Investigation of the Effects of the Epoch of Reionization on the Star Formation Histories of Dwarf Galaxies

Laurel Farris

05 December 2014

Abstract

While the epoch of reionization has been recognized as a possible source of the suppression of star formation in dwarf galaxies, it is not entirely clear to what extent the star formation histories are affected. Furthermore, there are other possible mechanisms for quenching star formation, such as environmental effects from intergalactic interactions and stellar feedback. This paper summarizes the results of three separate papers analyzing the star formation histories of dwarf galaxies using data from the Hubble Space Telescope, with emphasis on the effects from reionization. Future projects will obtain data from new surveys, and work to distinguish environmental effects from those of reionization.

1 Introduction

The Lambda Cold Dark Matter (ΛCDM) model predicts a larger quantity of satellite and dwarf galaxies around the Milky Way than have been observed. This is referred to as the "missing satellite problem" and is one of the motivations for investigating the star formation histories (SFHs) of dwarf galaxies. If star formation (SF) was suppressed during the early age of the universe, these galaxies would have evolved with low luminosity, thus rendering them difficult to observe. A possible mechanism that could have been responsible for affecting SF in such a way is reionization, a process that occured about 2 billion years after the Big Bang. During the time leading up to this period, matter had begun to condense as the universe cooled. The collapse of material resulted in renewed heating of the gas, which was then reionized by the subsequent ultraviolet (UV) radiation. The gas was briefly evaporated, thus depleting low mass galaxies of the material needed to form stars, and their SF was slowed or halted completely.

In the introduction to their paper, Benítez-Llambay et al. state that the idea of reionization having had a pronounced effect on the SF of dwarf galaxies has been previously considered and investigated. However, according to the literature, there is a wide range of possible effects. Some models indicate that reionization truncated SF completely, while others predict that it merely suppressed it gradually over time. As a result, these dwarf galaxies have three end products, as described by both Benítez-Llambay et al. and Brown et al. "Fossils" are dwarf galaxies that completed their SF before the process of reionization began, “polluted fossils” experienced a suppression of SF, but it was renewed by post-reionization processes such as mass accrection and tidal shocks, and “survivors” are galaxies whose SF did not begin until after the epoch of reionization had run its course. According to Weisz et al., ionization does not necessarily evaporate all present gas, which would have resulted in a dramatic drop in SF. Instead, the low density gas would have evaporated away and colder, denser gas would have been left behind, allowing for continued SF, albeit at a much slower rate. Galaxies that formed at least the bulk ($> 90\%$) of their stars before reionization are considered “fossils.”

However, reionization is not the only mechanism that has the potential to quench SF. Environmental factors, such as ram pressure stripping, tidal stripping/stirring, etc. could have played a role as well. These factors are a probability especially within the virial radius of the Milky Way, where there are likely to be strong galactic interactions with the host. As most of the faintest galaxies known are within this proximity, separating environmental effects from reionization can be complicated. Weisz et al. describe a few of these processes: The effects of ram pressure stripping, caused by the hot halo of the host galaxy, can reach as far as 90 kpc from the Milky Way, sweeping away interstellar gas. Tidal stirring can deplete a dwarf galaxy of its gas as well, although this is a process that takes place over several Gyr, so it is not likely to have caused an abrupt drop in SF. Within the galaxies themselves, stellar feedback can serve as a mechanism for gas depletion. As heated material is expelled out into space, it is more likely to be stripped by way of one of the interactions described above. These mechanisms are described in more detail by Weisz, et al. in the discussion section.

This paper presents recent (within the past two years at the time of writing) results from three separate investigations into the SFHs of dwarf galaxies and the effects on them from reionization. All studies used data from the Hubble Space Telescope (HST), as new, previously unobserved dwarf galaxies have been detected by the Sloan Digital Sky Survey (SDSS). Brown et al. addressed the aforementioned missing satellite problem, using data from six ultra-faint dwarf (UFD) galaxies. With their low luminosity, lack of chemical evolution, and high abundance of dark matter, these objects are good candidates for fossils. Their primary goal was to derive the relative ages of these six dwarfs by comparing their color-magnitude diagrams (CMDs), thus determining when their stars formed relative to the epoch of reionization. Weisz et al. searched for fossils as well, using the criteria that they formed between 12.9 and 13.5 Gyr ago at redshifts in the range $6 < z < 14$. This paper was one of several investigating galaxy evolution as a whole, particularly the dwarf galaxies in the Local Group (LG). Benítez-Llambay et al. focused mainly on isolated dwarf galaxies, those that would not likely be affected by the environmental factors mentioned above. Their goal was to compare results from simulations to those of observed dwarf data.

