFH by comparing the current star formation rate (SFR) either through $H\alpha$ fluxes (Hunter & Gallagher 1986), or photometry of the brightest stars, with the average global properties of the galaxy (cf. Kennicutt 1983). Several examples include the Pegasus dI (Hoessel & Mould 1982), GR8 (Hoessel & Danielson 1983), and IC 1613 (Hodge *et al.* 1991). These methods could only provide average properties for the SFH, which can disguise a bursting history.

For galaxies in or near the Local Group, it is possible to obtain deeper photometry of the resolved stars and observe star formation events directly from the color-magnitude dia-

gram (CMD) (e.g., NGC 6822 & IC 1613, Hodge 1980). The Carina Dwarf Spheroidal is an excellent example, where there is evidence for at least two star formation events (Smecker-Hane *et al.* 1994), supporting an episodic SFH for dwarfs. The LMC and SMC are the closest gas-rich candidates, and recent work has extracted their SFHs from stellar populations (e.g., Mateo 1988; Bertelli *et al.* 1992; Gallagher *et al.* 1996; Vallenari *et al.* 1996a, 1996b). However, interaction with our Galaxy complicates their evolution.

Many excellent attempts have been made from the ground to obtain SFHs from CMDs of non-interacting dI's. This has been greatly aided through the use of synthetic photometry generated by Monte Carlo simulations with stellar evolution models. Several examples include Sextans B (Tosi *et al.* 1991), NGC 6822 (Marconi *et al.* 1995; see also Gallart *et al.* 1996a, 1996b, 1996c), and Leo A (Tolstoy 1996). Unfortunately, these methods have been limited by the depth and accuracy of the photometry available from the ground. Vast improvement can be made through use of the *Hubble Space Telescope* (HST). The superior angular resolution of the HST defeats much of the crowding of stellar images which greatly affects stellar photometry in systems at distances of order 1 Mpc. This allows deeper and more accurate photometry than possible from the ground.

Sextans A (DDO 75, A 1008-04) is a gas-rich dI with active star formation. It is located on the periphery of the Local Group at a distance of 1.44 Mpc (for discussion see Dohm-Palmer *et al.* 1997, hereafter Paper I). These qualities, along with its relatively nearby distance, makes it an excellent candidate for studying the star formation process. The active regions allow us to study the star formation directly. Determining the SFH from the stellar photometry will provide a link to the past that allows us to study the evolution of star formation in this system.

In addition, there are many supporting observations available in the literature that allow us to create a coherent picture of the evolution of this galaxy. Its metallicity has been measured to be $\sim 4\%$ solar from H II region spectroscopy (Skillman *et al.* 1989). The H I is concentrated in two clumps, which correspond to the major star forming regions (Skillman *et al.* 1988). The H I observations also indicate that the gas rotates in solid body rotation, but the axis of rotation is not aligned with the optical axis of symmetry, indicative of a barred galaxy. The highest surface brightness optical component has a peculiar square shape, which may be related to such a kinematic bar.

Previous ground-based studies of the stellar population have been conducted by several groups (see Paper I). Despite excellent efforts, the CMDs of these ground-based studies are severely hampered by crowding problems. The CMDs showed little detail other than a broad “blue plume” indicative of recent star formation, and an RGB containing an older stellar population. The young stars are concentrated in, al-

though not exclusive to, localized associations which correspond with the H II regions (Aparicio *et al.* 1987). In contrast, the older population exists throughout the galaxy.

Paper I describes in detail the measurement, calibration and accuracy of the stellar photometry used for this study. Paper III will present an analysis using Bayesian Statistical Inference (Tolstoy & Saha 1996) to extend the SFH beyond 1 Gyr. The present paper extracts the SFH over the past 600 Myr directly from star counts in the CMD. This time scale corresponds to a few orbital periods, thus it is possible to explore the link between the star formation process, and the dynamics of the galaxy. First, we briefly describe the data set and compare the CMD with stellar evolution models. From the MS, we determine the SFH over the past 50 Myr. We then describe a new method for extracting star formation rates from massive He-burning (HeB) stars that extends the SFH to 600 Myr. Finally, we discuss the spatial distribution of star formation over this time period.

2. DESCRIPTION OF THE DATA

The *HST* observations were obtained on 1995 December 1, and consisted of WFPC2 images in three filters: F439W (4000 s), F555W (1800 s), and F814W (1800 s). The stellar photometry was extracted using a modified version of the PSF fitting program DoPHOT (Schechter *et al.* 1993; Saha *et al.* 1996). The calibration to *B*, *V*, and *I* was done with the equations of Holtzman *et al.* (1995). Artificial star tests showed the data to be 50% complete down to $V=25.9$, $B=25.5$, and $I=25.2$.

Paper I describes in detail the measurement and accuracy of the stellar photometry, however, it is worth mentioning a few items here. The most significant benefit of using the *HST* to obtain photometry of Sextans A is the lack of crowding problems in the image. Comparisons of the bright stars as measured from the ground show that many of these stars are resolved into two or more stars by the *HST* data. This enhanced resolution significantly improves the dynamic range of our photometry and allows us to measure much fainter stars. In addition, the lack of crowding provides more accurate photometry for the brightest stars. This accuracy is most important for the colors, rather than the magnitudes, for separating populations in the CMD.

The CMD in *V* and *I* is shown in Fig. 1. There are many clearly defined populations, which we have outlined in Fig. 2. Clearly visible are the red giant branch (RGB) and the red clump stars just at the limit of photometry. In addition to these older stars, there is a prominent population of young blue stars. These stars, which in the past have been called the “blue plume,” have been resolved into two separate populations. There is a well defined main sequence (MS), indicating very recent star formation. Just redward of the main sequence is a clearly separate population that corresponds to massive He-Burning (HeB) stars at the bluest point in their “blue-loop” phase of evolution (e.g., Bertelli *et al.* 1994, hereafter B94). The corresponding red end of this phase can also be seen.

3. COMPARISON WITH STELLAR EVOLUTION THEORY

The derivation of a SFH depends heavily on a theoretical framework that is supplied by stellar evolution models. In order to make meaningful comparisons, it is important to have a reliable distance, a good estimate of the reddening, and knowledge of the metallicity. For Sextans A, we adopt $(m - M_0) = 25.8$ and $E(B - V) = 0.03$ (see Paper I).

Skillman *et al.* (1989) find the H II regions of Sextans A to have a metal content $\sim 4\%$ of Solar ($Z = 0.0008$). There are two appropriate sets of models available for comparison. The Geneva group provides evolution tracks for $Z = 0.001$ (Schaller *et al.* 1992). The Padua group provides evolution tracks for $Z = 0.0004$ (Fagotto *et al.* 1994), and isochrones for $Z = 0.001$ (B94). Both sets of evolution tracks needed to be converted from T_{eff} and L into the observed Johnson *B* and *V*, and the Cousins *I* passbands (the Padua isochrones are given for these passbands). This was done using the model atmospheres of Kurucz (1992) at the appropriate metallicity. These models do not apply to M stars, however; we are not concerned with such low mass stars in this paper.

Figure 3 shows the Geneva tracks plotted in the *V* and *I* CMD. The tracks align well with the various populations seen in the CMD. In particular, the red and blue supergiants line up with the extremes in the “blue-loop” phase. The RGB is difficult to compare with evolution tracks because many different age and mass stars can overlap. Furthermore, progressive changes in the metallicity over the history of the galaxy can produce similar effects as a spread in ages. With these caveats, it appears that the shape of the RGB in the models is similar to that observed.

Similarly, Fig. 4 shows the Padua tracks over the *V* and *I* CMD. The blue supergiants align well with the blue end of the “blue-loops.” However, the red-end of the “blue-loops” for the highest mass stars appear slightly too blue compared to the brightest ($V < 21$) red supergiants. There are two possible explanations for this. First, the adopted nuclear energy generation rates for $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ affect the extension of the “blue-loops” during the He-burning phase (B94). The Padua group adopts a lower value for this rate compared to the Geneva group, which explains why the high mass Geneva tracks extend further to the red. Second, the Padua evolution tracks are for a metallicity one half that of Sextans A, and the extension of the “blue-loops” is a function of metallicity (B94).

A better comparison with the Padua evolution models is with the isochrones for $Z = 0.001$. Galaxies have a continuous age distribution of stars, so the isochrones are not meant to represent the entire CMD. Rather, it is useful to use the isochrones to identify the age ranges in which the galaxy may have been forming stars. Figure 5 shows the comparison between the models and the observed stars. Note that the red extreme of the “blue-loop” phase aligns better with the red supergiants, but still not perfectly for the handful of very bright stars. In addition, the shape of the RGB matches well the observed shape, and the MS aligns with the locus of observed MS points.

