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REIONIZATION AND THE FATE OF DWARF GALAXIES

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RESUMEN

Nuestra comprensión de los orígenes y evolución de las galaxias enanas ha cambiado muy rápidamente. Nuevas observaciones nos han brindado mejor percepción en las relaciones entre las dos principales familias de galaxias enanas, las enanas elípticas y las enanas irregulares. Las simulaciones teóricas han presentado nuevos problemas, y han eliminado otros. Sin embargo, es posible que estemos empezando a observar algunas de los resultados más robustos de estas simulaciones. Por ejemplo, las observaciones de galaxias del Grupo Local en el Telescopio Espacial muestran evidencia del impacto de la radiación ionizante de fondo en sus historias de formación estelar. De ser ésta la interpretación correcta, alteraría significativamente nuestra comprensión de la evolución de las galaxias enanas.

ABSTRACT

Our understanding of the origins and evolution of dwarf galaxies has been changing very rapidly. New observations are giving better insight into the relationship between the two main families of dwarf galaxies, the dwarf ellipticals and the dwarf irregulars. Theoretical simulations appear to be both posing several problems and eliminating them. However, it is possible that we are beginning to observe some of the more robust results of these simulations. For example, HST observations of Local Group galaxies show evidence of the impact of the ionizing background radiation on their star formation histories. If this is the correct interpretation, it greatly alters our understanding of dwarf galaxy evolution.

Key Words: **GALAXIES: CLUSTERS — GALAXIES: DWARF — GALAXIES: EVOLUTION — GALAXIES: STELLAR CONTENT**

1. AN OLD PROBLEM: THE ORIGIN OF DWARF ELLIPTICALS

It is important for this talk that I clarify my use of the word origin. Frequently, when one is referring to the origin of a galaxy, one means the time when a dark matter halo established its gravitational identity. However, in this talk, the origin which I am referring to is the point when a dwarf galaxy ceases to form stars.

At some point early in its history, a galaxy which we observe to be a dE today was an actively star forming galaxy; thus, it had cold gas. Structurally, dE galaxies are quite similar to present day star forming dwarf galaxies (dIs, see next section). Thus, the defining moment of the creation of a dE is when it loses its cold gas. Since many dE galaxies show the presence of an intermediate age population, the origins of dE galaxies, as defined here, are not constrained to a single epoch. Some dEs are consistent with no intermediate age stars, and thus, were created quite early in the history of the Universe (e.g., Ursa Minor; Olszewski & Aaronson 1985), while others show star formation up to very recent times (e.g., Leo I; Gallart et al. 1999). Thus, the process or processes which convert actively star forming dwarf galaxies into dE galaxies have been taking place over the entire history of our Universe.

2. SIMILARITIES BETWEEN DES AND DIS

2.1. *Background*

The primary distinction between dE and dI galaxies is the presence or absence of cold gas. This is usually measured through HI emission at 21 cm. The typical values of M(HI)/L for dIs range from 0.1 to 10, while most dEs are non-detections in HI or show ratios of 10^{-3} or less (Skillman 1996). Otherwise, dE and dI galaxies have many similar properties. Most importantly, it has been known for a long time now that dEs and dIs have similar structures (Faber & Lin 1983; Kormendy 1985; Caldwell & Bothun 1987; Binggeli & Cameron 1991).

When trying to understand the possible relationships between dE and dI galaxies, there are several observations to consider. Perhaps most important is the strong morphology – density relationships observed in both the group (e.g., Einasto et al. 1974) and cluster (e.g., Binggeli et al. 1990) environments. Because of their low masses, both are recognized as fragile systems (e.g., Dekel & Silk 1986). For a long

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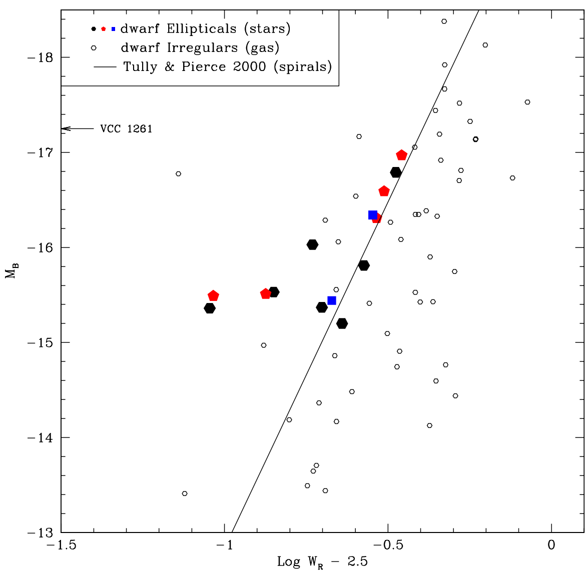

