IMPACT OF REIONIZATION ON THE STELLAR POPULATIONS OF NEARBY DWARF GALAXIES

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ABSTRACT

Cold dark matter models for galaxy formation predict that low-mass systems will be the first sites of star formation. As these objects have shallow gravitational potential wells, the subsequent growth of their stellar populations may be halted by heating and gas loss due to reionization. This effect has been suggested to have profoundly influenced properties of present-day dwarf galaxies, including their stellar populations and even survival as visible galaxies. In this Letter we draw on results from quantitative studies of Local Group dwarf galaxy star formation histories, especially for Milky Way satellites, to show that no clear signature exists for a widespread evolutionary impact from reionization. All nearby dwarf galaxies studied in sufficient detail contain ancient populations indistinguishable in age from the oldest Galactic globular clusters. Ancient star formation activity proceeded over several Gyr, and some dwarf spheroidal galaxies even experienced fairly continuous star formation until just a few Gyr ago. Despite their uniformly low masses, their star formation histories differ considerably. The evolutionary histories of nearby dwarf galaxies appear to reflect influences from a variety of local processes rather than a dominant effect from reionization.

Subject headings: cosmology: observations — (cosmology:) early universe — galaxies: evolution — galaxies: dwarf — (galaxies:) Local Group — stars: Population II

1. INTRODUCTION

When did galaxies, or protogalactic fragments, first form stars? When did they undergo their first major episodes of star formation that produced the old Population II stars that we can still observe today? Did all of the early substructures begin to form stars at the same time, or were there considerable differences from object to object? Did re-ionization squelch subsequent star formation in low-mass substructures (Efstathiou 1992), accounting for the lower than predicted number of Local Group satellite galaxies (e.g., Bullock, Kravtsov, & Weinberg 2000; Somerville 2002; Benson et al. 2002, 2003; Tully et al. 2002)? How do the early star formation histories that we can infer from their stellar fossil record fit in with standard cold dark matter (CDM) paradigm?

Theory predicts that the earliest stars formed in low mass systems at \( z \sim 30 \) (e.g., Barkana & Loeb 2001), a redshift that is not accessible for study with the current observational tools (e.g., Fan et al. 2001, 2003; Hu et al. 2002; Kodaira et al. 2003; Pelló et al. 2004). An alternative approach concentrates on the local fossil record contained in those present-day galaxies that we can study in the greatest detail. The highest accuracy in age-dating stellar populations can be reached where stellar populations are resolved into individual stars down to and below the strongly age-sensitive location of the main-sequence turn-off (MSTO). This limits us to nearby galaxies. The Milky Way and its satellites are sufficiently close and uncrowded to make stars below the oldest MSTOs accessible with relative ease, and to break the age-metallicity degeneracy for old, low-mass stars spectroscopically (see Grebel 1997; Grebel, Gallagher, & Harbeck 2003, hereafter GGH03; Cole et al. 2004). The dwarf satellites of the Milky Way offer the additional advantage of being close to the mass scales predicted for primitive sites hosting the first star formation in CDM models.

While Population III stars were presumably very massive, shortlived objects, stars at the low-mass end of the subsequent, “second” generation of early star formation may still exist today and can be observed as extremely metal-poor stars (Mackey, Bromm, & Hernquist 2003). But these “Population II.5” stars (Mackey et al.) are rare and to date have only been detected in the Milky Way (e.g., Chiba & Beers 2000; Christlieb et al. 2002). An additional difficulty lies in age-dating these individual stars.

We therefore concentrate on stars belonging to Mackey et al.’s (2003) “third” epoch of star formation, i.e., Population II stars. In the Milky Way, these populations comprise both field stars and old globular clusters. We require that these ancient stars formed in sufficiently high numbers that they (1) are still easily detectable today, and (2) produced well-defined, measurable MSTOs usable for age dating, defining our “oldest measurable episodes of star formation.” We further focus on ancient stellar populations in nearby dwarf galaxies, which have sufficiently low masses that their star formation should have been interrupted or possibly permanently squelched by the reionization of the universe (e.g., Thoul & Weinberg 1996; Barkana...
& Loeb 1999; Tassis et al. 2003). The old stellar populations in dwarf galaxies thus should contain a record of a key phase in the early evolution of the universe (e.g., Gallagher & Wyse 1994).