There is clearly a range in ages for the observed stars of Sextans A. Rough comparisons with the isochrones indicate

FIG. 1. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the left indicate the average error at the given V magnitude. The thick lines indicate the completeness at levels 0.25 and 0.50. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. There are several prominent features. One is the main sequence on the blue side of the diagram. Just redward of the main sequence is a separate population of core Helium burning stars. On the red side, the RGB is well defined, and there are hints of the red clump just at the photometric limits.

stars as young or younger than 10 Myr, as well as a population several Gyr old that produces the RGB.

Comparison of mixed age populations with theoretical isochrones can be somewhat deceiving because the stars do not equally populate each isochrone. Rather, they spend more time in certain phases. For example, stars are more likely to be found at the extremes of the “blue-loops,” rather than in between. The isochrone tables provided by B94 allow us to extract the color and magnitude for these populations as a function of age. Figure 6 shows the path of the MS turnoff, the blue HeB stars, and the red HeB stars through the V and I CMD. The three populations align very well with the observed stars. The exception, as noted above, is the red HeB, which is slightly bluer than the few observed stars for $M_V < -4$.

4. RECENT GLOBAL SFH OF SEXTANS A

4.1 CMD Interpretation

To interpret the recent SFH of Sextans A, we rely upon our knowledge of stellar evolution. There are two main populations we can use to glean the recent SFH. Traditionally the MS is used, specifically using the strength and position of MS turnoffs. This works very well for isolated generations of stars, such as in clusters. However, the MS in galaxies with continuous star formation can be difficult to interpret because each successive generation lies on top of the previous. This is also true of the RGB. We can, however, examine the luminosity function of the MS to look for gaps, flat regions and other features that may give a clue to the SFH (e.g., Butcher 1977). In addition, there have been sev-

FIG. 2. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the left indicate the average error at the given V magnitude. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. The major populations have been outlined and labeled. These include: the main sequence (MS), blue He-Burning stars (blue HeB), red He-Burning stars (red HeB), red giant branch (RGB), red clump (RC), and asymptotic giant branch (AGB).

eral statistical methods developed for extracting SFHs from these chronologically overlapping populations (e.g., Tolstoy & Saha 1996).

With these data we have a second population that can give a direct measure of the SFH up to 600 Myr into the past. Because of the high accuracy of the *HST* photometry, we have been able to separate the blue HeB stars from the MS. When low metallicity massive stars evolve off the MS, they loop over to the Red Super-Giant Stage then back to the Blue Super-Giant stage across the top of the CMD. The phase in which they burn He in their core is mostly spent at the blue edge of these loops, and is a relatively long-lived phase. The ends of these loops form a line down the CMD just redward of the MS (e.g., B94). The position along this line is determined by the star’s mass. Since mass also determines the age at which a star reaches this phase, we can assign an age to each magnitude along this line. B94 present a diagram of age vs M_V for these stars, which we repeat in Fig. 7, along with a comparison of the same relation for the Geneva evolution tracks (Schaller *et al.* 1992). Note that the age-magnitude relation agrees extremely well between the two groups.

The blue HeB stars provide a parallel track to the MS in which to observe star formation events. From the number of stars at each magnitude, we can calculate the SFR for the age corresponding to the time it takes stars to reach this phase of evolution. There are two advantages to using the blue HeB as an indicator of SFH:

- The blue HeB stars are about 2 mag brighter than the MS turnoff stars of the same age (see Fig. 7). This allows us to probe the SFH further back in time for the same photometric limits than we could from MS turnoffs.
- There is little confusion from overlapping generations. All of the blue HeB stars of a certain magnitude come from the same generation of stars. As will be discussed below,

FIG. 3. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the right indicate the average error at the given V magnitude. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. The lines indicate the stellar evolution tracks for $Z=0.001$ from the Geneva group (Schaller *et al.* 1992). The mass for each track is indicated in units of $M_{\odot}$. The tracks line up well with the various populations seen in the CMD. In particular, the red and blue supergiants line up with the extremes in the blue-loop phase.

there is some confusion from stars leaving the MS, but this is a small effect.

One disadvantage to using the blue HeB stars is that the SFH can probe back at most 1 Gyr. Photometric errors can reduce this even further. The blue HeB stars older than 600 Myr blend with the red clump and horizontal branch, becoming degenerate in time (see Figs. 6 and 7)

To turn the star counts at each magnitude along the blue HeB into a SFR, we need to apply a normalization. The fundamental equation that determines the number of star counts in any given location of the CMD is

$$C(M_V, V-I) = \int_{\log m_1}^{\log m_2} \int_{t_1(\log m)}^{t_2(\log m)} \phi(\log m, t) \times R(t) dt d \log m, \quad (1)$$

where ϕ is the initial mass function (IMF) normalized to unity, m is mass, R is the star formation rate in units of $M_{\odot} \text{ yr}^{-1}$, and t is time. Potentially, the IMF is a function of time, however, we will assume it is time-independent in this paper. The limits of these integrals are determined by stellar evolution models, and the time limits in particular depend upon the mass as well. In most cases of interest, the location within the CMD contains stars all the same mass, thus the mass integral reduces to a single mass. For those points in the CMD where different mass tracks cross, the mass integral will reduce to two additive components, each with different time limits.

4.2 Main Sequence

We first apply Eq. (1) to the MS. We wish to analyze the CMD in discrete bins. Within each bin, we assume that the mass and the SFR are constant. We also assume the IMF is

FIG. 4. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the right indicate the average error at the given V magnitude. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. The lines indicate the stellar evolution tracks for $Z=0.0004$ from the Padua Group (Fagotto *et al.* 1994). The mass for each track is indicated in units of $M_{\odot}$. The blue end of the blue-loop path aligns well with the observed blue-supergiants. The red end of the blue-loops appears slightly too red compared to the brightest red supergiants. This is likely because the tracks used are for a metallicity one half that appropriate for Sextans A.

constant with time. Further, we assume that the MS is simply a function of magnitude, and not color. The MS reaches a level where the data begin to become incomplete. To account for this, we have applied a completeness correction such that

FIG. 5. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the right indicate the average error at the given V magnitude. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. The lines show the stellar isochrones presented in B94, with the logarithm of the age indicated. The features of the isochrones align well with the observed features. In particular, the extremes of the blue-loops align with the blue and red supergiants. The MS lies along the observed locus of the MS. The shape of the RGB matches the observed shape and position quite well. Clearly the observed stars in Sextans A cover a large range of ages. There are stars as young as 10 Myr and some older than 1 Gyr.

FIG. 6. The CMD in V and I for Sextans A. The points have been corrected for interstellar reddening. The crosses on the right indicate the average error at the given V magnitude. The right axis shows the absolute V magnitude assuming a distance modulus of 25.8. The lines show the tracks of the MS turnoff, the blue HeB stars, and the red HeB stars for $Z=0.001$ (B94). These populations align very well with the observed stars. The exception is the red HeB which appears slightly too blue compared to the very few stars with $V < 21$.

each star is given an increased weight, depending on its magnitude, to account for the missing stars. For example, a star detected at the 50% completeness level would count as two stars. The completeness level was calculated based on artificial star tests (see Paper I). This correction is most important for $V > 25$, which corresponds to ages > 90 Myr on the MS.

The counts in a single bin along the MS can be assumed to be due to stars of the same initial mass. However, each bin will have stars from all generations younger than the turnoff age (TO) for that mass. Thus, Eq. (1) becomes

$$C_n(M_V) = \phi(\log m_n) \Delta \log m_n \sum_{n=0}^{\text{TO}} R_n \Delta t_n, \quad (2)$$

where n is the bin number, and $\Delta \log m_n$ and Δt_n depend upon the bin size. $\Delta \log m_n = [(d \log m)/(dM_V)]_n \Delta M_V$, where ΔM_V is the bin width, and $(d \log m)/(dM_V)$ is determined from the relation between M_V and $\log m$ for the MS. Δt_n is the difference in TO ages between bins, $\text{TO}_n - \text{TO}_{n-1}$. Thus, the counts in any given bin are given by

$$C_n(M_V) = \phi(\log m_n) \left(\frac{d \log m}{dM_V} \right)_n \Delta M_V \times [R_1 \text{TO}_1 + R_2 (\text{TO}_2 - \text{TO}_1) + \dots + R_n (\text{TO}_n - \text{TO}_{n-1})], \quad (3)$$

where R_1 is the SFR from the youngest bin, R_2 the next youngest, and so on. Figure 8 demonstrates this procedure graphically.

