SMALL BUT INTRIGUING: DWARF GALAXIES IN THE LOCAL UNIVERSE

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Astronomy 233*
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Editors

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Astronomy 233 “From Rocks to the Universe: How Modern Telescopes Are Being Used to Answer the Major Questions in Astronomy” was taught during the fall semester of 2005 by Professors Don Campbell and Martha Haynes with the always willing and able assistance of Astronomy graduate student Ryan Yamada. The course is intended to provide students interested in majoring or concentrating in astronomy with an introduction to current forefront topics in the field and also to expose them to aspects of a professional research career such as the current “symposium”.

As one of the first Knight Institute sophomore seminars to be offered at Cornell, Astronomy 233 this semester revolved around the discussion of issues related to the origins of cosmic objects on scales from planets to galaxies. Emphasis was placed on understanding both the context and the methodology of such issues as the search for extrasolar planets, observational tests of the cold dark matter paradigm and the influence of environment on galaxy evolution. The latter part of the course explored the broad issues associated with the “missing satellite” problem and inspired us to study in more detail some of the least massive and least luminous galaxies in the nearby universe which are the subject of this symposium.

As part of our discussion of diminutive galaxies, students were placed in the role of summarizing papers selected from the professional literature pertaining to “Small but Intriguing: Dwarf Galaxies in the Local Universe.” The papers contained herein represent their original work, with minor editing mainly to conform to the style used in producing this volume. The students are asked to forgive us for modifications made in the editorial process.

All of us wish to compliment the authors on their contributions, on their diligence and enthusiasm, and on their patience.

Martha P. Haynes

Ryan S. Yamada

Donald B. Campbell

Ithaca, New York
29 November 2005
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1. What We Learn From the Orbit of the Sagittarius Dwarf Galaxy

Cheryl M. Sorace

ABSTRACT Law et al. (2005) looked to model how our own Milky Way was gravitationally impacting the Sagittarius Dwarf Galaxy (Sgr). They compared the locations of M giant stars as determined by 2MASS to computer simulations that attempted to replicate their observed locations and velocities. To do this, a number of parameters were varied including the mass and location of Sgr, and the potential of the Milky Way Halo. From their simulations Law et al. concluded that evolution had occurred in Sgr’s orbit about the Milky Way. The mass of the Milky Way and Sgr, and the distance between the two was also predicted, and three different possible models for the movement of Sgr provided. Looking for debris from Sgr in the Solar neighborhood was suggested as a possible way to chose between models, as two models predict debris and one does not. Finally, it was shown that the data provided further evidence for a dark matter halo around the Milky Way.


1.1 Introduction

The Sagittarius Dwarf Galaxy (hereafter Sgr) shown in Figure 1.1 was discovered in 1994 by Ibata et al. (1994). It is a small, relatively metal rich galaxy, located about 14 kpc away from the Milky Way, though estimates of its distance vary. Because of its close proximity to our galaxy, Sgr is currently being massively disrupted by the Milky Way’s gravity. Totten & Irwin (1998) presented the first data showing that Sgr had been distorted to extend all the way across the sky.

Several papers have used information about the shape of these distortions to extrapolate information about Sgr
and about the Milky Way. In particular, Law et al. (2005b; hereafter LJM05) looked at the current positions of M giants expelled from Sgr to estimate the Milky Way’s potential curve, and Sgr’s current mass and orbit.

1.2 The Sagittarius Tidal Tails

In their paper, which is the fourth in a series, LMJ05 looked up position and velocity data in the Two Micron All Sky Survey (2MASS) database for the M giant stars in the Sagittarius tidal tails. M giant stars are M spectral class stars of a fairly consistent age which can easily be identified from information in the 2MASS database. They then used these data to set up N-body simulations (simulations of the gravitational interactions between multiple bodies) of the interaction between Sgr and the Milky Way. In these simulations, Sgr was modeled as a system of many small bodies, while the Milky Way was modeled as a single large mass. A sample of the output of these numerical simulations, from LJM05, is shown in Figure 1.2. The length of the Milky Way’s halo, the flattening of the halo potential, and the contribution of the Galactic disk to the rotation curve (i.e., the mass and morphology of the Milky Way) were allowed to vary. Additionally, the rotational velocity of Sgr and its velocity radially towards/away from the Milky Way, as well as its location compared to the Galactic Center and its mass were permitted to vary. Its distance from the Galactic Center was calculated by estimating its distance from the Sun and the Sun’s distance from the Galactic Center, and combining the two.

To cut down the amount of computational time required, constraints based on the knowledge of the physics of the situation were placed on the variables. For example, one of the constraints, that the radial velocity of an object does not change from one orbit to the next, as seen from looking at stars in different orbits, could be checked by a simple test particle, and situations that failed to satisfy it discarded without a full simulation. Similar lines of reasoning were applied to all variables other than the mass of Sgr. Because M giant data were used, the simulations were fitted only to debris that contained M giants. Fortunately, this covers most identified debris of Sgr. Furthermore, it was later determined that these simulations fit other young debris populations fairly well. Thus, it was assumed that M giant locations made a good model of all recent debris locations. LJM05 further assumed that Sgr had been roughly spherical and non-rotating before it collided with the Milky Way.
After running simulations with many different sets of parameters (see Figure 1.2), LMJ05 were able to make some general statements about the system. The best fitting oblate ($q=0.9$), prolate ($q=1.25$), and spherical ($q = 1$) models of the Milky Way were identified and compared. It was found that the velocity trends of the M giants in the leading debris favored a prolate shape for the Milky Way, in direct contradiction to models presented in the third paper of the series (Law et al. 2005a) which showed that the precession direction of the debris all but demanded oblate halos. It was pointed out that the fact that no one type of potential could simultaneously account for all observed data suggests that Sgr’s orbit has changed fundamentally over time. The cause of this disruption is unknown. Though LJM05 speculate that either a change in the Galactic potential (the distribution and overall shape of the mass in the galaxy), an encounter with a massive piece of the Milky Way, or, most likely, dynamical friction (caused when pieces of the Milky Way accumulated in the wake of Sgr and gravitationally slowed it down) caused this change, they admit that none of these explanations is particularly satisfactory. It was however noted, that whatever the cause, the orbit evolved roughly 2–3 Gyrs ago. Due to this evolution, the fits that were calculated using the younger M giant stars, and therefore more recent orbits, failed to extrapolate back to fit data taken using older stars located in debris from previous orbits.

Each of the three best-fit simulations implied a mass for the Milky Way of about $3.8–5.6 \times 10^{11} M_\odot$. It was further noted that models that fit real world observations featured rotation curves that were very flat out to larger radii, supporting evidence that the Milky Way is surrounded by a dark matter halo. The mass still contained within Sgr was estimated to be $2–5 \times 10^8 M_\odot$. Sgr was determined to be located between 10–19 kpc at closest approach to, and 56–59 kpc at furthest distance from the Milky Way, and to have an orbital period of between 0.85 and 0.87 Gyr, with smaller orbits and shorter periods corresponding to oblate models of the Galactic dark matter halo, and larger orbits and longer periods, prolate models. These numbers agreed tolerably with those determined by other groups using other simulations.

Between the three models, it was found that the prolate model for the Galactic dark matter halo fit the velocity distribution on the leading tail best, as mentioned above. It was also found that both the oblate and the spherical, but not the prolate model predicted that debris from Sgr is currently inundating the immediate Solar area. LJM05 thus suggest that looking for debris in the Solar neighborhood could be a way of differentiating between the models of the Galactic potential.

1.3 Conclusion

LJM05 compared observed locations of M giant stars in the Sagittarius Dwarf debris stream to simulated models to obtain information about Sgr’s current mass and orbit, and about the Galactic potential (the shape and mass of the Milky Way). They were able to get their simulations to approach to a good degree the current orbit, but only the current orbit, of Sgr, and obtain fairly consistent values of its mass and location across different Galactic potentials. They were also able to arrive at a consistent number for the mass of the Milky Way. However, they were unable to decide on the shape of the Galactic potential as some of the data/simulations favored an oblate one and others a prolate one. They suggested looking for debris from Sgr in the solar neighborhood as a way of differentiating between the two, as the oblate model predicts its presence, and the prolate one does not. Finally, they noted that all simulations that reasonably approximated observed velocity distributions featured a rotation curve that remained flat at large distances, providing further evidence for the existence of dark mater halo of some shape around the Milky Way.

1.4 References

2. The Star Formation History of the Dwarf Spheroidal Galaxy, Carina

Colin Zarzycki

ABSTRACT In an attempt to better understand the star formation of dwarf galaxies, Hurley-Keller, Mateo, & Nemec (1998) utilized deep B and V photometry of the dwarf spheroidal, Carina (residing at a distance of roughly ~150 kpc), as well as a variety of numerical models and simulations, and concluded that the galaxy experienced three bursts of star formation (~15, ~7 and ~3 Gyr ago). Of note is that at least half of the galaxy’s noted star formation occurred in the intermediate period, with roughly 10-20% occurring in the oldest era, while roughly 30% formed recently. This leads to interesting (and somewhat perplexing) questions about the physics behind brief “bursts” of star formation, and why the intermittent periods were tranquil.