Fig. 1. The luminosity-line width relation for dwarf elliptical galaxies [note that the values shown are the observed maximum linewidths, which are possible underestimates of the full rotation velocity; see van Zee et al. (2004a) for a full discussion of possible correction factors to the observed widths]. Dwarf ellipticals with blue cores (squares) and red cores (pentagons) follow the same relation as spiral galaxies (line; Tully & Pierce 2000) and dwarf irregular galaxies (open dots; van Zee 2001). (From van Zee et al. 2004b)

time, dEs were considered to be non-rotating systems, and lack of rotational support distinguished them from the dIs (e.g., Bender et al. 1991). Many dEs in the cluster environment have nuclei (e.g., Caldwell 1983). In contrast, the typical dI does not show the presence of a nucleus, but centrally concentrated star formation is common (and defines the class of blue compact dwarf galaxies). Finally, almost by definition, dEs and dIs must have different star formation histories (as dEs have no current star formation and almost all dIs do). Although it has been known for quite a while that the Milky Way dSph companions show a great variety of star formation histories (e.g., Mateo 1998), it is now emerging that dIs may too.

2.2. *Recent Results*

2.2.1. *Rotation in dEs*

One of the properties which was long thought to separate the dEs from the dIs was rotation. Bender and collaborators found very little evidence of rotation in the few systems that they observed. However, recent programs to observe dEs have discovered that a significant fraction of dEs show significant rotational support (de Rijke et al. 2001; 2003; Pedraz et al. 2002; Geha et al. 2002; 2003; van Zee et al. 2004a). Interestingly, van Zee et al. (2004b) find a Tully-Fisher relationship between luminosity and velocity width for the Virgo dEs which do show rotation (Figure 1). It is intriguing that the rotating and non-rotating dEs are not distinguished structurally (Figure 2).

2.2.2. *dI Star Formation Histories*

Recently, my collaborators and I have published a star formation history (SFH) for a halo field in IC 1613, a Local Group dI, based on relatively deep HST WFPC2 observations (Figure 3; Skillman et al. 2003). This is the deepest color-magnitude diagram (CMD) of an isolated dI. Although detailed SFH studies exist for other dIs, no dIs at distances beyond the Magellanic Clouds have been observed to the depth of the present study of IC 1613 ($M_V \simeq +3.4$). Given the density-morphology relationship in the Local Group, the dI galaxies are at much greater distances than the dSphs, and, thus, have correspondingly shallower CMDs. As a result, it has been difficult to make direct comparisons between the CMDs of dI and dSph galaxies.

The complete SFH for the halo field in IC 1613 is shown in Figure 4. The main feature seen in the SFH is an extended event from $\sim$ 2 Gyr ago until $\sim$ 6 Gyr ago. While there has been star formation since that event (a significant amount coming 0.5 Gyr ago), the bulk of the stars in this region of IC 1613 come from the earlier age. Although Dolphin et al. 2001 found RR Lyraes in this field, the ancient ($\geq$10 Gyr) SFR was well below the lifetime average. Thus, to first order, star formation in IC 1613 appears to have occurred predominantly at intermediate ages. This is also characteristic of several of the outer MW dSph satellites (specifically Carina, Fornax, Leo II and Leo I). A particularly interesting (and to me surprising) comparison is that between IC 1613 and Leo I; both appear to be dominated by star formation at the same intermediate ages (Gallart 1999; Dolphin 2002). In Figure 4 we compare the SFH and age metallicity relationship for IC 1613 and Leo I (both using the method of Dolphin 2002). Figure 4 shows that the SFHs and age-metallicity relationships for IC 1613 and Leo I, when derived via identical methodology, are nearly identical.