In this Letter we consider the star formation histories of nearby dwarf galaxies as derived from their resolved stellar populations. We compare levels and relative time scales for ancient star formation with the predicted effects of reionization based on time constraints from high-redshift quasars and Wilkinson Microwave Anisotropy Probe (WMAP) measurements (Kogut et al. 2003; Spergel et al. 2003).

### 2. REIONIZATION

Reionization of the universe, which occurs via photoionization, can have a major impact on the evolution of low mass galaxies. Photo-heating of gas associated with a galaxy raises its temperature to the point where retention becomes an issue for small systems (Babul & Rees 1992, Efstathiou 1992). The details of this process are very complex, with shielding and radiative transfer playing important roles. Many models predict that small galaxies should experience the bulk of their star formation before reionization (e.g., Ricotti, Gnedin, & Shull 2002; Somerville 2002; Dekel & Woo 2003; Tassis et al. 2003; Susa & Umemura 2004), and allow a restart of star formation only well after reionization. For example, Susa and Umemura (2004) confirm the suppression of star formation in galaxies with total masses of $M \lesssim 10^9 M_\odot$ and collapse occurring at $z \lesssim 5$ (see also Ferrara & Tolstoy 2000). Thus all low mass galaxies should have formed the bulk of their stars in about the first 1 Gyr after the Big Bang (see also Barkana & Loeb 1999; Tassis et al. 2003). We adopt a flat universe model with $\Omega_m = 0.27$ and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003).

While some models show star formation extending past reionization, the levels are low. We therefore can test the theory through measurements of stellar age distributions in Local Group galaxies. Susa & Umemura (2004) did so and found qualitative agreement based on the star formation histories presented by Mateo (1998). However, new observations since have become available and so we can revisit this comparison with more quantitative data. Similarly, we wish to revisit the conclusions presented by Gnedin (2000) on the basis of the Grebel (1999) and Mateo (1998) reviews for a nearly simultaneous drop in the star formation rates of Local Group dwarf spheroidal (dSph) galaxies about 10 Gyr ago, which he associates with reionization. With typical masses of $10^7 M_\odot$ (Mateo 1998), dSphs are the galaxies most likely to have been stripped of star-forming material due to reionization.

To make this comparison, we need to constrain the redshift of reionization and find an associated time to compare with the timescales derived from stellar populations in dwarf galaxies. Further complications occur because reionization rates vary with location depending on the densities of matter and Lyman continuum photons. We assume that reionization typically occurs at $20 < z_{\text{reion}} < 6.4$ with the upper bound coming from WMAP and the lower from quasar absorption line studies (Spergel et al. 2003; Fan et al. 2003). With our choice of cosmology this translates to a time interval of about 0.2–0.9 Gyr after the Big Bang.

### 3. RELATIVE AGES OF OLD POPULATIONS IN NEARBY GALAXIES

Age-dating techniques for resolved old stellar populations are summarized in Krauss & Chaboyer (2003), including MSTO ages of stellar ensembles. This is the most widely used method since it is the observationally easiest technique. The derivation of absolute ages is model-dependent and may result in age uncertainties of up to a few Gyr. Relative age-dating techniques are easier to employ and allow one to reach a higher differential accuracy (provided that the underlying assumptions hold, e.g., no variations in $[\alpha/Fe]$ among the populations to be compared). The relative dating techniques for old populations typically rely on the position of the region around the MSTO relative to other reference points in color space. Alternatively, fiducials (e.g., the mean ridge line of a coeval stellar population in color-magnitude space) registered to the MSTO region, or luminosity functions including the MSTO are used (see Stetson, VandenBerg, & Bolte 1996; Sarajedini, Chaboyer, & Demarque 1997).

Old populations with ages $\gtrsim 10$ Gyr have been detected in all Local Group galaxies studied in sufficient detail and depth. No galaxies without an old population have been found so far (see Grebel 2000, 2001), but we are not yet certain that all dwarf galaxies formed stars before the reionization epoch at $z \sim 6$.

#### 3.1. Old dwarf spheroidal galaxies

“Old” dSphs comprise all dSphs that contain horizontal branch stars but no intermediate-age populations as traced by a red clump or a young blue main sequence. The four nearby Milky Way companions Draco, Ursa Minor, Sextans, Sculptor, the M31 satellites Andromeda I–III, V, VI, and the isolated dSphs Cetus and Tucana are members of this class (e.g., Grebel 2000; Sarajedini et al. 2002; GGH03; Harbeck, Gallagher, & Grebel 2004). When using horizontal branch (HB) morphology as a relative age indicator, old dSphs seem to be 1–2 Gyr younger than the bulk of the Galactic globular clusters (Harbeck et al. 2001), but age is not the only explanation for the second-parameter effect (e.g., Salaris & Weiss 2002) and so a younger age is not assured from the HB morphologies.