Note that to properly extract the SFR, we need to know the SFR from each previous bin. Thus, we can recursively find the SFR by starting with the youngest bin, and working backward through time. One difficulty with this procedure is

FIG. 7. A comparison of the absolute V magnitude with age between the HeB phase and the MS turnoff. The data are taken from the isochrones of B94 for $Z=0.001$, and the evolution tracks of Schaller *et al.* (1992). Note that the HeB stars are roughly 2 mag brighter than the MS turnoff stars for the same age. Also, the two sets of models agree extremely well in their age-magnitude relation for the blue HeB stars.

that the calculated SFR of the oldest bins then depends on that determined for the youngest bins. In the youngest bins, the counting statistics are low. The errors associated with this, therefore, propagate through the entire SFH determined from the MS.

A second problem, illustrated by bin 5 in Fig. 8, is that negative SFRs can be calculated. This occurs if the bin is over-subtracted by the sum of previous rates. The over-subtraction can result from erroneously high counts in younger bins, or from low counts in the oversubtracted bin.

There are three functions we need to assume in determining the SFR from the MS luminosity function.

- First is the relation between M_V and the stellar mass along the MS. This can be obtained from stellar evolution models. We used the data given by B94 as a lookup table.

- Second is the relation between M_V and the turnoff age along the MS. Again, we can use stellar evolution models in a lookup table (see Fig. 7; B94).

- Third is the IMF. We adopt a power law with a Salpeter (1955) slope of $\Gamma = -1.35$, for the mass range 0.5 to $100 M_\odot$. This slope is consistent with models of nearby galaxies (Kennicutt 1983; Kennicutt *et al.* 1994; Gallagher & Hunter 1984). For comparison, we also use the field star IMF determined by Scalo (1986) under the assumption of a constant SFR. This has a steeper slope of $\Gamma = -1.7$, which is found to be inconsistent with models (Kennicutt *et al.* 1994), but provides a useful impression of how changing the IMF slope affects the analysis.

Using these functions we can calculate the value of the SFR as a function of time. The actual value calculated depends entirely on the chosen model. Future changes in these models will require changes in the SFRs calculated here. The stellar evolution tracks contain several sources of systematic uncertainty, such as the treatment of convection and mass loss, as well as the lack of rotation in the models. These systematic uncertainties are difficult to characterize; a com-

parison between the Geneva and Padua evolution tracks is somewhat deceiving in this regard because they have quite similar input physics. Thus, we include in our error estimates only the uncertainty due to random fluctuations, with the understanding that the calculations are model dependent, and subject to the same systematic uncertainties as the models.

Despite these warnings, we do have reason to feel confident that the models are mostly correct. As discussed in Sec. 3, the models reproduce all of the major features observed in the Sextans A CMD. Furthermore, the MS luminosity and lifetime are fairly secure, and should not change much with future modifications of the models (Chiosi *et al.* 1992).

Most importantly, changes in the models will not alter the presence of general features in the SFR with time, such as peaks and valleys. The normalizing functions used are smooth power laws. Thus, any observed star formation events come from the data, and not the normalization. Although the actual value of the rate of a star formation event may be uncertain, the presence of such an event is secure.

In addition to the stellar evolution models, the IMF is a large systematic uncertainty in our determination. In particular, we are uncertain if the IMF is universal, or if it varies with environment (e.g., metallicity and local density). Fortunately, there is some evidence that the IMF does not vary much with metallicity (Matteucci & Tosi 1985; Massey *et al.* 1995a; Massey *et al.* 1995b). We wished to be able to adjust the slope of the IMF, and so, we used an analytic function rather than a lookup table. The normalization constant is chosen so that the integral over all masses is unity. To normalize this properly, the turn-over below $0.5 M_{\odot}$ needed to be modeled. For this, we used the values given by Scalo (1986). For the Salpeter slope, the normalized IMF is

$$\phi(\log m) d \log m = 0.394 \left(\frac{m}{M_{\odot}} \right)^{-1.35} d \log m, \quad (4)$$

while the Scalo slope gives

$$\phi(\log m) d \log m = 0.331 \left(\frac{m}{M_{\odot}} \right)^{-1.7} d \log m. \quad (5)$$

Finally, we need to convert the rate into units of $M_{\odot} \text{ Myr}^{-1}$. As described so far, we have a rate with units of one star per Myr. To get the amount of mass associated with this, we multiply by the average initial mass. This is found by determining the average mass weighted by the IMF. For the Salpeter slope, this is 0.81, while for the Scalo slope this is $0.53 M_{\odot}$.

For comparison with other galaxies, it is useful to convert the SFR into a SFR/area. For the global SFR, we simply divide by the area covered by the observation. The field of view of the WFPC2 chips covers 0.92 kpc^2 at the distance of Sextans A.

Figure 9 shows the luminosity function for the MS in Sextans A. We have included the turnoff age scale at the top. Using the MS alone, we are only able to look back ≈ 100 Myr. The lack of obvious features in the luminosity function indicate there has been relatively constant (globally averaged) star formation over the past 100 Myr within the field of

FIG. 8. The lower panel is a schematic illustration of the procedure for calculating the SFR from a MS luminosity function, as described by Eq. (3). The thick line is the luminosity function. The dashed lines show the implied counts in subsequent (older) bins based on the slope of the IMF. For each bin, the SFR is determined by the difference between the counts and the sum of implied counts due to previous (younger) bins. The results are shown in the upper panel. If adjacent bins follow the IMF slope, this implies no star formation between them, as is true for bins 3, 7, and 9. If adjacent bins have a slope that is flatter than the IMF slope, it is possible to oversubtract and get a negative SFR, as shown by bin 5.

view. The presence of the most massive stars also indicates that there is SF younger than 10 Myr, in agreement with the presence of H II regions (Hodge *et al.* 1994).

We have applied the normalization process described above to convert the MS luminosity function counts into a SFR as a function of time (Fig. 10). From the age-magnitude relation, the natural bin widths are logarithmic in time. However, this is difficult to interpret since the youngest bins sample a different length of time than the oldest bins. We have re-binned the data into linear time bins over the past 100 Myr. The smallest time interval to which we are sensitive depends upon the photometric errors (δM_V) by the relation $\delta T = (dT/dM_V) \delta M_V$. Both the derivative and the photometric error are largest for the faintest, and oldest, bins. For the photometric error we adopt 0.2, which is larger than the errors for 80% of all MS stars. The derivative at 100 Myr is 80 Myr mag^{-1} . Thus, we are sensitive to features longer than 16 Myr.

At the youngest end, the calculation is sensitive to shorter features. We have explored a wide range in bin size, and although we observe some variation on smaller time scales at the youngest end, it is not significant within the errors of the counting statistics; the smaller the bin size, the larger these errors become.

Note that at several points the SFR drops below zero. These points are, however, still consistent with zero within the errors of the counting statistics. The negative points result from oversubtracting based on the large SFR determined from the youngest bins. As mentioned above, the large errors of the brightest bins propagate through to all fainter bins. This highlights the great difficulty of using the MS to di-

FIG. 9. The V luminosity function of the MS stars. The bin width is 0.2 mag, and the data have been corrected for reddening and incompleteness. The errors reflect both Poisson counting noise and errors due to the incompleteness correction. Plotted above the luminosity function are the ages for the MS turnoff (B94). Based on the MS turnoff alone, we are only able to probe back 100 Myr of SFH. There are no obvious features over this time period.

rectly determine the SFR when the SFR is relatively constant with time.

For the region within the field of view, there is variation by a factor of roughly 2, with a peak at 30 Myr of $\sim 6500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$, for a Salpeter IMF. With the steeper Scalo IMF, this value is $\sim 9000 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. The location of this young activity within the galaxy will be discussed in Sec. 5.2. Conversely, within errors, this variation is not very significant, and is consistent with a nearly constant SFR over the past 50 Myr. Older than 50 Myr, there are large variations in the SFR, but the errors are so large that the rates are all consistent with a constant SFR, including zero.

4.3 HeB Stars

We now apply Eq. (1) to the blue HeB stars. Again, we analyze the data in discrete bins, and assume that the mass and SFR are constant over these bins. We also assume the blue HeB is a function of magnitude, and not color. As with the MS, we have applied a completeness correction to the data. However, this is not an important effect for the blue HeB stars, since they are only found well above the limits of our photometry.