2.1 Introduction

Many studies have been undertaken in recent years involving dwarf galaxies, including Carina (Figure 2.1). Earlier observations and analysis of Carina suggested that the galaxy has a multi-episode history, especially a 1994 study undertaken by Smecker-Hane et al. (1994) which showed at least two separate horizontal branches herefore at least two different, distinct groups of stars of similar age. Even after these surveys however, the scientific community is still left with questions in regards to the number of episodes, and the magnitude of those episodes. Improved methods of analysis were needed to determine more precisely the facts in regards to the small dwarf spheroidal galaxy. Utilizing simulated color magnitude diagrams (CMDs) and comparing them to actual observed data from the Carina galaxy, as performed by Hurley-Keller, Mateo & Nemec (1998; hereafter HMN98), offers a much more detailed and precise representation of the galaxy’s star population and history.

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2. The Star Formation History of the Dwarf Spheroidal Galaxy, Carina

2.2 Observations

The observations necessary for this study were acquired in March of 1989 and 1990 using an 800 x 800 pixel Texas Instruments charged-coupled device (CCD) at the Cerro Tololo Inter-American Observatory 4m telescope. Three fields of stars measuring 15.16 square arc minutes were observed within the galaxy itself. These fields were relatively similar in star completeness, density, and type. From these fields, the stars were assigned V magnitudes and B-V colors simultaneously to create a trio of CMDs from three separate fields in the galaxy. These are shown in Figure 2.2 from HMN98.

When the color magnitude diagrams where analyzed from the three fields and subsequently superimposed upon one other, it was noted that there were three separate, identifiable main sequence turn off (MSTO) points: an old MSTO at around V = 23.2, a young turnoff at around V = 22.3, and an intermediate-age MSTO at roughly V = 22.7, as evident in Figure 2.2.

2.3 Analysis

From the analyzed CMDs, a pseudo-luminosity function (pseudo-LF) is constructed. This method breaks down the CMDs by grouping stars into bins of variable size that contained a fixed number of stars. By holding the number of stars fixed, but allowing the volume to vary, each bin represents the stellar density of a given era; therefore the smaller a bin is, the more stars per unit volume, the more dense the stars are in space, which finally lead to the conclusion of a heightened rate of star formation in that time period. The pseudo-LF is
2. The Star Formation History of the Dwarf Spheroidal Galaxy, Carina

FIGURE 2.3. Pseudo-LF bins in the main sequence and red giant branch areas of the observed Carina CMDs. From HMN98.

technically defined as the ratio:

\[ R_i = \frac{N_i/A_i}{N_{RGB}/A_{RGB}} \]

where \( A_i \) is the area of the bin, \( N_i \) is the number of stars in that bin, \( N_{RGB} \) is the number of stars in the brightest red giant branch bin, and \( A_{RGB} \) is the area of that brightest red giant branch bin (HMN98).

After experimentation, it was discovered that 30 stars per bin in the subgiant red branch and 50 stars per bin in the MSTO were sufficient to reduce large fluctuations in the data, without smoothing out key attributes (as seen in Figure 2.3). When observing the subgiant branch, it is clear that there is a heightened density in the third, sixth, and seventh bins from the top in Figure 2.3. These correspond to an increased number of stars at approximately 3 and 7 Gyr (HMN98).

These CMDs seem therefore to suggest that Carina had brief periods of strong star formation which were preceded and followed by relatively sterile eras. The strong MSTOs clearly define two older populations, roughly 15 and 7 Gyrs, and the inability of any models previously run simulating just two periods of star formation to agree with the enhanced density of stars in the galaxy’s subgiant branch implies the existence of a younger population in that region, \( \sim 3 \) Gyr (HMN98). These inferences allow for the conclusion that Carina’s main stars population came from three, distinct epochs.

Utilizing a large number of computer models, HMN98 therefore attempted to fit the data in the CMDs with projected results when using various time scales for star formation as well as different strengths of these formations. In essence, the group ran multiple computer simulations which they then overlaid upon the observed data in an attempt to reproduce the effects seen in the Carina information. These models utilized a set of metal-poor isochrones (numerical data providing information in regards to the age of stars due to composition) provided by Trippico, Dorman & Bell (1993) and an \([\text{Fe/H}]\) ratio of \(-2.23\) was chosen for the old population, and \([\text{Fe/H}] = -2.0\) for the two newer formations (VandenBerg 1983). Because of the metal-poor aspect of the galaxy, utilizing a constant metallicity ratio for large periods of star formation was determined unlikely to change the
results of the simulations, since the difference in composition throughout the galaxy is small (HMN98). Many models were termed “failures,” in part because of the high constraints which were being placed upon a relatively small number of stars. If the standards for a model “succeeding” were lowered, more models would be potential matches, but it would also increase the likelihood of false and dissimilar matches. After several tedious trials, a small group of models successful in mimicking the data showed some very important similarities. Almost all showed an important episode of star formation approximately 7 Gyr ago. The models also prove that the dominant era of star formation in Carina was indeed the intermediate one since only models with the middle population at least 20% stronger than the young population survived the criteria necessary (see Figure 2.4). The young population was difficult to get a grasp on because the star formation age is constrained by the magnitude of the corresponding subgiant branch peak. Episodes that lasted 0.5 Gyr were just as likely to fit the data as episodes lasting 1 Gyr (HMN98).

2.4 Results

From the data, it is clear that Carina underwent three periods of intense star formation, set amongst large periods of inactivity. All studies indicate at least one very large period (measuring upwards of 4 Gyr) of very little star formation occurred. The method in which this happens is not very well understood. Present day simulations by A. Babul show that a galaxy can undergo a pause in star formation this long only by ejecting gas out to a distance of \( \sim 20 \) kpc from the galactic center (HMN98). If this was true for Carina, however, because of its position relative to the Milky Way, it should theoretically lose that gas forever, inhibiting any further star formation (HMN98). So while it has become very clear from the observations that Carina has had short, intense periods of star formation, set among quiet lulls in activity, the exact causation mechanisms for these bursts of star generation remain definitively unknown.
2.5 References

3. The Structural Features of the Fornax dSph

Jeffrey Reep

ABSTRACT Dwarf spheroidal galaxies have become a valuable area of research in astronomy. In particular, ones such as the Fornax dwarf orbiting the Milky Way provide a great tool to astronomers due to the relative ease in studying them. Coleman et al. (2005) have recently completed a survey of this dwarf, employing color-magnitude diagrams to analyze Fornax’s structure. In particular, they found strong evidence that Fornax possesses a detailed extratidal structure.


3.1 Introduction

Shapley discovered the Fornax dwarf spheroidal galaxy (dSph), shown in Figure 3.1, in 1938. According to Baade & Hubble (1939), Fornax appears elliptical in shape, elongated in the NE–SW direction. Those authors also noted that Fornax has at least two globular clusters (five are now known). Their distance and magnitude estimates were not terrible, but more modern techniques have approximated the Fornax dwarf as having an absolute magnitude $M_V$ of $-13.2$ and a distance of $138\pm8$ kpc (Mateo 1998).

Nowadays, Fornax is known to be the second-largest dwarf galaxy orbiting the Milky Way (only Sagittarius is larger). The ages of the stars in this galaxy are extremely varied; there are stars well over 10 Gyr old, as well as some younger than 2 Gyr. The dominant population appears to be of intermediate age. It is clear that in the Fornax dSph, star formation has continued nearly to the present time. Dinescu et al. (2004) surveyed Fornax, however, for HI and found no traces of it. They have thus proposed that star formation ceased about 200 Myr ago when the Fornax dSph passed through the Magellanic plane and was stripped of its gas.

Coleman et al. (2005; hereafter C05) have proposed that the kinematics of the Fornax dSph will help to determine the history of the galaxy. Unfortunately, the radial velocities are too low for spectroscopy, and

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because of its distance, it is very hard to obtain spectra of adequate signal–to–noise (S/N) ratio for a decent amount of stars. However, they determined that the mass–to–light ratio of Fornax is somewhere between 5.3 and 26 $M_\odot/L_\odot$ (the large range is due to various published values of the surface brightness). These results imply that the majority of the galaxy’s matter is composed of dark matter.

### 3.2 Analysis of the Fornax Structure

The recent survey by C05 was essentially an attempt to use color-magnitude diagrams to locate extratidal stars, i.e., stars in the Fornax dSph but beyond the tidal radius. As aforementioned, a large problem with studying the Fornax galaxy is that the S/N ratio of spectra is quite large. Hence, it is hard to determine which stars are actually extratidal ones, and which are foreground stars in the Milky Way. C05 took a CCD survey in the V and I bands over a $3.1^\circ \times 3.1^\circ$ area of the sky to shed light on the problem.