MSTO techniques show the oldest populations in the nearby old dSph galaxies Draco (Grillmair et al. 1998), Ursa Minor (Feltzing et al. 1999; Mighell & Burke 1999; Wyse et al. 2002), Sculptor (Monkiewicz et al. 1999), and Sextans (Lee et al. 2003) to be indistinguishable in age from the oldest globular clusters in the Galactic halo and bulge within measurement uncertainties of $\sim 1–1.5$ Gyr.

Although these dSphs are dominated by old, metal-poor populations, they are not single-age, single-metallicity populations as found in globular clusters. Spatial gradients in HB morphology indicate variations in the star formation history as a function of position even in old dSphs (Harbeck et al. 2001). All old dSphs exhibit significant metallicity spreads that may exceed 1 dex in $[\alpha/Fe]$ (see GGH03). Hence the early star formation episodes must have been sufficiently long-lasting and a sufficient amount of the newly generated metals must have been retained to lead to the observed enrichment. The measured elemental abundance ratios indicate both Type Ia and Type II
supernova enrichment (Shetrone et al. 2001; Tolstoy et al. 2003), requiring time scales of 1 – 2 Gyr. Chemical evolution modelling suggests even longer star formation time scales of more than 4 Gyr (Ikuta & Arimoto 2002).

### 3.2. Mixed-age dwarf spheroidal galaxies

Other dSph galaxies contain substantial intermediate-age populations. Here the bulk of the stars was formed much less than 10 Gyr ago. Still, these mixed-age galaxies have old populations (including globular clusters) as old as the oldest Galactic globular clusters (Sagittarius: Montegriffo et al. 1998; Layden & Sarajedini 2000; Fornax: Buonanno et al. 1998; Carina: Monelli et al. 2003; and Leo II: Mighell & Rich 1996). Remarkably, in Fornax star formation ceased only as recently as 100 – 200 Myr ago (Grebel & Stetson 1999; GGH03). The available data indicate that star formation proceeded fairly continuously; only Carina exhibits a clearly episodic star formation history with a pause of several Gyr after the old population formed (Smecker-Hane et al. 1994; Monelli et al. 2003).

### 3.3. Other dwarf galaxies and satellites

The Large Magellanic Cloud (LMC), the closest companion of the Milky Way, has a mass of $5.3 \pm 1.0 \cdot 10^9 \, M_\odot$ (Alves & Nelson 2000) and should therefore have been able to retain its gas after reionization. Its old globular clusters are as old as ancient Galactic globulars (Olsen et al. 1998; Johnson et al. 1999). Deep studies of the LMC field population (e.g., Smecker-Hane et al. 2002) also reveal ancient MSTOs and an overall smooth and continuous field star formation history. The Small Magellanic Cloud (SMC) is a dwarf irregular (dIrr) galaxy with $2 \cdot 10^9 \, M_\odot$ (Westerlund 1997). SMC 121, the only globular cluster in the SMC, is $\approx 2$ – 3 Gyr younger than the oldest Galactic globular clusters (e.g., Mighell et al. 1998; Shara et al. 1998). While RR Lyrae stars have been detected among SMC field stars (e.g., Graham 1975), field MSTO data with sufficient area coverage are still lacking to address the question of pre-reionization star formation in the SMC.

Less massive dIrr and transition-type dwarf galaxies are located at larger distances from the Milky Way. Here the evidence for the presence of old populations is usually based on the detection of HB stars but the existing data do not reach the MSTO region, preventing more accurate age dating. Even so, the available data indicate star formation activity began early and proceeded smoothly over time with no major interruptions.

### 4. DISCUSSION

With our choice of a flat universe cosmology and time scale for reionization (see §2) reionization was complete $\sim 12.8$ Gyr ago, about 0.8 Gyr after the Big Bang. If we adopt these numbers (Fig. 1), then the low-mass dSphs would have had only $\sim 1$ Gyr after the Big Bang to form stars before star formation would have been inhibited by heating caused by reionization and feedback (e.g., Tassis et al. 2003) or all gas would have effectively been removed by photoevaporation (Barkana & Loeb 1999).