For the blue HeB stars, there are no overlapping generations. We can assign a single mass and age to each magnitude. Thus, both the mass and time integrals become a single bin. However, we do need to consider contamination by stars in other phases of evolution. Specifically, stars that are leaving the MS pass through the locus of blue HeB stars. We call these MSTO stars. Thus, the count in a single bin is

$$C_n(M_V) = \phi(\log m_n) \Delta \log m_n R_n \Delta t_n + \phi(\log m'_n) \Delta \log m'_n R'_n \Delta t'_n, \quad (6)$$

where we have used unprimed values for the blue HeB stars and primed values for the MSTO stars. Accounting for the

FIG. 10. The global SFR for the area of Sextans A within the field of view. These values were calculated from the MS luminosity function. The bins are 8 Myr wide, and they have been corrected for incompleteness. As described in the text, we have applied a normalization to the luminosity function that removes the IMF with a Salpeter slope, and corrects for the overlap of different ages on the MS. We have used the Padua evolution tracks for $Z = 0.001$ as a model for the M_V -age relation. This is a recursive process that starts with the youngest bin. The low counts in the youngest bins contribute large uncertainties to all the bins. The errors reflect only random statistical errors, not systematic errors arising from the uncertainties in the adopted model. At several points, the SFR drops below zero, however, within the noise of the counting statistics these are consistent with zero. For ages older than 50 Myr the errors are much larger than the observed variations. This is consistent with a constant SFR.

MSTO stars is a secondary correction that is very small, as we show below.

For a given magnitude, the masses of the blue HeB and MSTO stars will be different, thus different IMF corrections are necessary. Similar to the MS, we have $\Delta \log m_n = [(d \log m)/(dM_V)]_n \Delta M_V$, but we now need a relation between M_V and $\log m$ for both the MS and the MSTO.

Furthermore, for a given magnitude, MSTO stars enter this region at a different time than the blue HeB stars. Thus R_n and R'_n are SFRs from different ages. Fortunately, the MSTO stars enter this phase before the blue HeB stars do, and thus come from a younger age. We can set up a recursive relation again. We solve for R_n in successive bins by determining R'_n from a previous bin that corresponds to the age of the MSTO stars. If the MSTO age is younger than the youngest bin, we assume the SFR is zero.

Δt_n is different in this case than for the MS. Here Δt_n is the length of time the star spends in the bin. For the blue HeB stars this is the lifetime of the blue HeB phase, and for the MSTO stars this is the amount of time it takes to cross the locus of the blue HeB. These life times will be a function of mass, and therefore depend upon the magnitude of the bin.

There are four relations needed to calculate the SFR from the blue HeB stars.

- First is the relation between mass and M_V for both the blue HeB and MSTO. For this we adopt the model calculations of B94.

- Second is the relation between age and M_V for both the blue HeB and the MSTO. Again, this comes from B94.

FIG. 11. The lower panel is the actual normalization functions applied to the blue HeB luminosity function to convert the counts into $M_{\odot} \text{ Myr}^{-1}$. The normalization is defined as $(\phi(\log m)\Delta \log m \Delta t)^{-1}$. For this plot we used the Salpeter slope for the IMF. The upper panel shows the fraction of stars calculated to be MSTO stars within each bin. This secondary correction, in most cases, is negligible (less than 1%). This is primarily due to the short lifetime of the MSTO stars as they cross the locus of the blue HeB stars. Only at the faintest end of the blue HeB does the MSTO lifetime become large enough to present an appreciable correction of a few percent.

- Third is the IMF. As discussed in Sec. 4.2, we compare the results for both a Salpeter slope [1955; Eq. (4)] and the Scalo slope for a constant SFR [1986; Eq. (5)].
- Finally, we need the lifetime of the evolutionary phase for both the blue HeB and MSTO.

As described in Sec. 4.2, the calculation of the SFR depends upon the adopted model, which can introduce systematic uncertainties. While the actual rate calculated is model dependent, the presence of star formation features as a function of time is not, since the normalization functions are smooth and continuous.

There are, however, several known uncertainties with the blue HeB stars. First, the HeB phase of very massive stars ($M > 15 M_{\odot}$) is not well understood, so the luminosity and lifetime of such stars is highly uncertain (Chiosi *et al.* 1992). The stellar evolution tracks are significantly different between the Geneva and Padua groups; for example, the Geneva track for $M = 15 M_{\odot}$ does not have a blue-loop while the Padua group does. These massive stars reach the HeB phase by 20 Myr or younger, so that only ages older than 20 Myr are reliable.

Second, the extension and lifetime of the blue phase of core He-burning depends on several poorly understood mechanisms, such as convection and mass loss (Chiosi *et al.* 1992). Refinements in these mechanisms may produce changes in the lifetime, which would alter the calculated SFRs. With this understanding, we can use the models to calculate the SFR as a function of time.

From the Padua evolution models (Fagotto *et al.* 1994) we determined the amount of time each mass star spends in the blue HeB and blue-loop crossing MSTO phases. These lifetimes as a function of mass are described well by a power

law. To obtain a smooth function we used a least-squares fit to the data. These fits are

$$\Delta t_{\text{blueHeB}} = 436 \text{ Myr} \left(\frac{m}{M_{\odot}} \right)^{-2.55} \quad (7)$$

and

$$\Delta t_{\text{blue-loop/MSTO}} = 38.9 \text{ Myr} \left(\frac{m}{M_{\odot}} \right)^{-2.92} \quad (8)$$

The normalization for both the blue HeB and MSTO used in calculating the SFR are shown in Fig. 11. Note that the normalization correction, $\equiv (\phi(\log m_n)\Delta \log m_n \Delta t_n)^{-1}$, is larger for the MSTO than for the blue HeB. This indicates we expect more counts from the blue HeB than for the MSTO at all magnitudes. To see this, assume a constant SFR for all time. Then $R_n = R'_n$. The ratio of blue HeB counts to MSTO counts is then

$$\frac{\phi(\log m_n)\Delta \log m_n \Delta t_n}{\phi(\log m'_n)\Delta \log m'_n \Delta t'_n} = \frac{\text{normalization (MSTO)}}{\text{normalization (blue HeB)}} \quad (9)$$

The MSTO normalization is about 2 orders of magnitude higher than the blue HeB normalization. This is primarily due to the shorter lifetime of the MSTO stars compared to the blue HeB stars. Thus we expect the counts from MSTO stars to be a few percent of the total counts. The upper panel of Fig. 11 shows the fraction of MSTO stars that we calculate, accounting for the varying SFR. This correction is less than 1% for most magnitudes. Only at the faint end, where the MSTO lifetimes become appreciable, does the correction rise to a few percent.

Figure 12 shows the luminosity function for the blue HeB stars. Also plotted are the ages for each magnitude adopted from B94. Notice that we are able to extend the SFH back in time a factor of ten further than we could with the MS. Unfortunately, after 600 Myr these stars pile up and merge into the red clump so that time resolution is greatly reduced. For SFHs older than this we must rely on other methods.

The HeB luminosity function of Sextans A shows a depressed region at $M_v \sim -4$, between the ages of 80 and 180 Myr. This indicates a quiescent period, where, as we calculate below, the SFR drops off by a factor of 10. This was not obvious in the MS luminosity function because our data begins to become incomplete at about the magnitude corresponding to 100 Myr MS turnoff. This indicates that the SFR in Sextans A may not have been constant over the last 1 Gyr. An important caveat is that the field of view covers only a quarter of Sextans A. There may have been quite active star formation in a region outside the field of view during this time.

We have applied the normalization correction described above to the blue HeB luminosity function. The result for a Salpeter IMF is shown in Figs. 13 & 14. The bins of Fig. 13 are 8 Myr for comparison with the SFR determined from the MS stars (Fig. 10). There is a peak in the SFR of $7500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$ at ~ 30 Myr. For the steeper Scalo IMF slope, this value is $12,000 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. Within errors, this agrees with the peak in the SFR determined from the MS

stars. Beyond 50 Myr, the SFR falls off to approximately $1000 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ ($1500 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ for the Scalo IMF) by 100 Myr ago. The SFR determined from the MS stars for this age range is inconclusive because the errors are so large.

Fortunately, the SFR can be determined to older ages. This is shown in Fig. 14. Again, the age sensitivity is determined by the photometric errors through the relation $\delta T = (dT/dM_V) \delta M_V$. Because of its position in the CMD, the errors of these stars are in general better than those of the MS. In this case, 80% of the stars have errors in V less than 0.15. The derivative at 600 Myr is 330 Myr mag^{-1} . Thus, the method is sensitive to features longer than 50 Myr. This limit is set by the oldest bins. The sensitivity is considerably shorter for the youngest bins where both the errors and the age derivative are smaller. Shorter variations in these youngest bins is explored in Fig. 13 and discussed above.