In the 1960's, King (1962) developed models for describing star clusters; these models have been found applicable also to elliptical galaxies, the bulges of spiral galaxies and to entire clusters of galaxies. Essentially, these models use a few key parameters of a star cluster – or galaxy – (core radius, tidal radius, and central density) to allow one to describe features such as the surface brightness and star density. The models depend on the assumption that the velocity distributions in the system (cluster or galaxy) are essentially Gaussian, but are often extended to systems in which only the surface brightness (no velocities) is measurable. The surface brightness is simply the total brightness spread over the entire area. The equation for the surface brightness $\Sigma(r)$ takes the form

$$\Sigma(r) = \Sigma_0^* \left[1 + (r/r_c)^2\right]^{-\beta}$$

where $r_c$, the “core radius” is the radius at which the surface brightness $\Sigma(r)$ falls to half of its central value $\Sigma_0$, $\beta$ is the “King exponent” and $\Sigma_0^* = \Sigma_0 \cdot 2\beta$. The density function $f(r)$ then takes the form
\[ f(r) = k \left[ (1 + (r/r_c)^2)^{1/2} - (1 + (r/r_t)^2)^{1/2} \right]^2 \]

where \( r_t \) is the tidal radius, \( k \) is the central density, and \( r_c \) is the core radius. These equations have been found to provide excellent approximations for many galaxies in addition to star clusters and clusters of galaxies.

C05 proceeded to check the outer region (i.e., extratidal) to see how the density behaved. The probability density distribution appears to be a combination of two Gaussian functions – that is, it peaks at two separate points (with a smaller third peak out to the Northwest of the center): 350 stars deg\(^2\) and 525 stars deg\(^2\). In addition, the team split the galaxy into two regions, the Northwest-Southeast and Northeast-Southwest, and measured the probability density functions for each region. Indeed, each comes out nearly Gaussian with the same peaks as before. All this data clearly demonstrates that the Fornax dSph does have a large amount of extratidal structure.

C05 finish their analysis with a brief examination and explanation of the density distribution. According to them, the distribution resembles those of large galaxies. Such structures have been observed to occur when a large galaxy collides with a much smaller one. This theory seems to fit with Fornax, as the over-density in the Northwest region may well be the remnants of a smaller galaxy (or perhaps a globular cluster). Also, although technically a dwarf, Fornax is still more massive than the rest of the dwarfs orbiting the Milky Way (excluding Sagittarius).

### 3.3 Conclusion

The observations of the Fornax dSph for the last 70 or so years have provided astronomers with interesting details of dwarf galaxies. Being one of the closest dwarf galaxies, it is a prime candidate for research. Astronomers have a particularly devoted interest in these dwarves because they may have the key to unlocking the mystery of dark matter. Fornax itself has a mass-to-light ratio possibly as high as 26 \( M_\odot/L_\odot \), implying that a large fraction of its mass is contained in dark matter.

C05 have recently completed a survey of the Fornax dSph, using CCDs in the V and I ranges. The results have uncovered a lot of the details about the structure of the galaxy. Through comparing some of the structural facets with other observed galaxies, they can develop theories about the formation of this dwarf. In time, a full understanding of the creation and evolution of the galaxy may unlock the secrets of its dark matter. The density distributions in particular seem useful in providing some answers.

### 3.4 References


4. The Star Formation History of LGS 3

Seth Jacobsen

ABSTRACT Using new observations from the Hubble Space Telescope, Miller et al. have recalculated the distance (620 ± 20 kpc) to and determined the star formation of the dwarf galaxy LGS 3. They determined that its star formation history includes a burst early (over 10 Gyr ago), but its star formation rate has decreased over time and stopped completely 100 Myr ago. The unusual combination of dI and dE/dSph characteristics is hypothesized to be the result of geographic placement in the Local Group and/or original characteristics such as size, composition, and density.


4.1 Introduction

To understand the connection between dwarf irregular (dI) and dwarf elliptical (dE) or dwarf spheroidal (dSph) galaxies, Miller et al. (2001; hereafter M01) propose that LGS 3 (see Figure 4.1) serves as a bridge between the two disparate galactic types, dI and dE/dSph. Knowledge of such a connection will shed light on an array of astrophysical problems such as stellar evolution, primordial abundances and chemical evolution, and the formation of larger galaxies and structure in the universe due to their possible nature as the earliest structures formed.

Previous work classifies LGS 3 as a dI, despite its containing a surprising number of blue stars. LGS 3 lacks a detectable HII region, which means that there is not much current star production. It would have been classified as a dSph but Thuan & Martin (1979) detected HI emission associated with LGS 3, suggesting a dI connection.

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4. The Star Formation History of LGS 3

M01 obtained new images with the Hubble Space Telescope of LGS 3 as illustrated in the left panel of Figure 4.2, to construct a complete color-magnitude diagram (CMD) for LGS 3, shown in the right panel. The main features of the CMD are a narrow red giant branch (RGB), a few asymptotic giant branch (AGB) stars just above the RGB, a red clump and blue loop stars, a “blue plume” of main-sequence stars, and a blue horizontal branch (HB). The average distance was determined to be 620 ± 20 kpc, which is appreciably smaller and more accurate than previous values in the literature. The observed structural and kinematic properties and updated derived physical parameters are given in Table 4.3 in the Appendix.

<table>
<thead>
<tr>
<th>Age Range Gyr</th>
<th>SFR $\times 10^{-5} M_\odot$ yr$^{-1}$</th>
<th>Mean [Fe/H]</th>
<th>$\sigma$[Fe/H]</th>
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<tr>
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<td>0.6 ± 0.2</td>
<td>-1.25 ± 0.50</td>
<td>0.26 ± 0.31</td>
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<td>0.2-0.4</td>
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<td>13.0-15.0</td>
<td>26.6 ± 6.2</td>
<td>-1.32 ± 0.10</td>
<td>0.31 ± 0.07</td>
</tr>
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</table>

TABLE 4.1. Global Star Formation History of LGS 3. From M01.

M01 used a synthetic CMD-matching technique in order to compute the star formation history (SFH). The star formation rate and metallicity as a function of time for the galactic solution are given in Table 4.1. LGS 3 formed most of its stars in a burst very early and its star formation rate (SFR) has been decreasing for the last 10 Gyr. The metallicity has also been slowly increasing throughout time as each new generation of stars appears.

After concluding that the present radii relative to the center of LGS 3 reflect the radii where these stars were
formed, M01 adapted the CMD models to explore for spatial differences in the SFH for three radial zones shown in Table 4.2. The SFR in the outermost zone has been decreasing for some time and has been nonexistent the last 200 Myr. The SFR in the intermediate zone was relatively constant until 2 Gyr and then it decreased by a factor of two. The inner zone maintained a steady SFR that was slightly higher than the intermediate zone. There has not been any significant star formation anywhere in LGS 3 in the last 100 Myr or there would be more blue stars.

<table>
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<th>Age Range Gyr</th>
<th>SFR/SFR (10Gyr)</th>
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<td>0.1-0.2</td>
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<td>0.4-0.6</td>
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<tr>
<td>0.6-1.0</td>
<td>0.73 ± 0.09</td>
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<tr>
<td>1.0-2.0</td>
<td>0.73 ± 0.18</td>
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<tr>
<td>2.0-5.0</td>
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<tr>
<td>5.0-15.0</td>
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TABLE 4.2. Radial Star Formation History of LGS 3. From M01.

As shown in Figure 4.3, M01 created CMDs for the same radial zones. The outer zone contains an extended blue HB from a very old population. The intermediate zone has added a blue plume from star formation 2 Gyr ago and a few blue stars that are only 200–300 Myr old. In the center of the galaxy, there is the highest ratio of blue to red stars suggesting that the most recent star formation occurred here. There is a very even distribution of the oldest stars. Alternatively, the main-sequence stars are the most unevenly distributed.

A low but very smooth distribution of HI centered on the optical galaxy, shown in Figure 4.4, makes LGS 3 unique compared to most other star-forming dwarf irregular galaxies that are thought to have holes because of stellar winds and supernovae. M01 point out that gas moving at 5 km s$^{-1}$ can travel a distance of 500 pc, a length larger than the diameter of most HI holes, in 100 Myr, meaning that star forming events have most likely not occurred in a 100 Myr. The gas density is about a factor of ten too small to initiate star formation on average throughout LGS 3. Since none of the gas has been expelled recently, a little over half of the current gas mass, $2 \times 10^5 \, M_\odot$, inside LGS 3 has become enriched with heavy elements over time from stellar evolution.
4. The Star Formation History of LGS 3

FIGURE 4.4. Contours of HI column density from YL97 superposed on the ground-based V image from Lee (1995). Unlike other dI galaxies with gas, the HI has a smooth distribution that follows the stellar distribution. Contour levels are 2.5, 5.0, 7.5, 10.0, and 12.5 \times 10^{19} \text{ cm}^{-2}. From M01.