The data analyzed by all three groups are described separately in Sec. 2, the important results are summarized in Sec. 3, the authors' conclusions are given in Sec. 4, and possible future work is summarized in Sec. 5.

2 Data/Observations

The six UFDs were surveyed using two cameras on the HST: the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). The data were taken through two filters on each camera: the F606W (broad V) and F814W (I) (Brown et al. 2013).Bootes I, Coma Berenices, Ursa Major I, Hercules, Leo IV, and Canes Venatici II. The first three are "near" galaxies, within a distance of 100 kpc, and were observed out to a faint V magnitude limit of about 28. The latter three are "distant" galaxies, at distances farther than 130 kpc, and were observed out to a faint V magnitude limit of about 29. As their primary goal was to derive the relative ages of these objects, the authors solved the issue of age-metallicity degeneracy by using Keck/DEIMOS spectroscopy to determine the metallicity distribution independent from age. This age comparison could then help to reveal any synchronization (or lack thereof) in the SFHs of each of galaxy before, during, and after the epoch of reionization. The coding packages are described in Sec. 2 (Brown et al. 2013).

Weisz et al. extracted a sample of 38 LG dwarf galaxies to search for signatures of reionization effects. This sample included a wide variety of stellar masses (some were less than $10^5 M_\odot$, while others were greater than $10^7 M_\odot$. The overall sample included 21 dwarf spheroidals, 4 dwarf ellipticals, 8 dwarf irregulars, and 5 transition dwarfs. A list of the observational properties of each galaxy in the sample (magnitudes, distance from host galaxy, etc.) is included in their paper in table 1. To derive the SFH for each galaxy, they used the Padova library as this was the only one available to cover the required range in galactic properties. A Kroupa IMF was used in the range $0.15 < M_\odot < 120$. The reader is referred to a previous publication of Weisz et al. (2014) for details regarding the code.

Benítez-Llambay et al. focused their analysis on isolated dwarf galaxies, excluding satellites of larger galaxies such as the Milky Way and Andromeda to eliminate the possibility of the SF being affected by the environmental factors discussed in the introduction. Their project was divided into two parts: analysis of real dwarf galaxy data from HST and that of their own simulations. The sample of observed data consisted of 46 dwarfs with published SFHs. The spatial range for this group extended to a distance of about 4.5 Mpc from the Milky Way, not including galaxies within 300 kpc of each other, as they were restricting their sample to isolated galaxies only. Each had a B magnitude between -7 and -16, with corresponding masses between $10^5 M_\odot$ and $10^9 M_\odot$. Galaxies with a higher mass than this are not thought to be affected by reionization. The data were restricted to those with a stellar population that could be modeled with more than 10^4 particles. Details regarding the catalog information, specifically the SFHs of each galaxy, are referenced in their paper, in the caption for table 2.

The simulations of Benítez-Llambay et al. were run as part of the CLUES project, using the *Gadget-2* code (see Sec. 2 of their paper for more details). A UV radiation background was set at a redshift of $z = 6$ to model reionization. The rates of photoionization and photoheating as a function of redshift are shown in figure 1 in the paper. Both were used in the simulation to model the abundances of hydrogen and helium. The upper limit of the virial mass of each system was capped at $2 * 10^9 M_\odot$, as reionization was not expected to influence systems more massive than this. The objective was to stay consistent with other codes attempting to model the faint end of the galaxy stellar mass function (aka. low luminosity dwarf galaxies).

3 Results/Analysis

To determine the ages of their six UFDs, Brown et al. analyzed the CMD for each one. A good indicator of age is the main sequence turn-off (MSTO) point: since higher-mass stars burn through their fuel supply faster than lower-mass stars, they are the first to turn off the main sequence. The location of this point moves further down the H-R diagram as time progresses, so a relatively low MSTO indicates an old population (Holtzmann, ASTR 555, 2014). To visualize the relative ages of all six UFDs, the CMDs were combined into one diagram, normalized to that of Hercules. Each CMD was similar, indicating an age difference between them of less than 1 Gyr, and they were collectively found to be similar to the CMDs of old globular clusters (see figure 1 for diagrams of the individual CMDs and figure 2 for a composite diagram of all six UFDs in their paper). This widespread synchronization indicates that the SFHs were affected by a global phenomenon (such as reionization) rather than local influences (such as supernovae or gas depletion), which would have had a different effect on each galaxy.