There are four events whose effects can be detected within the field of view. They are not entirely obvious, but can be spotted in conjunction with the spatial coherence discussed in Sec. 5. Note that although we can identify star formation events based on the spatial information discussed in the next section, the global SFR appears to be relatively constant over the entire field of view.

Region 1 is the young association in the lower right portion of the image (see Sec. 5 and Fig. 19). This peaks at about 200 Myr at $\sim 1750 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ ($2200 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ with a Scalo IMF). Region 2 is a larger region that sits just left of center in the lower part of the image. This peaks at $\sim 370 \text{ Myr}$ with $2250 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ ($2800 \text{ M}_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$ with a Scalo IMF). The small peak at 430 Myr corresponds to a region that runs off the lower left corner of the image. Finally, between 500 and 600 Myr there is a large diffuse region throughout the lower part of the image. Because of photometric errors, the division between the HeB stars and the RGB is fuzzy. For times older than $\sim 600 \text{ Myr}$, there is likely some contamination from RGB stars scattering into that region of the CMD.

4.4 Cumulative Stars Formed as a Function of Time

As discussed in Sec. 4.2, the differential calculation of the SFR from the MS stars is very uncertain because it relies upon a recursive process starting with the youngest bins. On the other hand, the cumulative star formation from the present back to the MS turnoff age can be calculated with much greater precision. This is the more natural quantity available from the MS since each magnitude bin contains stars from all generations younger than the turn-off age for that bin. Thus, there is no reliance upon an iterative process; each bin is independent, with independent errors.

For this calculation, the only normalization is to remove the IMF. We have applied a Salpeter IMF normalization to the MS luminosity function to obtain the cumulative star formation (Fig. 15). Notice that the slope of this curve yields the SFR at each given age. Thus, we can determine the SFR from only a few bins of the luminosity function, rather than from all younger bins. In the upper panel of Fig. 15 is the SFR based on the average slope between each bin and its two nearest neighbors of the cumulative star formation curve.

FIG. 12. The V luminosity function of the blue HeB stars. The bin width is 0.15 mag. The data have been corrected for reddening and incompleteness. The errors reflect both Poisson counting noise and errors due to the incompleteness correction. Plotted above the histogram is the age for the blue HeB stars as given by B94. At roughly 100 Myr there is a depression in the luminosity function, indicating a quiescent period with little star formation.

Also plotted as a dotted line is the cumulative star formation as calculated by the blue HeB stars. Since these stars do not have overlapping generations, it is more natural to calculate the SFR, rather than the cumulative star formation. Thus, we have applied the normalization of Sec. 4.3 to the blue HeB stars (Fig. 13), and integrated from the present backward through time. For consistency, we have then calculated the SFR based on the slope of the cumulative star formation curve.

The agreement between the MS and blue HeB cumulative star formation curves is excellent. The only significant disagreement is between 60 and 70 Myr where the MS function decreases. This is, of course, unphysical. The slopes on either side of the dip result in first a negative SFR followed by a large SFR, which does not agree with the blue HeB stars. We suspect this is caused by an underestimate of the incompleteness correction. At this time period (corresponding to $M_V \sim 24.4$) the incompleteness starts to grow large. In addition, the MS is quite broad at this point due to photometric errors. The incompleteness changes significantly with color over this width. The correction was applied to the luminosity function, and, thus, does not account for the variation over color. A more sophisticated treatment was not warranted because the SFR can be calculated from the blue HeB stars for this time period.

Notice, also, that the SFR calculated in this manner agrees very well with the SFR as calculated in Secs. 4.2 and 4.3. The errors are larger for the blue HeB calculation in this case because the SFR now depends on three bins, while each bin was independent in the former case.

4.5 Discussion of the Recent Global SFH of Sextans A

We now compare our results with those of previous measurements of the SFR. To make direct comparisons, we will

FIG. 13. The SFR for Sextans A within our field over the last 100 Myr, based on the blue HeB stars. The bins are 8 Myr to match the MS SFR in Fig. 10. The data have been corrected for incompleteness. As described in the text, the blue HeB luminosity function has been normalized to account for the IMF and the changing lifetime in this phase with mass. For this plot we have used the Salpeter IMF slope, and used the Padua stellar evolution tracks for $Z=0.001$. We also applied a secondary correction for the presence of MSTO stars. This secondary correction is very small, amounting to less than 1% in most cases (see Fig. 11). The errors reflect only random statistical errors, not systematic errors arising from the uncertainties in the models. There is a peak in the SFR of $\sim 8500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$ at 30 Myr, within errors, this agrees with the peak in the SFR determined from the MS stars. Beyond 50 Myr, the SFR falls off to $1000\text{--}2000 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$.

have to normalize the previously found values for the total area of Sextans A. We use the diameter $D_{25}=5'.9$ (de Vaucouleurs *et al.* 1991), which, for the distance of Sextans A, gives a total area of 4.8 kpc^2 . However, it is obvious from the images of Sextans A that the current star formation regions are patchy and do not extend over this entire area. Our field of view covers the most active region in Sextans A, so we expect the SFR/area calculated here to be larger than the average SFR/area for the whole galaxy.

Hoessel *et al.* (1983) calculate a birthrate for massive stars ($M \geq 9 M_{\odot}$) based on CCD stellar photometry over the entire galaxy. They find a total birthrate of $80 \text{ stars Myr}^{-1}$. For the Salpeter IMF [Eq. (4)], we find that stars with $M \geq 9 M_{\odot}$ comprise 0.7% of all stars. Including the average initial mass of $0.81 M_{\odot}$, and normalizing to the area, gives a total SFR/area of $1900 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$.

Stars more massive than $9 M_{\odot}$ last only $\sim 30 \text{ Myr}$. The average SFR/area in our field of view over the last 30 Myr is $5000 \pm 1500 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. As we expected, this is larger than the Hoessel *et al.* (1983) calculation because our field of view contains the currently most active region in Sextans A.

Based on $H\alpha$ luminosity, Hunter & Plummer (1996) calculate the current SFR to be $6000 M_{\odot} \text{ Myr}^{-1}$. They also cover the full area of the galaxy, so the SFR/area is $1300 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. This value is for the current instantaneous SFR ($\leq 3 \text{ Myr}$; Hunter & Gallagher 1986). The youngest bin in our data is from the MS (8 Myr; Fig. 15) is $3800 \pm 700 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. Again, this is larger than the $H\alpha$ value, as we expect.

FIG. 14. The SFR for Sextans A over the last 600 Myr, based on the blue HeB stars. The bins are 25 Myr. The data have been corrected for incompleteness. As described in the text, the blue HeB luminosity function has been normalized to account for the IMF and the changing lifetime in this phase with mass. For this plot we used the Salpeter IMF slope and the Padua $Z=0.001$ stellar evolution models. We also applied a secondary correction for the presence of MSTO stars. This secondary correction is very small, amounting to less than 1% in most cases (see Fig. 11). The error bars reflect only random statistical errors, not systematic errors due to uncertainties in the models. There are four events that can be pointed out in this diagram. They are not obvious, but can be spotted in conjunction with the spatial coherence discussed in Sec. 5.4. Region 1 is the young association in the lower right portion of the image. This appears to peak at about 200 Myr. Region 2 is a larger region that sits just left of center in the lower part of the image. This peaks at roughly 370 Myr. The small peak at 430 Myr corresponds to a region that runs off the lower left corner of the image. Finally, between 500 and 600 Myr corresponds to a large diffuse region throughout the lower part of the image. Because of photometric errors, the division between the HeB stars and the RGB is fuzzy. For times older than $\sim 600 \text{ Myr}$, there is likely contamination from RGB stars scattering into that region of the CMD.

Hoessel *et al.* (1983) argue that the SFR must have been lower in the past, otherwise, Sextans A would contain more mass in stars than we observe from its luminosity. Aparicio *et al.* (1987) reach the same conclusion, with one alternative. They suggest that the IMF could be flatter at the high mass end. This would lower the SFR implied by the number of high mass stars observed. The SFH derived in this paper does show that the SFR falls off dramatically to a level of $1000\text{--}2000 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$ by 100 Myr ago (Fig. 14).