4.3 Conclusion

The star formation history of LGS 3 is dominated by a very early burst throughout followed by a low level of continuous star formation in the center. The large early burst of star formation occurred when the gas supply was large and extended, forming a broad sheet of metal-poor stars. The SFR in the outer region declined more rapidly then in the center as the gas supply was used up and/or stripped off in the outer parts; the star formation rate fell to a halt 100 Myr ago. However, star formation continued toward the center, although this slowly fell off as well. This continued star formation in the center is typical of some of the low-mass dI galaxies and larger dE/dSphs. Since the SFHs of low-luminosity dI and dE/dSph galaxies are remarkably similar, LGS 3 is only distinguished as a dI because of the amount of gas that it retains for possible future star formation.

This distinction is why LGS 3 is so important. Discovering why LGS 3 developed the way it did rather than into a standard dI or dE/dSph may perhaps bridge the gap between the classes of dwarf galaxies. This distinction could just be an inherent property, a factor of its original characteristics. But, this evolutionary key may be held by the environment in which each dwarf develops. Blitz & Robishaw (2000) argue that stripping from the hot halos of nearby larger galaxies can explain the loss of gas in dSphs, often found near larger galaxies, that is not found in dIs, found scattered throughout the Local Group. Whether classified as irregular or spheroidal, galaxies like LGS 3 are important for studying the evolution of dwarf galaxies because they are the lowest mass galaxies that have managed to retain some HI and have star formation until very recently.

4.4 References

4. The Star Formation History of LGS 3


4.5 Appendix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Distance modulus</td>
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<td>Asymptotic M/L</td>
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<td>Gas mass fraction</td>
<td>9 × 10^-0.1</td>
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TABLE 4.3. Global Properties of LGS 3. From M01.
References. – (1) M01; (2) Schlegel et al. 1998; (3) Lee 1995; (4) Cook et al. 1999; (5) YL97
5. New Light on Small Galaxy Formation

Philip Wu

ABSTRACT The purpose of this paper is to present the recent discovery of the Andromeda IX (And IX) dwarf spheroidal satellite galaxy of M31. And IX is the faintest galaxy found in the Local Group ($M_V = -8.3$). According to the INT WFC survey data, And IX is found to have mainly metal deficient Red Giant Branch (RGB) stars, and a lack of an intermediate-age (1-10 Gyr) stellar population. By observing the measured metallicity and the tip of the red giant branch luminosity, And IX is found to be 735 kpc away, placing And IX approximately 45 kpc from M31. Despite being the faintest known galaxy and having a low metallicity, And IX follows the same ratio of luminosity/metallicity and luminosity/surface brightness defined by the other dwarf spheroidals in the Local Group. The observed properties of And IX show that it was formed from a once more massive but stripped galaxy or from an intrinsically low mass seed. It also exhibits a high mass to luminosity ratio, $M/L \sim 93 M_\odot/L_\odot$, which means that it is a system dominated by dark matter. And IX also presents the intriguing possibility of fainter galaxies lying below the limits of detectability which will bring models of the dwarf galaxy population into better accordance with the observed data.

5.1 Introduction

From Sloan Digital Sky Survey data, a new Local Group member named And IX was found by Zucker et al. (2004). And IX has also been visible in maps from the M31 INT Wide-Field Camera Survey. And IX, as shown in Figure 5.1, was found at a location of 1.8° East and 1.9° North of the nucleus of M31. It was found as an excess of red giant branch (RGB) stars on the blueward side of the general M31 RGB locus. With the absolute luminosity of $-8.3$ mag and a central surface brightness of 26.8 mag arcsec$^{-2}$, And IX is the faintest galaxy yet known.

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5. New Light on Small Galaxy Formation

Harbeck et al. (2005; hereafter H05) used a Color Magnitude Diagram (CMD) of And IX’s RGB to show that And IX is truly a dwarf spheroidal (see Figure 5.2). By comparing the ratios between luminosity/metallicity and luminosity/surface brightness of And IX with those of other dwarf spheroidals in the Local Group, H05 also showed that And IX is an ordinary dwarf spheroidal in the Local Group. H05 also use such properties as the luminosity and metallicity of And IX to make implications about the formation of And IX.

### 5.2 Observation and Data Analysis of And IX

And IX was observed by using the WIYN 3.5 m telescope with a mosaic camera consisting of two orthogonal CCD’s, each with a total viewing field of $9.5' \times 9.5'$. Six images of And IX were obtained with different filters: two in V-band, one in I-band, and three in narrowband filters centered on the near-infrared TiO and CN bands. The data were reduced in the standard way of overscan, bias, and flat-field corrections.

The CMD of And IX’s RGB is located approximately 2 mag below the tip of RGB (TRGB) of M31, at luminosity of $I \sim 24.5$ mag. The CMD of And IX’s RGB is shown in Figure 5.2. As seen in the CMD, the luminosity of the tip of RGB is about 20.45 mag. Using the absolute I-band luminosity of $-3.95$ mag for the TRGB and a foreground reddening of $E(B-V) = 0.076$ and $A_I = 1.94 E(B-V)$ from Schlegel et al. (1998), the distance modulus for And IX is $24.33 \pm 0.1$ mag. The distance modulus of $24.33 \pm 0.1$ mag corresponds to a distance of $735 \pm 15$ kpc, which is only 45 kpc from M31. From a statistical study of a kinematic grouping of stars close to the center of And IX, the mean velocity of And IX is estimated to be $216 \pm 3$ km s$^{-1}$. In the model of Ibata et al. (2004), the escape velocity of M31 at 45 kpc is 550 km s$^{-1}$. Although there is a lot of uncertainty as to the velocity calculation due to the stars from the M31 halo, And IX is most likely bound to M31.

The metallicity of And IX was estimated by plotting the mean ridge lines of the Milky Way globular clusters M15, M2, and 47 Tuc from Da Costa & Armandroff (1990). The metallicities of these globular clusters are $-2.26$, $-1.62$, and $-0.76$ dex, respectively. From the CMD of And IX with the plotted mean ridge lines (shown in Figure 5.2), one can see that And IX’s RGB is closer to the M15’s mean ridge line, which gives And IX
5. New Light on Small Galaxy Formation

FIGURE 5.3. The top panel shows the ratio of the tidal radius to the core radius. The middle panel shows the luminosity-surface brightness relations. The bottom panel shows the luminosity-metallicity relations. The open circles represents the other dwarf spheroidals in the Local Group while the filled circles represents And IX. From H05.

the metallicity close to −2 dex. This low metallicity would imply a lack of younger (younger than 10 Gyr) stellar population. By using the narrowband filters, it was confirmed that And IX has no intermediate stellar population, or carbon stars. Thus And IX consists only of an older (older than 10 Gyr) stellar population, as predicted by its low metallicity.

5.3 Conclusion

From the analysis of And IX’s CMD, it can be concluded that And IX is a dwarf spheroidal galaxy. Furthermore, due to the lack of a bright main sequence, an extended asymptotic giant branch, or a young red clump, And IX appears to be an old, very metal deficient galaxy. However, despite its low luminosity, metallicity, and surface brightness, And IX still follows the luminosity-metallicity and luminosity-surface brightness relations similar to other dwarf spheroidals in the Local Group (as shown in Figure 5.3). Thus, And IX seems to be an ordinary dwarf spheroidal that is just old and metal deficient.

And IX is a very intriguing dwarf spheroidal due to its close distance to the giant galaxy, M31. By comparing the observed properties of And IX with predicated properties from galaxy formation models, one can gather some insight on the formation of And IX. Also this comparison can be used to give new constraints to such models, hence improving the models’ accuracy.

From the observed properties of And IX, one possible hypothesis for the formation of And IX is the stripping of a larger stellar mass before it was chemically mature. This hypothesis would be in agreement with the apparently normal position of And IX in the luminosity-metallicity and luminosity-surface brightness diagrams for dwarf spheroidals while also being in accordance with the observed very low metallicity. However, none of the tidal stripping models of Kravtsov et al. (2004) reach the stellar mass of And IX, which might suggest that ram pressure played an important in stripping the ISM during the formation of And IX. Another possible hypothesis for the formation of And IX is that it is intrinsically a low-mass galaxy. One critical factor that backs this hypothesis is the balancing of the gas loss to the giant galaxy M31, and the gas needed to form stars. Another critical factor is the possibility of sufficient redshift to collapse the gases into stars.
Using a mass to light ratio estimation given by Richstone & Tremaine (1986), the M/L of And IX is found to be $\sim 93 \, M_\odot/L_\odot$, which is even greater than Draco dSph (Milky Way’s most dark matter dominated satellite). Using the same estimation, the M/L of the Draco dSph is only $\sim 91 \, M_\odot/L_\odot$. Therefore, And IX gives an intriguing possibility of the existence of more highly dark matter dominated dwarf spheroidals that are just below the limits of detectability. These dwarf spheroidals might be the missing link between the predicated properties of the universe from galaxy formation models and the observed properties, such as the total mass of the universe or the number of low mass dark subhalos.

5.4 References

6. Old Stars and Low Metallicities: Surprises in Leo A

Lisa I. Grossman¹

ABSTRACT Schulte-Ladbeck et al. made Hubble Space Telescope observations of Leo A as a follow-up to a study by Tolstoy et al. Their field of view was offset from the centrally located field of Tolstoy et al., and they found that the average stellar age increases with distance from the center of the galaxy. They found that Leo A has a minimum age of 9 Gyr, but a very slow star formation rate. They concluded that even though Leo A has a low oxygen abundance, it is not a young galaxy, and therefore low oxygen abundance does not rule out the possibility of old stars.