One possible interpretation of Figure 4 is that, absent the youngest stars, is it possible that there are no differences between the stellar populations of isolated dI and dSphs which are more distant from

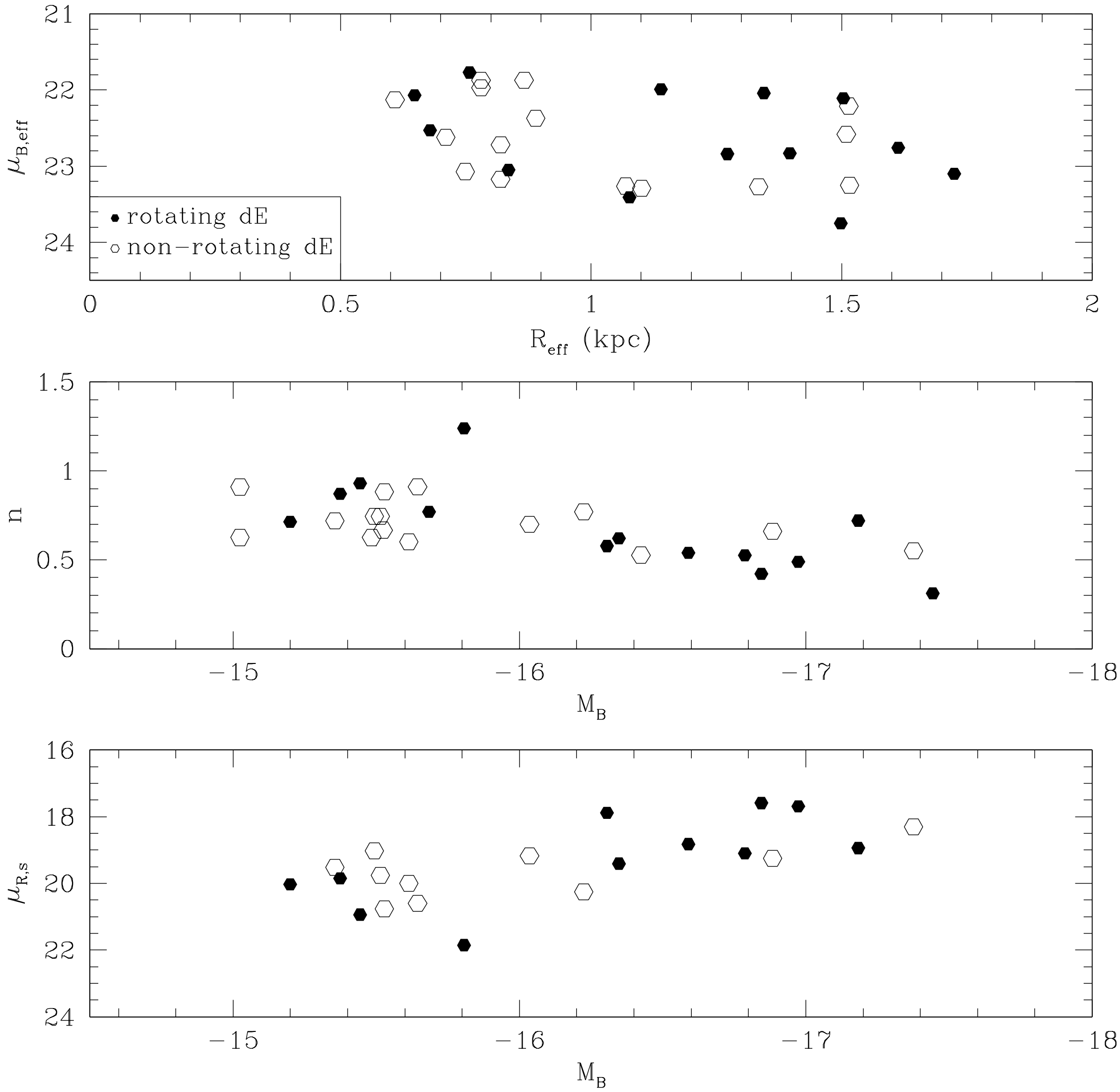

Fig. 2. Structural parameters for Sérsic fits to dwarf elliptical galaxies in Virgo with measured kinematic properties (Pedraz et al. 2002; Geha et al. 2003; van Zee et al. 2004a); rotating (filled hexagons) and non-rotating (open hexagons) dE galaxies have similar structural properties. (a) Model independent parameters of half-light radius and effective surface brightness. (b) Absolute magnitude and Sérsic shape parameter. (c) Absolute magnitude and central surface brightness from a Sérsic fit to the R-band surface brightness profile. The non-rotating and rotating dwarf elliptical galaxies cannot be distinguished based on structural parameters. (From van Zee et al. 2004b)

their parent galaxies. The implication is that some dI and dSph galaxies have similar progenitors; the differences which we see today are due to environmental influences during the lifetimes of the galaxies which allow one type of galaxy to retain its gas and form stars up until the present and another not. Certainly the morphological census of the Local Group has evolved with time.