The cumulative SFHs of the of the 38 galaxies studied by Weisz et al. are shown in figure 1 in their paper. The MSTO is clearly marked on each plot; the younger the population is (ie, the more stars that are on the main sequence), the more reliable the derived SFHs are since the evolution of main sequence stars is better understood. As expected, the more massive galaxies (dwarf spheroidals and dwarf ellipticals) did not show signs of SF quenching since, as mentioned above, reionization is not expected to have an effect on galaxies with large masses. There were a few dwarf spheroidals that continued to form stars even after suppression by reionization, but it was the fainter dwarf sheroidals that formed the bulk of their stars before this period. Only five of these galaxies were found to be true fossils: And V, And VI, And XIII, Hercules, and Leo IV. The latter two were also subjects of the study done by Brown et al. and were the only two found to have had their SF completely suppressed by reionization. Several other authors referenced in the literature also found these two to contain stars between the ages of 11 and 12 Gyr, which is consistent with the time of the epoch of reionization. Leo was an especially interesting case because it was massive enough to eliminate reionization as a possible reason for the truncation of its SF, yet it ceased to form stars around this time as well.

The sample of observed dwarfs analyzed by Benítez-Llambay et al. was divided into three age groups: old, intermediate, and young. Each of these groups corresponds to a time period when the universe was of the age between 0 and 4 Gyr, 4 and 8 Gyr, and 8 Gyr - present time, respectively. The star formation rate (SFR) was then plotted as a function of both age and corresponding redshift. The SFR was highest during the old period, then there was a significant drop during the intermediate period, followed by a slight increase during the young period. To test the influence of mass on changes in SF, the data were split into two groups: one whose galaxy masses were less than $2 * 10^7 M_\odot$, and one greater. Both groups showed the same decrease in SF during the intermediate range, revealing that mass did not have an effect on the suppression of SF (see figure 4 in their paper).

The simulations from Benítez-Llambay et al. showed the same diversity in SFH that was evident in the SFHs of the observed dwarfs. While some of the stars may have formed before this period (old), reionization caused a halt in early formation and delayed any future formation until after the intermediate era (young). In general, the sample of nearby dwarfs showed a dominant older population, with fewer stars in the young population and almost none in the intermediate population.

4 Conclusions

Brown et al. concluded that reionization was indeed the cause of the truncation of the SFHs for their six UFDs. Each of these dwarfs was found to have an older stellar population (> 12 Gyr) and similar SFHs. The reason for the missing satellites is that these galaxies either formed very few stars or none at all as a result of the ionization process. Therefore, due to this lack of luminosity, they remain undetected. An issue that remains is whether environmental effects can be clearly separated from reionization effects. Leo IV passed close (90kpc) to the Milky Way about 2 Gyr ago, and since then its SF has ceased, but there is no indisputable evidence that this interaction was the direct cause.

Weisz et al. also confirmed that there is an ambiguity between reionization and environmental effects when analyzing dwarf galaxies. The only way to be sure that a galaxy has not been affected by environmental factors is if it is located outside the virial radius of the Milky Way, out of reach of the influences of its host galaxy.

The conclusions of Benítez-Llambay et al. were similar: while there appear to be a lower quantity of dwarf galaxies than are predicted by the ΛCDM model, the reason for this is very likely due to reionization, which takes us closer to successfully constraining this model.

5 Future Work

For future analyses, Brown et al. plan to improve the metalicity of their selection criteria. The paper from Weisz et al. was a continuation of an ongoing project, and they referred to several ways in which they plan to continue this research. The main goal is to improve our understanding of galaxy evolution in general, and particularly that of LG dwarf galaxies. In the future they plan to analyze the quenching timescales of dwarf shperoidals of the LG and compare the results from their SFHs to "state-of-the-art" simulations. They discussed the difficulties in distinguishing between galaxies whose SF was reignited because of late gas capture and those that had retained hot gas in their halos until it cooled enough to condense and form stars. Future space missions, such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and Large Synoptic Survey Telescope (LSST) system will be useful for obtaining data for field dwarf galaxies (ie. those beyond the virial radius of the Milky Way), so long as their resolution is on par with that of the HST. Benítez-Llambay et al. plan on looking deeper into satellite (ie. dwarfs within a radius less than 300 kpc) SFHs to further analyze the evolution of galaxies that were most likely affected by ram pressure stripping and tidal effects. They are currently investigating the issue of two separate populations within the same galaxy that have stark contrasts in ages, metalicity, spatial distributions, and kinematics.

6 References

Benítez-Llambay, A., Navarro, J. F., Abadi, M. G., et al. 2014, ArXiv:1405.5540v2

Brown, T. M., Tumlinson, J., Geha, M., et al. 2013, ArXiv:1310.0824v1

Weisz, D. R., Dolphin, A. E., Skillman, E. D., et al. 2014, ArXiv:1405.3281v1