FIGURE 6.1. Composite optical image of Leo A obtained with the Subaru Telescope S uprime-Cam at the National Astronomical Observatory of Japan, November 20-21, 2001. Exposure time: 50 min. (Blue), 30 min. (Green), 20 min. (Red). The field of view is ~13.4’ × 10.7’. From http://www.naoj.org/Pressrelease/2004/08/05/Fig1_LeoA_BVI_72.jpg

6.1 Introduction

As evident in Figure 6.1, Leo A, a dwarf irregular galaxy located 795 kpc from the Milky Way, resides in the backwaters of the Local Group, isolated from large galaxies and galaxy clusters (see Figure 6.2). Its development has therefore not been affected by interaction with these larger bodies, and so the details of its history, particularly its age, are of great interest to astronomers who are curious about galaxy formation models and the conditions of the early universe. Leo A is also the most metal-poor galaxy of the Local Group, indicating that it has produced extremely few stellar generations. As stars evolve off the main sequence, they pollute the interstellar medium with heavy elements like oxygen and carbon, which are then incorporated into the next generation of stars. Galaxies whose stars have been through a very small number of generations are therefore relatively deficient in the heavy elements.

Tolstoy et al. (1998; hereafter T98) studied a central portion of Leo A and determined that it is a fairly young

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6. Old Stars and Low Metallicities: Surprises in Leo A


galaxy, with a star formation onset time of less than 2 Gyr ago. As a follow up to this study, Schulte-Ladbeck et al. (2002; hereafter S02) observed Leo A with Hubble Space Telescope single-star photometry, but offset their target field (see Figure 6.3) from that of T98 to determine whether Leo A has any older stars or evidence of previous generations of star formation. Their data, contrasting with those of T98, identify stars with ages of at least 9 Gyr and possibly greater in Leo A, indicating that a low metallicity does not necessarily mean that a galaxy is devoid of old stars.

6.2 Age Differs with Radius

S02 obtained single-star photometry images of the halo of Leo A. They made color magnitude diagrams (CMD) of four different chips, or regions of their field of view of the galaxy, using three different filter combinations. A sample CMD from one of the filter combinations is shown in Figure 6.3. The main sequence turnoff point is absent from their CMDs; the galaxy is too distant for stars of such low luminosities to be detected. The density of stars in general decreases with increasing distance from the galaxy’s center, which can be clearly seen in the images of Leo A shown in Figures 6.1 and 6.3, but S02 also found that the average stellar age increases with galactocentric distance. Young main sequence (MS) stars in the blue plume are bright and abundant towards the center of the galaxy (at the upper left edge of S02’s field of view), but thin out and become fainter as they approach the edge. Blue loop stars, descendants of massive and intermediate-mass stars, also make up the young population of Leo A. The blue loop is a very specific region of the CMD, and as such, is a clear indicator of the presence of a fairly young stellar population. The density of these stars similarly decreases with distance from the galactic center. S02 used I-band luminosity functions to display how the intermediate-age and old stellar content changes with radius, and found that while there is a small, gradual decrease in the number of red giant branch and asymptotic giant branch stars from the center to the edge, their populations decrease at a much smaller rate than that of the younger stars. The average age of the stellar population of Leo A increases from the center of the galaxy to the periphery. This provides a ready explanation for why S02’s data differs from T98’s: T98’s galactocentric field of view gave the impression of an overall young galaxy because of the higher density of young stars in the center.
6. Old Stars and Low Metallicities: Surprises in Leo A

6.3 Age and Star Formation History

The absence of the main sequence turnoff point in the CMDs made it extremely difficult for S02 to ascertain the precise ages of Leo A’s varied star population, so they turned to other methods. After determining the distance modulus of Leo A to be $m - M = 24.5(\pm 0.2)$, S02 fitted their data to isochrones, galaxies of known ages and similar-looking CMDs, laying one CMD over the other and seeing how closely they matched up. Isochrones were selected based on the magnitude of the tip of the red giant branch and metallicity. They found that the young stellar content within their field of view had ages between about 0.2 and 2 Gyr, and the rest of the population had to be at least 5 Gyr to fit with the metallicity. The existence of a red horizontal branch (RHB) indicates that there are stars with ages up to about 10 Gyr. They then compared their data to synthetic CMDs produced based on various hypotheses about Leo A’s star formation history. The results of these comparisons indicate that there has been very little star formation in the outer regions of Leo A in the past 0.1-1 Gyr. S02 could not come up with a model that matches the data if most of the stars are within 0.9 and 1.5 Gyr old or if none of the stars have significantly greater ages than 2 Gyr, as would be the case in the scenario proposed by T98. Their models of Leo A’s star formation history denote an overall declining star formation rate (SFR) from early times to today, making Leo A an unlikely candidate for a delayed-forming dwarf galaxy. S02 believe that Leo A’s stars formed at a very slow rate, spanning billions of years, and that its first stars were in place before the cosmic SFR density started to decline. Leo A is thus one of many galaxies in the Local Group to have formed stars very early on. This weakens the idea that low metallicity and low oxygen abundance can be used as an indicator of absolute age.

6.4 Conclusions and Implications

Astronomers were first attracted to Leo A by its low metallicity and very blue color – traits that generally indicate galactic youth. The discovery of a truly young galaxy in the Local Group would eliminate certain models of galaxy formation, such as the idea of hierarchical galaxy formation, in which larger galaxies are built from smaller ones which formed very early on and drew together. Under this model, there is no place for
small, young galaxies. It would also give astronomers an opportunity to explore star formation in a pristine environment. However, from the fact that Leo A exhibits a red horizontal branch and a low metallicity, S02 concluded that Leo A is at least 9 Gyr old, far too old to be considered a young galaxy. Confirmation of older ages would require more research of regions further out in the halo. The presence of old stars in Leo A and galaxies like it means that we cannot assume that a galaxy has formed recently on the basis of its oxygen abundance alone.

6.5 References


7. M32’s “Active” Nucleus

Catherine Elder

ABSTRACT Ho, Terashima & Ulvestad (2003) detected the nucleus of M32 in X-rays using images from Chandra. The Chandra data they analyzed shows that the X-ray emission previously detected is offset from the kinematic center of the galaxy. They also used data from the Very Large Array to set an upper bound on nuclear radio power.


7.1 Introduction

Shown in Figure 7.1, the dwarf elliptical galaxy M32 is located in the Local Group closest to Andromeda about 810 kpc from our Galaxy. The possibility of a black hole in the center of M32 was first suggested in 1984 based on ground based observations of the velocities of the stars moving around the center. These observations were possible because M32 is located closer to our Galaxy than most galaxies. The Hubble telescope later observed a cusp of light and made better measurements of the velocities of the stars both of which supplemented the evidence for a super massive black hole (Van der Marel, 1998). Verolme et al. (2002) recently determined that the mass of M32’s black hole is \( M_{BH} = (2.5 \pm 0.5) \times 10^6 \, M_\odot \). Ho, Terashima, & Ulvestad (2003; hereafter HTU03) report conclusive detection of the nucleus of M32 using X-ray data from Chandra high resolution images. They also used a radio continuum image from the Very Large Array (VLA) to derive an upper limit at 8.4 GHz on the radio nuclear power. Our galaxy, M31 and M32 all have bulges at their centers. They probably also have massive black holes in their centers. M32’s nucleus is harder to detect than Sgr A and M31 which both emit nonstellar radiation at X-ray and radio wavelengths. M32’s nucleus is harder to detect because it does not seem to be accreting matter. HTU03 use the X-ray images from Chandra in addition to the limits at

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7.2 Observations and Results

HTU03 used data from Chandra using the Advanced CCD Imaging Spectrometer (ACIS). As evident in Figure 7.2, three unresolved X-ray sources are visible. X-1 is in the same place as the position of the M32 nucleus identified with the Two-Micron All-Sky Survey (2MASS). Chandra and 2MASS are both reliable, so HTU03 identified X-1 as the X-ray counterpart of M32’s nucleus. This means X-1 lines up with the kinematic center of the galaxy. X-3 is the brightest source in the region and is slightly to the southeast of X-1. The flux of X-3 is comparable to the flux of M32’s nucleus measured in previous observations. Those observations were probably dominated by X-3. Based on previous arguments by Lowenstein et al. (1998), X-3 is probably a low mass binary. X-2 is only visible at low energies.

HTU03 edited, calibrated, imaged, and restored data from VLA. The images were made to maximize sensitivity which meant a small sacrifice of resolution. At 8.4GHz, they assign an upper limit to the flux of an unresolved source at the position of the nucleus of 30 μJy.

Multiple groups have observed M32’s nucleus using the Hubble Space Telescope. These observations give upper limits to the detection of an unresolved component (point source) but do not conclusively detect the nucleus.