A potentially important environmental factor is the radiation background. The ionizing background can heat the ISM in low mass halos and reduce the rate of radiative cooling by reducing the number of neutral atoms. The photoionizing background will reduce the fraction of gas which collapses, suppressing star formation until later times ($z \leq 1$) when the background decreases and the gas can cool (see discussion in Skillman et al. 2003 and §5).

There are other dI galaxies for which it has been suggested that most of the stars have been formed relatively recently. Our earlier study of Leo A (Tol-

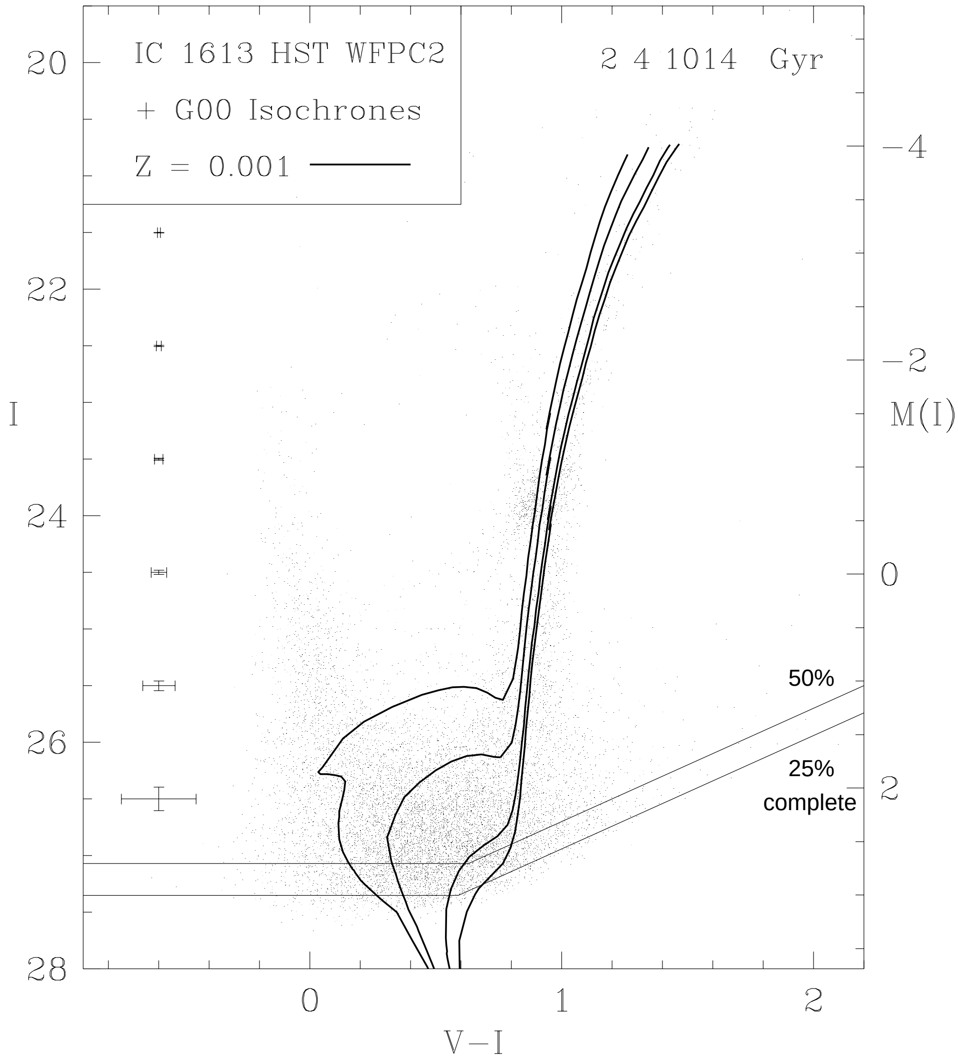

Fig. 3. CMD of IC 1613 derived from HST WFPC2 observations. Isochrones for a metallicity of $Z = 0.001$ and ages of 2, 4, 10, and 14 Gyr from Girardi et al. (2000) have been added in order to show the limitations of the observations in terms of MS ages. MS turnoffs back to intermediate ages (∼5 Gyr) are well represented in the observations, but the oldest MS turnoffs (∼10 Gyr) fall below the 50% completeness limit and are not represented. Thus, constraints on the oldest populations will need to come from the evolved stars.