Converting the relative ages of old Galactic globular clusters, against which the Galactic satellites are being compared, into absolute ages is fraught with uncertainties. However, Krauss & Chaboyer (2003) find a best-fit age of 13.4±2 Gyr for the old Galactic globulars, which agrees well with the cosmological time frame established above. We conclude as follows:

- There is evidence for ancient star formation in the Milky Way and its low-mass companions at times consistent with and required by CDM models of dwarf galaxy formation,
- Within the accuracy of relative MSTO age dating ($\sim 1$ Gyr), all dSphs for which such data are available share a common epoch of ancient star formation with the Milky Way (Grebel 2000, 2001), and
- As predicted by standard classes of CDM models for low-mass galaxies, no dwarf galaxies without ancient stellar populations are observed although the data are incomplete (e.g., in the SMC).

No clear indications exist for an imprint of the epoch of reionization on the star formation histories of nearby dSphs. Modern data show that star formation extended over $\sim 2$ Gyr or more even in the “old” dSphs. The intermediate age systems for the most part had continuous star formation up until at least $\sim 5$ Gyr in the past, corresponding to a redshift of $z \approx 0.5$; the majority of stars in these systems formed at lower redshifts (see Fig. 1). We also find galaxies with properties in common with the dSphs, the transition dIrr/dSph galaxies, where star formation continues into the present epoch (GGH03).

The steep drop in star-formation activity in response to photoionization (e.g., Gnedin 2000 and Susa & Umemura 2003), is not observed in these objects. Only the Carina dSph displays the kind of gap in star formation that is expected if star formation were truncated during reionization and then restarted at low redshift, although this might be difficult to detect observationally if the restart occurs much before $z \sim 1$.

Apparently processes other than reionization shaped the star formation histories of most nearby dwarf galaxies. If reionization were a dominant influence on the evolution of stellar populations of dwarfs, then we might expect to see relatively uniform behavior among these systems. This is clearly not the case. Gas-free dwarfs with older stellar populations preferentially are found near giant galaxies, while the dIrr/dSph galaxies with small gas reservoirs and the HI-rich dIrrs avoid giants. Evidently local conditions are a major factor in the well known dwarf galaxy morphology–star formation history–environment connection (GGH03).

Even among the gas-free dSphs, galaxies in similar locations can have radically different star formation histories (e.g., Grebel 1997 and §3). This complexity may be due to a variety of factors affecting the evolution of small galaxies; e.g., feedback, gas stripping, time dependence of gas infall, etc. (e.g., Somerville 2002). While reionization could be one such factor, it does not appear to have been sufficiently strong to produce coherent patterns of star formation among the Galaxy’s dwarf companions.

These results suggest that the gas supplies of nearby dwarfs were not so drastically reduced by reionization that their star formation experienced long-term disruptions. For example, gas already within dwarf galaxies may not be expelled by reionization, as suggested by analytic
models (Somerville 2002, Benson et al. 2003). Since the satellites of giant systems are expected to form near their host (Fukushige & Makino 2001; Hayashi et al. 2003), they will be in a unique environment from early times, and thus are subject to a variety of external influences, including tides in addition to the processes discussed earlier (Kravtsov, Gnedin, & Klypin 2004). Another possibility arises from the uncertainties in the total masses of dSphs, i.e., whether they are or originally were much more massive than they appear from analyses based on their optical structures (e.g., Odenkirchen et al. 2001; Kleyna et al. 2001; Hayashi et al. 2003). If the Galactic dSphs are remnants of more massive galaxies (but see Kissen, Grebel, & Harbeck 2003 for counterarguments), this would also allow them to more easily survive reionization.

Although low-mass galaxies continue to pose problems for CDM galaxy formation models, they remain important windows into understanding this process. However, the opportunity to extend optical measurements of MSTO ages throughout the Local Group (e.g., Brown et al. 2003) will be lost with the end of the Hubble Space Telescope.

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Impact of Reionization on Dwarf Galaxies

Fig. 1.— Sketch of the approximate duration of star formation episodes in dwarf spheroidal galaxies. Darker shades indicate higher star-formation activity. Cosmological galaxy evolution models predict a drop in or the cessation of star-formation activity in low-mass dwarfs due to reionization, but this is not observed.