7.3 Discussion

Usually, if a galaxy has a bulge, it means it has a central massive black hole. Some black holes are inactive. Eskridge et al. (1996) detected X-ray emission from a central region, but the ROSAT positional accuracy and resolution were not adequate. Lowenstein et al. (1998) observed with a higher resolution and thought that the X-ray emission lay slightly offset from the optical position of the nucleus. Chandra has better resolution and positional accuracy and sensitivity. Using the new Chandra data, HTU03 have shown that the X-ray emission comes from three different sources, evident in Figure 7.2. X-1 is the kinematic center. M32 has the second
lowest luminosity X-ray nucleus known. Relative to the size of the black hole, M32’s luminosity is higher than that of any other nucleus in the Local group. M32’s spectral slope is almost identical to that of Sgr A*. Its radio upper limit is similar to that of M31. In general, radio to X-ray luminosity ratios vary a lot so it is difficult to predict what it should be. There it is difficult to draw conclusions about M32 based on its radio to X-ray luminosity ratio.

A useful spectral energy distribution (SED) can’t be made for M32’s nucleus, because the nucleus of M32 cannot be detected in ultraviolet, optical, near infrared or mid-infrared wavelengths. M32 has a very low nuclear accretion luminosity which suggests that there is nothing to be accreted. No cold gas has been detected. The data from Chandra observations is the only evidence for gas near the nucleus. HTU03 have detected diffuse thermal plasma in the annular region of M32. This region is 15″ to 44″ from the center. HTU03 do not know if it continues towards the nucleus as well or not. There must be some gas in the center because M32 is an evolved galaxy and evolved stars lose mass in the form of gas. Based on calculations by Padovani & Matteucci (1993), stellar populations lose mass at a rate of $\dot{M}_* = 1 \times 10^{-6} M_\odot \, \text{yr}^{-1}$. Bondi accretion of hot gas was also considered by HTU03 using the Bondi accretion rate: $M_B = M^2 n T^{-3/2}$ where $M$ is the mass, $n$ is the density and $T$ is the temperature. They determined that for M32, $M_B = 3 \times 10^{-7} M_\odot \, \text{yr}^{-1}$, but it is likely to be higher because they assumed a constant density at $r < 15''$, and the density probably increases closer to the center. The result of these two calculations is that $\dot{M}_* = M_B$. This could mean one of three things. First, it could mean that they could be wrong about $\dot{M}_*$ or $M_B$. Second, it could mean they are right about $\dot{M}_*$ which would mean that the radiative efficiency is very small. Because the luminosity and accretion rate in M32’s nucleus are both very low, radiatively inefficient accretion would not be very surprising. Third, the accretion rate might be much less than $\dot{M}_*$. This would happen if gas was pushed out of the nucleus, for example, by a supernova explosion. However, they don’t think M32 would have any recent supernovae because there is no evidence for recent star formation.

7.4 Conclusion

HTU03 successfully detected the nucleus of M32. They showed that it has 3 discrete X-ray sources. The dominant X-ray source, X-3, is not in the kinematic center of the galaxy, rather it is to the southeast. X-3 is probably a low mass binary star. They believe there is a black hole in the center, but it is hard to detect because it is inactive. Accretion does not seem to occur. This is either because the accretion is inefficient or because the gas escapes accretion.

7.5 References

8. A Review of Kinematics of the Dwarf Irregular Galaxy GR 8

Ken Soong

ABSTRACT In studying small but intriguing dwarf galaxies in the local universe, I review A. Begum and J.N. Chengalur’s (2003; hereafter BC03) article on the kinematics of the dwarf irregular galaxy GR 8. BC03 interpret their data of GR 8 as an indication that the velocity of GR 8 cannot be derived from either the pure rotational motions of the galaxy or from the pure radial expansions of the galaxy. BC03 conclude that the most reasonable model is comprised of both rotational and radial components.


8.1 Introduction

GR 8 was first discovered by Reaves (1956) during a survey for dwarf galaxies in the direction of the Virgo Cluster. The original distance estimates for GR 8 were somewhat smaller than more recent estimates. Recently Tolstoy et al. (1995) estimated a distance of 2.2 Mpc. Consistent with this, van den Bergh (2000) does not classify GR 8 as a member of the Local Group, which extends to a distance of approximately 1.14 Mpc. GR 8, shown in Figure 8.1.1, has a patchy appearance in optical images, with the emissions being dominated by bright blue knots.

BC03 presented deep, high velocity resolution Giant Meterwave Radio Telescope (GMRT) observations of the HI emission from GR 8 and from those observations interpret the kinematics of this galaxy.

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8.2 The HI Distribution in GR 8

BC03 presented deep, high velocity resolution GMRT HI 21 cm synthesis images for the faint dwarf irregular galaxy GR 8. The HI distribution is clumpy and shows three major concentrations. This is highlighted in Figure 8.2 which shows the integrated HI emission at high resolution. Although the HI distribution in the galaxy is very clumpy, there is nonetheless substantial diffused gas. As can be seen in Figure 8.2, each HI clump is associated with a clump of optical emission. However, for each clump, the peak optical emission is generally offset from the peak of the HI emission.

FIGURE 8.2. Left: The integrated spectrum for GR 8. The dashed line shows a Gaussian fit to the profile. The heliocentric velocity is \( \sim 217 \, \text{km s}^{-1} \) and the velocity width at the 50% flux level is \( \sim 26 \, \text{km s}^{-1} \). Center: Contours of the GMRT integrated HI emission map overlaid on the digitized Palomar Sky Survey optical image of GR 8. Right: The high resolution 4′ × 3′ image of the HI emission. All figures are from BC03.

BC03 concluded from the HI emission data that the velocity field is consistent with a velocity field that would be produced by a rotating disk with an approximately north–south kinematical major axis. However the kinematical major axis is substantially misaligned with the major axis obtained by ellipse fitting the HI brightness. In addition to this misalignment, the kinematical center of the velocity field is offset from the center of the HI disk. Furthermore, the velocity field of GR 8 shows clear departures from what would be expected from an axisymmetric rotating disk. The most important departure is that the isovelocity contours (equal velocity contours) in the outer regions of the galaxy show large scale kinks. In addition, the velocity field shows several asymmetries, prominently between the northern and southern half of the galaxy.

8.3 Discussion

The morphology and kinematics of GR 8 are somewhat peculiar. BC03 in their discussion elaborated many scenarios and models that attempt to explain the kinematics of the dwarf galaxy GR 8. BC03 explained that if the HI gas and the stars in GR 8 are both in disks, then the stellar disk would have to be more inclined and have a different position angle than the gas disk. Further, the kinematical and HI major axis of this galaxy are perpendicular to each other, so the kinematical center is offset from the morphological center and the observed velocity field is systematically asymmetric. This misalignment and off-centered kinematics implies that GR 8 cannot be modeled as a pure axisymmetric rotating disk.

BC03 stated that, in order to provide a feel for the velocity field that would be produced by circular rotation, the disk has been taken to be elliptical, with an axis ratio of 2:1, so that despite having an inclination of 60° (the inclination angle derived from the velocity field by Carignan et al. 1990) the projected model HI disk matches the fairly circular appearance of the observed HI disk. Although the model produces closed isovelocity
8. A Review of Kinematics of the Dwarf Irregular Galaxy GR 8

Contours along the apparent morphological HI minor axis, the peculiar behaviors of this dwarf galaxy are not reproduced. Additionally, this model of the unusual highly non-circular disk raises serious concerns. The inner regions of the galaxy will complete one rotation in ~80 Myr, while the rotation period at the edge of the disk is ~1 Gyr. Hence, this differential rotation will wind up any elongation in the disk on a timescale that is short compared to the age of the galaxy.

Alternatively, as first proposed by Lo et al. (1993), the observed velocity field of GR 8 could also be the result of radial expansion or contraction in the gas. BC03 reasoned that since radial motions are probably driven by energy from star formation, it is not necessary for the expansion center to be coincident with the geometric center of the HI disk. In models of dwarf galaxy formation and evolution, energy injected into the ISM from stellar winds and supernova explosions could drive significant expansive motions in the gas. In light of this and the ongoing star formation in GR 8, BC03 illustrated that it may be reasonable to assume that there are large scale radial flows in the galaxy. BC03 derived a relation for the line of sight velocity which, when evaluated with reasonable variables values, was able to explain many features of GR 8. However, while a pure expansion model does produce the closed contours along the morphological minor axis, it does not produce the asymmetries in the velocity field.

BC03 next modeled a system with both expansion and rotation. Overall, the observed velocity field of GR 8 was quite well matched by their model with both rotational and expansion motions. The rotation was assumed to be centered on the morphological center of the galaxy, with inclination and position angle being the same as for the previous model. This reproduced the asymmetry in the kinks in the isovelocity contours between the eastern and western halves of the galaxy. Assuming that this interpretation is correct, it is natural to question what drives the expansion of the gas. Energy input from star formation is the obvious suspect. Of the sample of galaxies studied by Elmegreen & Hunter (2000) GR 8 showed the largest pressure anomaly; the pressure in the HII regions was found to be at least a factor of ~55 times larger than the average disk pressure. Since these HII regions tend to lie at the inner edges of the HI clumps, this excess pressure could possibly drive the clumps outwards. It is interesting to note that the star formation history of these clumps indicates that they have been forming stars continuously over at least the last 500 Myr (Dohm-Palmer et al. 1998).