We can compare the current SFR with the average SFR over the history of the galaxy. We estimate the total number of stars in the galaxy based on the luminosity and colors. For this, we use the population synthesis models of Bressan *et al.* (1994). They present the integrated colors and magnitude for single age stellar populations at a variety of metallicities. We used the $Z=0.001$ (5% Solar) models. To calculate the integrated colors and luminosity, we need to assume a SFH. Based on our determination from the blue HeB stars (Fig. 13), we use the simple form of a constant SFR with a factor of 5 enhancement over the past 50 Myr. Sextans A has $(B-V)=0.26$ and $M_V=-14.13$, adjusted for $(m-M)=25.8$ (Hunter & Plummer 1996). For this color, the population synthesis models indicate an age of 10.8 Gyr and $M/L_V=0.43 M_{\odot}/L_{V\odot}$. This value is subject to systematic effects,

FIG. 15. The lower panel shows the cumulative star formation from the present integrated back to the age shown. The solid line shows the stars formed based on the MS stars. This is calculated by normalizing the MS luminosity function for a Salpeter IMF, and assigning ages based on the Padua $Z=0.001$ evolution tracks. The dotted line shows the same value based on the blue HeB stars. In this case, the cumulative star formation was found by integrating the SFR as determined in Sec. 4.3 (Fig. 13). The upper panel shows the slope of the curves in the lower panel. The slope directly gives the SFR. The MS stars and blue HeB stars show excellent agreement.

most notably the choice of SFH can alter this by up to a factor of 2. The magnitude of Sextans A implies a luminosity $L_V = 3.8 \times 10^7 L_{V\odot}$. So the total mass in stars is estimated to be $1.6 \times 10^7 M_\odot$.

If the galaxy has been forming stars for 10.8 Gyr, this gives an average SFR/area of $310 M_\odot \text{ Myr}^{-1} \text{ kpc}^{-2}$. So between the ages of 100 and 600 Myr, Sextans A appears to be forming stars a factor of ~ 6 larger than the lifetime average. We conclude that the SFR older than 1 Gyr must have been much lower than what we measure for the past 600 Myr. The past 50 Myr is clearly a period of highly enhanced star formation by a factor of 20 or more compared to the average.

We conclude that Sextans A is currently undergoing a strong episode of star formation that started ~ 80 Myr ago. Prior to this episode, the galaxy formed stars at a lower and relatively constant rate that was still well above the lifetime average for the galaxy.

The recent episode of intense star formation during the past 100 Myr is a puzzle. The nearest possible candidate for interaction is Sextans B. This is $10^\circ.4$ away in the sky. If these two galaxies are at the same distance, they are separated physically by 260 kpc, too distant to have a significant influence on the dynamics of Sextans A at present. It remains a mystery why the star formation in this chemically unevolved galaxy suddenly turned on, when it had been rather quiescent for several 100 Myr previous. This is most likely telling us about the interplay between the gas dynamics and the star formation. Evidently some process is acting to orga-

nize recent star formation on a nearly global scale in Sextans A during the past 100 Myr.

Currently, the high surface brightness regions are dominated by the current star formation regions. Most of the light comes from massive stars, which last a few times 10 Myr. We have seen that the SFR older than 100 Myr was as much as a factor of 5 lower than the current rate. This means a factor of 5 fewer massive stars, and thus a surface brightness a factor of 5 smaller, at least among the star forming regions.

5. THE SPATIAL DISTRIBUTION OF THE STAR FORMATION

5.1 Density Calculation

Having isolated and identified various populations within the CMDs, it is possible to examine their spatial distribution. Including the spatial information in our analysis allows us to examine the local behavior of star formation within the galaxy, in addition to the global star formation of the galaxy as a whole.

To accomplish this, we created stellar density maps. These are represented as contours in Fig. 16. The density maps are created by first selecting a population of stars from the CMD. These stars are then placed on a blank image such that each star adds one to the pixel corresponding to its centroid. For this purpose, the centroids of the star list from each chip are transformed into a common coordinate system. We chose the coordinate system of the mosaic WFPC2 image generated by the IRAF² STSDAS routine wmosaic. In this mosaic image the PC scale is converted to that of the WF chips so that one pixel is 0.1 arcsecond in size.

This process creates a map of delta functions corresponding to the positions of the selected stars. The map was then convolved with a Gaussian kernel with a standard deviation of $8''$. This created a smooth map of the stellar spatial density. The map was then multiplied by a constant to convert the units from stars pixel^{-2} to stars kpc^{-2} . For the WF pixel size of 0.1 arcsecond, assuming a distance modulus of 25.8, this conversion is $1 \text{ pixel}^{-2} = 0.49 \text{ pc}^{-2}$.

The convolved map must also be corrected for edge effects. In the convolution process, the image is normalized by the integrated convolving kernel assuming the limits extend to infinity. Regions off the edge of the image are assumed to be zero. This artificially lowers the density near the edges. We can compensate by adjusting the normalization to be just the integral within the bounds of the image. Each point is thus divided by the two-dimensional integral of the convolution kernel, centered at that point, over the area covered by the WFPC2 chips. Care was necessary to account for the peculiar shape surrounding the PC chip. This is handled by integrating over the square encompassing the whole image, then subtracting the integral over the blank regions around the PC.

The major source of noise in the density maps is from Poisson counting errors. It is therefore useful to know the value of one star per convolution beam. The Gaussian beam

²IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

has an area of $2\pi\sigma^2 = 2\pi (0.056 \text{ kpc})^2 = 0.02 \text{ kpc}^2$. Thus one star per beam is 50 kpc^{-2} . The signal to noise of any point with value D would then be $\sqrt{D/50}$.

5.2 Distribution of MS, HeB, and RGB

Figure 16 shows a comparison of the spatial density over the field of view of three major populations in the CMD. The main sequence, for magnitudes brighter than our limits of photometry, is highly concentrated in the bright, blue association in the lower right (the Southeast portion of the galaxy) which is so prominent in the optical (Sandage & Carlson 1982) and $H\alpha$ images (Hodge *et al.* 1994). This indicates that the most recent star formation has taken place in a localized region rather than throughout the entire galaxy. This region corresponds to the densest H I clump (Skillman *et al.* 1988), as well as the brightest H II regions (Hodge *et al.* 1994).

In addition to the association, there is a low surface density bridge extending to the left, perhaps indicative of a trail of star formation across the face of the galaxy. This does not align, however, with the extension of the H I clump or the pattern of H II regions.

In contrast, the blue HeB stars are not strongly clustered in the association. Instead, they follow a bridge extending from the young association toward the left, with a similar density as the MS bridge. The HeB stars are massive evolved stars, and are thus older, on average, than the MS stars by 10 to several 100 Myr, depending on the mass of the star. Because of the difference in ages between these two groups we do expect different distributions if the star forming regions change with time. The fact that the older blue HeB stars are found more in the bridge toward the left, relative to the young MS, suggests an age progression across the galaxy from left to right.

Finally, the distribution of the oldest stars in the RGB is quite different from the younger stars. Again, this is not unexpected since these stars were born at a different time, and likely at a different place within the galaxy. They are also, in general, much older, and have had time to diffuse and spread out in response to the dynamics of the galaxy. The RGB stars occupy a bar extending from the lower left corner toward the upper right. These stars show no clustering in the association. The bar aligns with an H I depression through the middle of the galaxy and may reflect the dynamical bar proposed by Skillman *et al.* (1988) to account for the H I gas dynamics.

We can use this spatial information to analyze the SFH so long as the star formation structures remain coherent. With time, these structures will dissipate and lose coherence due to galactic dynamics, as well as internal diffusion. We expect that star formation structures will remain coherent for ~ 1 Gyr (see Appendix A), longer than our look-back time for the SFR based on blue HeB stars. In consequence, the young MS and HeB stars will retain the spatial distribution of their birth. In contrast, the distribution of the RGB stars reflects more on the long-term dynamics of the galaxy, rather than the location of star birth.

5.3 Spatial Coherence of the Evolution Sequence

As described in Appendix A, we expect stars younger than ~ 1 Gyr to retain the spatial distribution of their birth. We can use this information to test recent SFHs. From evolutionary models, we can identify temporally coincident regions within the CMD, and examine whether or not they have the same spatial distribution within the galaxy.

As an example, we have identified three fairly young populations: the MS, the blue HeB stars, and the red HeB stars. Using the isochrones of B94, we have isolated two regions corresponding to two different ages within each of these populations.

Figure 17 compares the distribution of these three populations for ages between 10 and 75 Myr old. One star per convolution beam corresponds to 50 kpc^{-2} . The contour levels thus correspond to intervals of 1 star for the HeB stars and 10 stars for the MS. The spatial distribution of these populations is very similar, indicating that these stars are siblings, born at the same time and in the same location. All three populations are concentrated in the young association in the lower right. The low counts in the red HeB map make this a little uncertain, but consistent with this picture.