stoy et al. 1998) suggested that the majority of the star formation had occurred in the last 2 Gyr. Dolphin et al. (2002) discovered RR Lyraes in Leo A, and thus the presence of very early star formation, but converting the number of RR Lyrae stars to an early SFR is very uncertain. A similar SFH is found for Sextans A. From a relatively deep ($M_V \simeq +2.0$) CMD, Dolphin et al. (2002) find that while there is evidence for very old stars in Sextans A, the SFR at intermediate ages (3 - 10 Gyr) was quite low, and the SFR has been the highest in the last 2 Gyr (see Figure 5).

3. THREE CHANNELS FOR DE FORMATION

From the above discussion, we can conclude that there are at least three channels available for the formation of a dE galaxy from a dI galaxy, and all three are quite likely:

- Stripping of gas from dIs to form dEs in the cluster environment seems to be inevitable and would naturally explain the density-morphology relationship. (Perhaps the same is true in the group environment?) Given the result of the ACS Virgo Cluster Survey presented by Cote

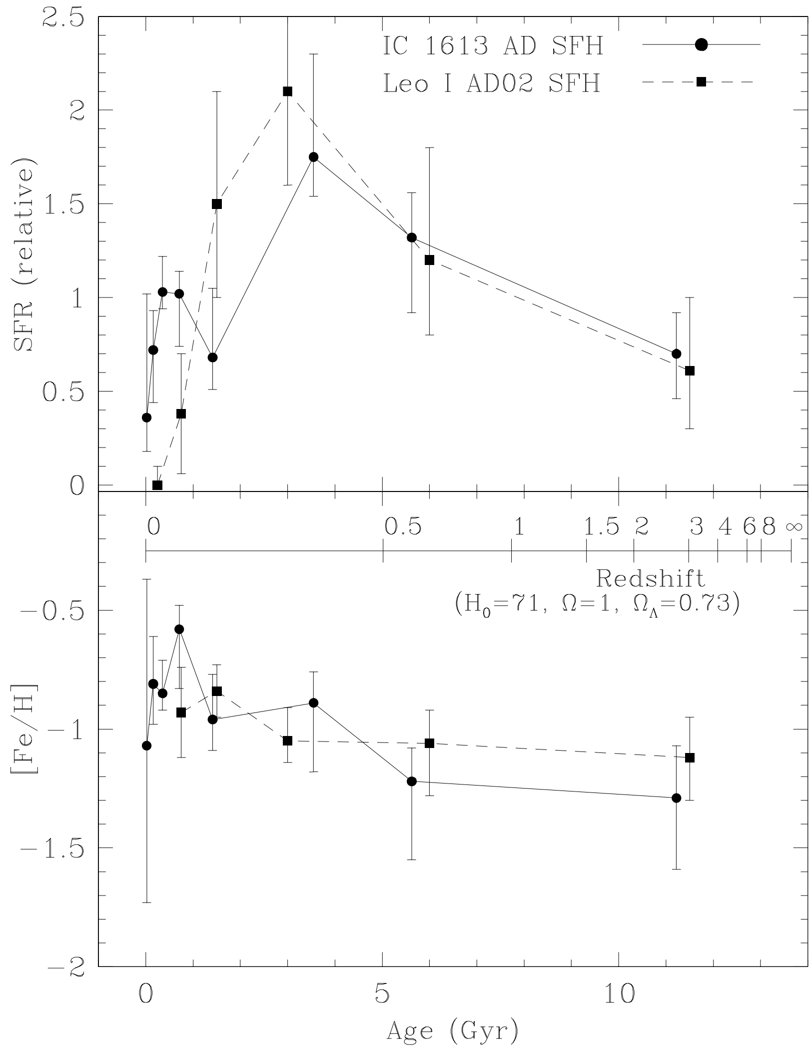

Fig. 4. Comparison of SFHs and metal enrichment histories for IC 1613 and the dSph Leo I (both derived via the Dolphin method, Dolphin 2002; Skillman et al. 2003). The star formation and metal enrichment histories appear nearly identical. A timeline comparing redshift to real time has been added for the noted cosmology. Note that the bulk of the star formation and chemical enrichment has occurred at $z < 1.0$.