To start with, BC03 treated radial motion as expansion. However, since the sign of the radial motion is unconstrained, it should also be noted that the velocity field could instead arise from infall. In this case, BC03 deduced that if gas is swirling inwards into the galaxy, then the model would be that GR 8 is forming from the merger of the three clumps. Further, the diffuse gas and stars are material that have been tidally stripped from the clumps and which are now settling down to form a disk.

8.4 Conclusion

Through HI emission observations, BC03 were able to interpret the kinematics of the dwarf irregular galaxy GR 8. BC03 interpreted GR 8 to have velocities arising from both the radial movement of the gas in the galaxy as well as the rotational movements. Furthermore, BC03 stated explicitly why the velocity curve of GR 8 could not be explained fully by either pure rotational or pure radial effects. Although BC03’s proposal of a combination of radial movement and rotational movement does provide a more fitting model of GR 8, it does not fully explain all features of the kinematics of GR 8, and thus leaves GR 8 still shrouded in a bit of mystery.

8.5 References

9. Novel Formation Theory of HS 0822+3542

James Rékai Nuttall¹

ABSTRACT This review examines the recent publication by Corbin et al. (2005) concerning the nearby, ultracompact dwarf galaxy HS 0822+3542. The paper uses photographic and photometric data to resolve the ultracompact blue dwarf into two objects of distinct origin and identifies evidence for an older generation of stars within each of them. This provides an interesting model for the generational evolution of dwarf galaxies in regions of low galaxy density and perhaps provides a model for the formation of a dwarf irregular from smaller globular clusters and galaxies.

FIGURE 9.1. Hα image of HS 0822+3542 obtained with the Palomar Observatory 60-inch telescope. From A. Gil de Paz: http://spider.ipac.caltech.edu/staff/agpaz/P0_BCDs/hs0822ha.gif

9.1 Introduction

Cosmological models suggest that the matter in the universe has become progressively more unevenly distributed over time. Extrapolating back using this model we can predict that the earliest stars and galaxies would have had to have formed in regions of relatively low mass density. Initial observations of the dwarf irregular galaxy HS 0822+3542 have suggested that it may be a good model for a prototypical galaxy. Corbin et al. (2005; hereafter C05) suggest an alternative explanation for the active star formation in this object based on the resolution of its internal structure into two discrete components.

As illustrated in Figure 9.1, HS 0822+3542 is a small, very faint, ultracompact blue dwarf galaxy (UCBD) located in a local void about 12.7 Mpc from the Milky Way. The nearest bright galaxy to HS 0822+3542 is more than 3 Mpc away. It is currently undergoing a starburst (forming OB stars at a rate above average) suggesting an abundance of gas of very low metallicity. The net flux indicates that the galaxy is made up of primarily young OB stars of very low metallicity. If this is indeed the case, then HS 0822+3542 may be an excellent model for an early galaxy.

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9.2 Theory of Star Formation in HS 0822+3542 as Caused by a Collision between Two Smaller Objects

C05 were primarily concerned with testing the hypothesis that all UCBDs are small dwarf galaxies in the process of assembling from smaller bodies of gas and stars. Critical to this point is the identification of stars in the observed galaxy that would predate the collision event. Earlier theories of the origin of HS 0822+3542 (Pustilnik et al. 2003, hereafter P03) associate the galaxy with another very blue object 11 kpc away, SAO 0822+3545, which is also undergoing a starburst period of very low metallicity stars. By comparing the relative proximity and characteristics of the starbursts in the two objects, P03 suggest that both dwarf galaxies are undergoing starbursts due to their recent interactions with each other. However, P03 admit that when the timescale of stellar development is modelled based on the observed stars of SAO 0822+3545, no model, either of instantaneous or steady state star development, corresponds well to an interaction with HS 0822+3542.

C05 examine HS 0822+3542 using the Hubble Space Telescope Advanced Camera for Surveys/High Resolution Channel (HST ACS/HRC), which furnishes photographic and photometric data that suggests another model to explain the starburst in the object. Their composite ACS image is shown in Figure 9.2. Based on the data, the authors make two important conclusions. The first is that the UCBD can be divided into two distinct objects. The second is that each of these objects has an endogenous population of older stars, such that no part of HS 0822+3542 is forming its first generation of stars.

From observations in the visual range from even a ground based telescope, it is obvious that the object is comprised of two distinct components. P03 recognize this feature of HS 0822+3542 but identify the variation in stellar density as two distinct stellar clusters as opposed to objects of separate origin. To prove their hypothesis that the object is in the process of aggregating from smaller galaxies, C05 rely on photometric data. Unfortunately, the object is too far away to resolve the individual spectra of its component stars; the authors instead rely on the net flux of the two high stellar density objects and extrapolate the age of their component stars by comparison with several models of star formation. The paper examines the flux of the two identified components of HS 0822+3542 under three different filters chosen to minimize the contribution of spectral lines. The net flux from these three filters is compared to instantaneous models of stellar development of varying age, for the two objects independently. The paper concludes that no single model best predicts the net flux of either component and consequently theorizes that the flux of the two components must contain contributions from older populations of stars. Any model of a single generation of stars is much more skewed towards lower wavelength emissions than observed in the net flux from either object. C05 acknowledge that...
the additional high wavelength light that the model for a single generation of young stars is most deficient in (yet is readily observed from both components) may be due to nebulous emission of the surrounding hot gas. The authors estimate the temperature and density of the gaseous component using data from the SDSS. They conclude that though the nebulous emission contribution to the flux may constitute 10-20% of the total, it cannot be the majority contributor. Given that the majority of the higher wavelength flux cannot be from the gaseous component, the authors conclude that there must be a population of older stars.

9.3 HS 0822+3542: Contribution to UCBD Evolution Theory

If HS 0822+3542 is forming new stars due to the tidal effects of a collision and has a population of old stars, why is it metal poor? If the findings of this paper are accurate and the UCBD does contain stars more than 10 Gyr old, then the metals formed by this first generation of stars must have been ejected by the galaxy and its metallicity is not indicative of its age. It is possible that due to the low mass of the object that any heavy elements formed would have escaped the gravitational pull of the galaxy due to the force of the first generation supernovae. This of course implies that the gas involved in the contemporary starburst must have come from another source. Modeling the starburst as the result of a collision between smaller objects provides the added benefit of a source for this metal poor gas as one of the globular components may be poaching the majority of the gas of the other provided that one of the objects had a relatively high density of hydrogen and fewer old stars. The hundredfold discrepancy in the luminosity of the two components suggests that the dimmer object may be the matter source. The mechanism by which the smaller body either acquired or retained a high density of pristine gas while generating an older generation of stars remains to be elucidated.

9.4 Conclusion

The major finding of C05 is that low metallicity should not be immediately associated with the age of an object in a void. It is also interesting to note that the collision event will likely result in a coalescence into a single dwarf galaxy. If this is the eventual outcome, then HS 0822+3542 can serve as a model for the assembly of a dwarf irregular independent of a galaxy cluster.

9.5 References


ABSTRACT We discuss new evidence gathered from Hubble Space Telescope/Advanced Camera for Surveys images and introduced in the Izotov & Thuan observations for the age and distance of the most metal-deficient blue compact dwarf galaxy known, I Zw 18. The resulting I versus V−I color magnitude diagram (CMD) confirms a large population of young blue and red supergiants and an older population of asymptotic giant branch (AGB) stars. Based on a distance to I Zw 18 of 12.6–15 Mpc derived from the brightness of its AGB stars, the CMD reaches limiting magnitudes 1–2 magnitudes below the tip of the red giant branch (TRGB) and reveals a conspicuous absence of red giant branch (RGB) stars. The oldest stars in the galaxy cannot surpass 2 Gyr and I Zw 18 is in fact a young galaxy.