Figure 18 compares the distributions for ages between 75 and 130 Myr. Some care must be used in interpreting the distribution of the MS stars since the selected region contains stars from younger generations as well. The HeB stars do not have this problem, but there are much fewer of them, so the distribution is not as certain. With these caveats, the spatial distribution of these three populations is similar, yet different from the younger stars. These older stars extend further toward the left, along the bridge mentioned earlier. This pattern, again, supports the scenario of an age progression across the galaxy from left to right.

5.4 The Recent SFH of Sextans A

It is well known that different regions of dwarf galaxies can have very different CMDs. The implication is that each region has its own SFH. In addition to containing clusters and associations, the general field of the LMC shows dramatic variation (Hodge 1961). Such variation has also been seen in many local group dwarf galaxies (WLM, Ferraro *et al.* 1989; IC 1613, Hodge *et al.* 1991; Leo A, Tolstoy 1996; NGC 147, Han *et al.* 1997), including Sextans A (Aparicio *et al.* 1987). We would like to examine the spatial variation of the SFH within Sextans A. This will not only tell us how the galaxy has evolved, but will illuminate the star formation process itself.

One way to look at differences in SFH is to calculate the SFR for each location in the galaxy and for each available time period. This creates a time sequence of SFR maps that can be viewed as a movie. We have normalized the blue HeB luminosity function to obtain the SFR in 10 Myr bins, as described in Sec. 4.3. For this, we used the Salpeter IMF. We then created a map of the spatial stellar density for each bin as described in Sec. 5.1. In addition to the spatial convolution, we convolved the movie in time with a Gaussian kernel with $\sigma = 30$ Myr. This helped to reduce the noise resulting from low number statistics. Combining the maps in sequence, we can play them as a movie.

FIG. 16. The spatial density of three populations of stars within Sextans A. One star per convolution beam is 50 kpc^{-2} . The lower right panel is the V vs $V-I$ CMD. Outlined are the three populations corresponding to the density plots. These are the MS, the HeB stars, and the RGB. The lower left panel shows the spatial density of the MS stars in both contours and greyscale. The young association in the lower right is densely populated with MS stars. The association has a dense clump of H I and several bright H II regions associated with it. There is also a lower density bridge that extends to the left. The upper left panel shows the density of blue HeB stars. These are not strongly clustered in the young association, but do show a bridge extension toward the left. The upper right panel is the density of RGB and red clump stars. The distribution of these older stars is quite different than that of the younger stars. They form a bar through the middle of the galaxy. This bar overlaps with a depression in the H I.

Figure 19 (Plate 114) shows a mosaic of 9 frames of the movie. The time separation between each frame is not uniform, and was chosen to highlight interesting features. The color bar is shown and ranges from 0 to $3700 \text{ M}_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. For reference, one star per convolution beam is roughly $60 \text{ M}_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. If the steeper Scalo IMF is used, the basic structures remain the same, but the values are increased by $\sim 30\%$. The movie is available in mpeg format on the WWW at address “<http://astl.spa.umn.edu/robbie/research/sexa/movie.html>.” It will also be published as an addendum to this paper in the January issue of the *Astronomical Journal*.

As time progresses, we see a patch of star formation move in from the lower left corner, at approximately 430 Myr. By this time, the blue HeB is well separated photometrically from the RGB. This region appears to grow and extend toward the middle of the image. As it does so, the SFR increases, peaking at about 370 Myr. This event then fades away as the young association in the lower right comes to prominence at 200 Myr, and continuing into the present.

The movie suggests that the star formation has predomi-

nately occurred in isolated regions rather than throughout the galaxy. Note, however, that the contrast between the peak rates in the star forming regions is at most a factor of 5 larger than the rest of the galaxy at any given time, except for times younger than 100 Myr. In fact, at their peak, these regions comprise only 25%–30% of the total star formation throughout the galaxy. The exception is the star formation in the lower right corner within the past 50 Myr. This young region contains fully half of the current star formation.

This leads us to two possible scenarios for star formation within Sextans A. One possibility is that the star formation occurred in highly concentrated regions, and that the stars diffused outward from their birthplace through either galactic dynamics or random motions. However, this is unlikely the case since we expect star forming regions to remain coherent entities for longer times than our SFH determination (see Appendix A).

More likely, the galaxy as a whole forms stars more or less continuously, with a small enhancement in certain locations at certain times. What drives these periodic enhancements is not clear, however, it could be related to the same

FIG. 17. The spatial density of three populations of stars within Sextans A. The density plots are shown in both contours and greyscale. One star per convolution beam is 50 kpc^{-2} . The lower right panel is the V vs $V-I$ CMD. Outlined are the three populations corresponding to the density plots. These are the MS (lower left), the Blue HeB stars (upper left), and the Red HeB stars (upper right). The selected portions of these populations correspond to ages between 10 and 75 Myr according to the isochrones of B94. The MS distribution should be interpreted with care, since the selected region will also contain any generation of stars younger than 15 Myr. These three populations, for this age range, are concentrated in the lower right association. Specifically, the HeB stars are located in the top portion of the association. These overlapping populations indicates that these stars likely formed together both spatially and temporally.

dynamical force that has created the peculiar shape of Sextans A. The star formation seems to avoid the central part of the galaxy, and instead remains concentrated along the eastern edge of the stellar “square” which is the main optical component of Sextans A. This feature may be a bar, in which case we are seeing another case of preferential star formation near the end of a bar in an irregular galaxy. Elmegreen & Elmegreen (1980) documented this trend and suggested it is caused by a tendency for gas to collect near the ends of stellar bars.

A variety of observations have established that star formation moves with time over the inner disks of irregular galaxies (see Hunter 1982 for a review). Our calculations further support this scenario. Furthermore, there is a clear age progression from left to right in the three regions. Propagating star formation is plausible since large, ionized supershells are currently present in Sex A (Hunter & Gallagher 1997) and the fragmentation of supershells is a likely location for star formation (Franco 1992). There is no evidence for a continuous wave of steady star formation passing through the galaxy, however, low level bridges connecting the regions hints that they may be connected in some way.

If we assume the star formation did propagate in some manner, we can calculate a propagation speed. There is a time difference of 170 Myr from peak to peak between the older region at 370 Myr, and the youngest region. The distance between these two regions is 470 pc. This gives a propagation speed of 3 km s^{-1} . This is significantly lower than the H I velocity dispersion, measured to be 8 km s^{-1} (Skillman *et al.* 1988). Presumably the H I random motions are not supersonic, so the propagation speed we calculate is sub-sonic. Thus, the star formation does not appear to propagate through sound waves, let alone by the super-sonic shocks produced by supernovae. This is difficult to reconcile with supernovae playing the major role in propagating the star formation, and perhaps indicates that the star formation regions are not causally related.

We can further probe the star formation process by looking at the size scale, time scale, and efficiency of the star forming region. The one episode that is contained fully within our field of view and time range is that which peaks at 370 Myr. This occupies a region $\sim 300 \text{ pc}$ across (0.07 kpc^{-2} area), and lasts for $\sim 200 \text{ Myr}$. The average value for the SFR/area within this region is $\sim 3000 M_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$.

FIG. 18. The spatial density of three populations of stars within Sextans A. The density plots are shown in both contours and greyscale. One star per convolution beam is 50 kpc^{-2} . The lower right panel is the V vs $V-I$ CMD. Outlined are the three populations corresponding to the density plots. These are the MS (lower left), the Blue HeB stars (upper left), and the Red HeB stars (upper right). The selected portions of these populations correspond to ages between 75 and 130 Myr according to the isochrones of B94. The MS distribution should be interpreted with care, since the selected region will also contain any generation of stars younger than 75 Myr. Compared to the younger population in Fig. 16, these older stars more densely populate the bridge toward the left.

Thus, this event creates roughly $4.2 \times 10^4 M_{\odot}$ in stars, for the Salpeter IMF. To calculate a star formation efficiency, we need to estimate how much gas was in this region to begin with. From the H I maps, the average H I column density over the currently active association is $\sim 25 \times 10^{20} \text{ atoms cm}^{-2} = 6.7 \times 10^6 M_{\odot} \text{ kpc}^{-2}$. If we assume a similar density for the event 370 Myr ago, the total H I mass involved in the event is $4.7 \times 10^5 M_{\odot}$. Thus, the efficiency of star formation was $\sim 9\%$. This same calculation assuming a Scalo IMF, gives a total mass of $\sim 5 \times 10^4 M_{\odot}$ and an efficiency of $\sim 11\%$. This is similar to the efficiency estimated for our Galaxy (Myers *et al.* 1986). These parameters are summarized in Table 1.