(2005) that a very high fraction of the Virgo dEs are nucleated, it would appear that the formation of a nucleus is a natural by-product of this process.

- Blow-away is an energetically favorable process, but it does not produce the density-morphology relationship. Nonetheless, it is likely to happen some times (preferentially in the lowest mass systems, Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000).

- Although some dEs are now known to show significant rotational support, tidal stirring (Mayer et al. 2001a,b) represents another promising channel for the conversion of dIs to dEs. This process may be the most likely for the non-rotating dEs.

4. WHY IT DOESN'T MATTER

Why isn't the signature of the process which removes the gas obvious in the structural parameters of a dE? Perhaps the uniformity of the dark matter halos dominates all other factors, so, in the end, all low mass systems without cold gas end up looking the same (Dekel & Silk 1986). Over the last two decades there have been a number of studies aimed at understanding the relationship between the dE and dI galaxies. Our inability to unambiguously identify the gas removal process on a galaxy-by-galaxy basis

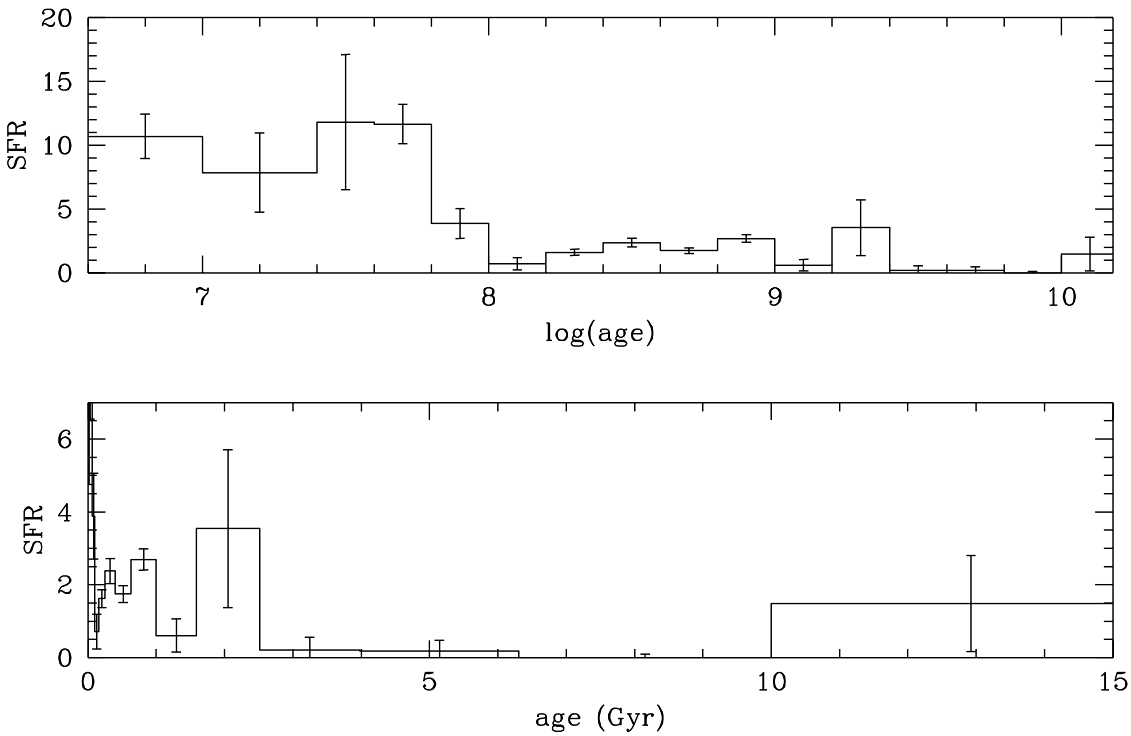

Fig. 5. The reconstructed star formation history of Sextans A (from Dolphin et al. 2003). The top panel is on a logarithmic time scale; the bottom panel has a linear scale. Both panels show the star formation history normalized to a lifetime average of 1.0. Note the relative paucity of star formation at intermediate ages.

is the fundamental impediment to solving this long lived problem.