A wide variety of physical effects may influence the spatial and temporal patterns of star formation. A clear theoretical model for this process is not yet properly understood. We therefore take a simple approach and compare our observations of the recent distributions of young stellar complexes in Sextans A with the fundamental predictions of the gravitational instability model for star formation.

The general characteristics of gravitational instabilities in

the interstellar media of dwarf galaxies and subsequent star formation are discussed by Elmegreen *et al.* (1996). They find that most stars will form in large star complexes where interstellar clouds become unstable. The size of such star complexes is given by $D_C \approx (\sigma_{H I} / W_{20}) D_{25}$, where $\sigma_{H I} / W_{20} \sim 0.2$ is the ratio of the turbulent H I velocity to rotation velocity amplitude (Skillman *et al.* 1988) and $D_{25} = 2.5 \text{ kpc}$ is the optical size of the galaxy. This model, then, predicts that star complexes will have sizes $D_C \sim 500 \text{ pc}$, close to what we observe. The time scale for active star formation within the complexes is just the turbulent velocity crossing time or about 60 Myr. This is shorter than the observed active lifetimes of star complexes in Sextans A, which we find to be 100–200 Myr. This longer period may be explained by magnetic field pressure that can slow, and in some cases prevent, the collapse of molecular clouds (Mouschovias 1976).

In summary, we have found that the location and strength of star formation changes with time. Between 100 and 600 Myr ago, the galaxy as a whole had been forming stars fairly continuously, with several spatial enhancements, by a factor

of ~ 5 , that come and go. The pattern of these enhancements suggests an age progression across the galaxy, however, there is no clear evidence for direct interaction between each region. The size of these star forming regions matches that predicted by gravitational collapse models, but lasts much longer than expected. The amount of mass formed into stars suggests an efficiency of $\sim 9\%$. Finally, the most recent star formation (< 50 Myr) is unusual compared to the past 600 Myr. This recent time period has a much higher SFR and is more densely concentrated than star formation of the past. This suggests that something unusual has occurred in the past 100 Myr to trigger this very active episode.

6. CONCLUSION

In summary:

- The *HST* has allowed us to obtain photometry of the resolved stars in Sextans A with an accuracy that has not been obtainable from the ground.
- The very accurate CMD contains many clearly defined features, including a separation between the MS and the blue HeB stars.
- The distribution of the MS, RGB, and HeB stars are in excellent agreement with predictions from stellar evolution models. This is a significant test for these models at very low metallicity.
- We present a method for extracting the SFH over the past 1 Gyr from the blue HeB stars.
- We also present a method for analyzing the spatial distribution of stars within the galaxy.
- Sextans A is currently undergoing an episode of activity that is roughly a factor of 20 larger than the average over the lifetime of the galaxy. By 100 Myr, the SFR falls to only ~ 5 times the lifetime average. Older than 100 Myr, and back to 600 Myr, the SFR appears relatively constant with fluctuations of order 20%.
- The SFR calculation is sensitive to the choice of IMF. The value of the SFR varies by up to a factor of 2 between the Salpeter and Scalo slope. However, the relative SFR between different times is only weakly dependent on the choice of IMF.
- Portions of the MS, blue HeB, and red HeB selected to be at the same age have similar spatial distributions within the galaxy. This gives confidence in the evolution models, and shows that star forming regions remain coherent longer than 600 Myr.
- Using the blue HeB stars as a tracer of star formation, we find that the fluctuations in SFR are correlated spatially within the galaxy, so that we can see the location, duration, and size of star formation episodes. The spatial correlations are further evidence for the one-to-one mapping of age and magnitude for the blue HeB.
- There are spatial enhancements of star formation that come and go with time in different locations. These regions are enhanced in SFR by a factor ~ 5 compared to the rest of the galaxy, and contain 25%–30% of the star formation activity within our field of view.
- The star formation events last on the order of 200 Myr

TABLE 1. Characteristic properties of star formation events in Sextans A.

Diameter	300 pc
Duration	200 Myr
Time Between	150 Myr
Mass	$4.2 \times 10^4 M_{\odot}$
Propagation Speed	3 km s^{-1}
Efficiency	9%

and reside in a region ~ 300 pc across. We estimate a star formation efficiency of $\sim 9\%$. Several factors may affect these numbers, including the distortion of star forming regions over time due to stellar random motions and galactic dynamics.

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APPENDIX A. TIME SCALE FOR DISSIPATION OF STAR FORMING REGIONS

A star forming region does not remain a coherent structure within a galaxy indefinitely. There are several effects that will tend to disrupt the coherence over time. Of interest to us are large star forming complexes that are ~ 100 pc across, similar to the Orion complex. Using Orion as a model (Genzel & Stutzki 1989), we would expect each star forming region to initially contain a large molecular cloud complex, several OB associations, and possibly a few open clusters.

In the simplest approximation, we expect the structure to remain coherent for several dynamical times within the galaxy. Sextans A is rotating nearly as a solid body (Skillman *et al.* 1988), so structures could remain coherent for even longer times since there is no shear due to differential rotation. The rotation rate of Sextans A is $V \sin i = 20 \text{ km s}^{-1}$ at 3.2 from the center. At a distance of 1.44 Mpc, this gives a rotation period of $T = 413 (\sin i)^{-1}$ Myr. Thus, we might expect remnant structures of star formation to last as long as ~ 1 Gyr.

Unfortunately, the dynamics of large complexes such as this have not been well studied. Instead, we must rely on dynamical and lifetime studies of the component OB associations and open clusters. Since OB associations are not gravitationally bound, they are quickly dissociated within 10–30 Myr (Brown *et al.* 1997); this is much shorter than the time scales we are interested in. It is unclear if these stars will remain bound to the larger complex once the association is disrupted. If the stars leave the complex directly with a typical velocity dispersion of $\sim 2 \text{ km s}^{-1}$ (Brown *et al.*

1997), they will remain within the bounds of the complex for at least 50–100 Myr.

Because open clusters are gravitationally bound, they are much longer lived than the associations. There are two principal effects that can disrupt a cluster; galactic dynamics and internal dynamics.

In a large spiral galaxy, differential rotation and interaction with spiral density waves will tend to disrupt open clusters. Binney & Tremaine (1987) provide a rough calculation for the disruption of open clusters due to interactions with molecular clouds. They find that a typical open cluster lasts ~ 600 Myr before being gravitationally disrupted. This has also been studied with n -body simulations by Terlevich (1987). It was found that the gravitational impulse of molecular clouds can remove stars from the cluster at a rate of $0.1\% \text{ Myr}^{-1}$. Thus the cluster is reduced by half in 500 Myr. In a dwarf galaxy such as Sextans A, the conditions are not so harsh as they are in a large spiral, thus we would expect

the open clusters to last at least 0.6–1 Gyr, if galactic dynamics are the only effect.

The second major effect is diffusion due to the internal dynamics of the cluster and complex. This can be described as diffusion in phase space through use of the Fokker-Planck equation (Binney & Tremaine 1987). For realistic situations this is most easily solved through n -body simulations (Terlevich 1987; Kroupa 1995). Kroupa (1995) has shown that, regardless of initial binary fraction, an open cluster's stellar density decays exponentially with a time scale of 230 Myr.

Based on these arguments, and provided that a star-forming region will last as long or longer than its component clusters, we can reasonably expect that we will be able to see coherent remnants of star formation regions at least 1 Gyr into the past. The fact that we do see spatial enhancements of these regions as long ago as 600 Myr is strong confirmation that these structures can remain intact for several galactic dynamical times.

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FIG. 19. A gallery of nine still frames from the movie showing the location of star formation in Sextans A over time. The time separation between each frame is not uniform, and was chosen to highlight interesting features. Shown is the star formation rate density ranging from 0 to $3700 \text{ M}_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. The SFR was calculated based on the blue HeB stars, as described in Sec. 4.3, with a Salpeter IMF and the Padua $Z=0.001$ stellar evolution models. Each frame is 1 kpc on a side. The movie has been convolved in both space ($\sigma_x=84 \text{ pc}$) and time ($\sigma_t=30 \text{ Myr}$) to reduce the noise in low number counts regions. One star per convolution beam is approximately $60 \text{ M}_{\odot} \text{ Myr}^{-1} \text{ kpc}^{-2}$. The movie suggests that the star formation may have propagated from region to region, as we see low level bridges connecting them.

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