5. REIONIZATION?

The effect of background ionizing radiation on dwarf galaxies was originally investigated as a possible solution to the origin of the Lyman-α forest (e.g., Rees 1986; Ikeuchi 1986). Later, many studies revisited this effect (Efstathiou 1992; Babul & Rees 1992; Chiba & Nath 1994; Quinn, Katz, & Efstathiou 1996; Thoul & Weinberg 1996; Kepner, Babul, & Spergel 1997; Barkana & Loeb 1999; Bullock et al. 2000) and the potentially important effects of early heating of the ISM on the evolution of dwarf galaxies were explored.

Within the collapse and dissipation model of galaxy formation (White & Rees 1978), the effects of reionization on the evolution of dwarf galaxies is twofold (see discussion in Benson et al. 2002a and references therein). The ionizing background heats the IGM which suppresses the collapse of low mass structures. The ionizing background can also heat the ISM in low mass haloes which have already formed and reduce the rate of radiative cooling by reducing the number of neutral atoms. The first effect has a strong influence on the low end of the galaxy luminosity function. The photoionizing background will reduce the fraction of gas which collapses with the dark matter especially in systems which are less massive than the "filtering mass" (Gnedin 2000b). Benson et al. (2002a) point out that the formation history is also an important parameter in determining the final gas content of a dark matter halo. In order to solve the perceived problem of the mismatch between the theoretically expected and observed low end of the galaxy luminosity function, much attention has been given to the effects of the suppression of the formation of dwarf galaxies (e.g., Bullock et al. 2000; Chiu, Gnedin, & Ostriker 2001; Somerville 2002; Benson et al. 2002b, 2003; Tassis et al. 2003). However, these studies generally concentrate on the luminosity function, and star formation histories of individual galaxies are not explored in depth.

The second effect is relevant to the question of suppressed star formation at intermediate ages. Can star formation in dwarf galaxies which have already formed before reionization be suppressed by the photoionizing background and then recommence at redshifts of 0.5 and lower? Babul & Rees (1992) point to the fast decline in the UV background between $z = 2$ and the present and estimate that new star formation would precipitate in dwarfs at $z \leq 1$. Calculating a specific SFH depends strongly on the influence of both external (the photoionizing background) and internal (stellar feedback) variables (Tassis et al. 2003). The evidence of an environmental dependence of the low end of the galaxy luminosity function (Tully et al. 2002; Trentham & Hodgkin 2002) may imply a very large range of SFHs due simply to environmental differences on the effects of photoionization (Benson et al. 2003).

In the end, the effects of suppressing the formation of low mass halos and later surpressing star formation in low mass galaxies appear unavoidable. In the simplest models of galaxy formation there is a large deficit of observed low mass systems in groups of galaxies. The incorporation of heating by supernovae and background radiation greatly mitigates this problem. These processes are expected to be important, and this is not an ad hoc solution.

6. THE NEXT STEP

If suppression of star formation by the background ionizing radiation is important, we expect to see the effects in the star formation histories of dwarf galaxies. Deep color-magnitude diagrams of the nearest dwarf irregulars are needed to provide secure star formation histories. Two programs have been awarded to do this with the *HST* in cycle 14. Our view of dwarf galaxy evolution has been biased by the proximity of the dwarf spheroidal companions of the Milky Way. The new *HST* observations will allow us to gain secure star formation histories for a sample of more distant isolated dwarfs.

7. CONCLUSIONS

All dwarfs which have been suitably observed show evidence of a population of stars with ages $\sim$ 10 Gyr. The star formation histories for these galaxies show a large variety. This has been known for some time now for the Milky Way dSph companions, but it now appears to be true also for dIs. The star formation histories may be revealing the effects of the x-ray background radiation responsible for reionization (i.e, delayed galaxy formation, squelching, suppression). Since there are probably several channels for dI to dE conversion, the comparison of properties of dEs and dIs hold great promise for telling us about the effects of environment on galaxy evolution.

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