10.1 Introduction

The blue compact dwarf (BCD) galaxy I Zw 18 (see Figure 10.1) has long been an object of astronomical interest. As the most metal–poor BCD and the lowest metallicity star–forming galaxy, and due to a conspicuously absent red giant branch, I Zw 18 is considered one of the best candidates for being a genuinely young galaxy. Previous studies have placed its age anywhere between practically zero, a brand new galaxy undergoing its first burst of star formation as evidenced by the abundance of B and early A stars (Hunter & Thronson 1995), to about 0.1–5 Gyr old, as is implied by the presence of a later-discovered asymptotic giant branch (AGB) (Ostlin 2000). The AGB likewise indicates that this is not its first burst of star formation and places the first star formation episode at about 0.5–1 Gyr ago, while the also-present population of red supergiants is likely aged only about 10–20 Myr. The diffuse structure slightly removed from the main body of the galaxy, hereafter

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10. I Zw 18: A Genuinely Young Galaxy?

called the C component, has been studied in less detail due to its faintness, but has been estimated to be about 200 Myr old (Aloisi et al. 1999). A galaxy this young in the local universe would be of great interest for cosmological and galaxy formation studies. For instance, the cold dark matter models predict that because low-mass dwarf galaxies originate from density fluctuations much smaller than those that give rise to giant galaxies, they could still be forming today. Finding a young dwarf galaxy in the local universe would put constraints on the spectrum of primordial density fluctuation. Furthermore, the proximity of such a galaxy would allow for more precise and sensitive study of structure, metal content, and stellar populations than can be performed on galaxies of high redshift. Also, the hierarchical model of galaxy formation uses small “building-block” galaxies to form larger ones. The building blocks are too faint to be studied at high redshift, and are much more likely to be understood if they are found in the local universe. Therefore, if I Zw 18 were concluded to be a truly young galaxy, it would be extremely useful for study. However, its evolutionary status remains unsettled, as the available images for color magnitude diagram study were not deep enough below the tip of the red giant branch to reveal whether or not a faint 1–2 Gyr population of red giant stars exists. The new deep Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) images of I Zw 18 used in the study of Izotov & Thuan (2004; hereafter IT04) go 1–2 magnitudes below the TRGB and put more stringent constraints on I Zw 18’s evolutionary status. The new deep ACS V band image is shown in Figure 10.2 and the resultant CMD is shown in Figure 10.3.

10.2 Morphology

This BCD consists of two components, a main body composed of two star-forming regions with an angular separation of 5.8" and a prominent diffuse feature known as the C component about 22" northwest, as is evident in Figure 10.1. The C component is embedded in an HI envelope with the main body (van Zee et al. 1998) and has a systemic radial velocity equal to that of the ionized gas in the main body (Dufour et al.1996a; Izotov & Thuan 1998; van Zee et al. 1998), establishing that it is associated with, though physically removed from the main body. The northwest knot of star formation in the main body contains Wolf-Rayet stars (Izotov et al. 1997; Legrand et al. 1997; Brown et al. 2002), an evolutionary phase of massive stars that tends to set in within a few million years of a starburst. This suggests that the northwest area is an active ongoing star formation region. The presence of ionized gas emission (Izotov et al. 1997) adds plausibility to this claim.

10.3 Distance

Due to the absence of a red giant branch (RGB), the distance to the galaxy cannot be determined by measuring the tip of said RGB (TRGB). Previous studies place the distance of I Zw 18 from the observer at 10–15 Mpc (Hunter & Thronson 1995; Dufour et al. 1996b; Aloisi et al. 1999; Izotov et al. 2001; Izotov & Thuan 2002). At 10 Mpc, the magnitude of the TRGB would be greater than that of the AGB, which does not hold true in other BCDs, so this distance has been determined to be too small. IT04 estimated the distance of I Zw 18 by comparing its absolute star magnitudes at different distances with those of other BCDs and came out with an estimate of between 12.6–15 Mpc, with the most likely value in the upper range.

10.4 Composition

The aforementioned lack of an RGB was validated by IT04 due to two distinct phenomena. The first is that their new data goes 1–2 magnitudes below the TRGB and still locates only a few faint red sources close to the detectability limit (which may be false detections due to their faintness or real stars with their colors reddened by dust or with erroneous colors due to the large photometric uncertainties). The second is their comparison
10. I Zw 18: A Genuinely Young Galaxy?

FIGURE 10.2. V-band image of I Zw 18 obtained with the Advanced Camera for Surveys on the Hubble Space Telescope. From IT04.

with another BCD galaxy, UGC 4483. The RGB population of UGC 4483 is one of the bluest known in BCDs. However, placing UGC 4483 at the same distance as I Zw 18 and taking into consideration both the changed probability of detection of its stars at the new distance with the exposure times used for I Zw 18, and the crowding effect that causes fewer stars to be resolved still leaves UGC 4438’s CMD with a noticeable (though diminished) RGB while I Zw 18’s is conspicuously missing. IT04 concludes that the absence of an RGB in I Zw 18 is not likely the result of a selection effect, but a genuine absence. Furthermore, since UGC 4483 is of similar metallicity to I Zw 18, the several blue giants observed in I Zw 18 which might otherwise be considered members of the RGB are probably not. They probably appear blue due to age effects (ie: youth) rather than a misestimate of metallicity, removing them from I Zw 18’s RGB. Also, the RGB stars of the CMD of UGC 4483 are distributed more uniformly than the narrow blue band seen in I Zw 18. I Zw 18 is genuinely lacking an aged red giant branch.

The stellar populations of the main body of I Zw 18 as detected by the HST/ACS observations of IT04 suggest two previous star formation periods in addition to the current one. One of these produced the 200 Myr old 6 mag AGB stars, and the other is responsible for the oldest stars in the main body, the 300-500 Myr 5 mag AGB stars. No AGB stars with ages of greater than 1 Gyr were seen. The C component consists of an older stellar population of faint red stars and a more recently developed population of blue stars, about 40 Myr old and localized in its southeastern half. According to IT04’s data, it seems to have had two star formation episodes, one 200-300 Myr ago and the other only 15-20 Myr ago. Its AGB stars are slightly brighter on average than those of the main body, indicating that it is slightly younger. IT04’s new deep ACS images allow for the first time an upper limit to be set on the overall age of this BCD, a limit of about 1–2 Gyr, with its actual age probably smaller, since only stars with ages less than or equal to 500 Myr were observed.

10.5 Conclusion

I Zw 18’s CMD is populated with stars of varying ages, from the youngest main sequence stars to blue loop stars and red supergiants. However, even though these data goes 1–2 mag deeper than the tip of RGB for a
distance of I Zw 18 in the 12.6–15 Mpc range, there was no RGB detected, making I Zw 18 the first galaxy with resolved stellar populations where no RGB stars are seen. Since there is no RGB, the RGB cannot be used to determine distance. Instead the brightnesses of I Zw 18 stars were compared to those of another metal-deficient BCD, UGC 4483 to derive a distance of 12.6–15 Mpc. Star formation episodes determined by brightness for this distance place an upper limit on I Zw 18’s age of 1–2 Gyr. I Zw 18 is a bona fide young galaxy.

10.6 References


11. The Blue Compact Dwarf SBS 0335-052

Franco A. Cedano

ABSTRACT The blue compact dwarf (BCD) galaxy SBS 0335-052 has many of the characteristics thought to be indicators of a young galaxy. Based on the findings of Pustilnik et al. (2000), it can be concluded that this young galaxy's star formation was triggered by its interaction with neighboring galaxy NGC 1376.

FIGURE 11.1. Optical image of SBS 0335-052, a low metallicity blue compact dwarf galaxy 54.3 Mpc away. From http://www.aip.de/groups/opti/pmas/SGALLERY/SBS0335/thuan1997_blurred.gif

11.1 Introduction

As illustrated in Figure 11.1, SBS 0335-052 is a blue compact dwarf (BCD) galaxy 16 kpc across located 54.3 Mpc away. It is gas rich, but only 1/10 of its baryonic mass is in stars. It has an extremely low metallicity, $Z$, of about $Z = 1/41 Z_\odot$ (Melnick, Heydari-Malayeri & Leisy 1992), making it the second most metal-deficient galaxy known in the universe. Low metallicity in a galaxy indicates it is hosting its first population of stars and therefore the galaxy is young. Pustilnik et al. (2001; hereafter P01) detected a large H1 complex (see Figure 11.2) associated with SBS 0335-052 found to have dimensions 66 by 22 kpc and also at a distance of 54.3 Mpc. There are two concentrations of H1 within the system, aligned east to west with a separation of about 22 kpc. The east and west peaks of H1 in the system have optical BCD galaxies, SBS 0335-052 and SBS 0335-052W respectively, associated with them. Observations of SBS 0335-052 by Papaderos et al. (1998) along with evolutionary models point to a stellar population of less than 100 Myr. Also Thuan, Izotov & Lipovetsky (1995) and Izotov & Thuan (1999) have suggested that BCDs with metallicity less than $Z = 1/20 Z_\odot$ can only occur with stars of mass $M > 9 M_\odot$. The main sequence lifetime of a 9 $M_\odot$ star is about 40 Myr, which agrees with the observations in Papaderos et al. (1998).

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11. Results

Figure 11.2 is a gray scale mapping of the HI distribution of SBS 0335-052 and the large spiral galaxy NGC 1376. Points E and W are the east and west peaks of HI in the elongated structure. The two points are separated by about 22 kpc.

The entire SBS 0335-052 system (both east and west HI concentrations) has a total HI mass of \( M_{HI} = 1.68 \times 10^9 \, M_\odot \). Accounting for a mass fraction of 0.245 for helium (Izotov & Thuan 1998), the total gas mass in the system is

\[
M_{\text{gas}} = 2.1 \times 10^9 \, M_\odot
\]

The total gas mass of the individual HI concentrations (corrected for He) is

\[
M_{\text{gas, west}} = 1.11 \times 10^9 \, M_\odot, \\
M_{\text{gas, east}} = 0.99 \times 10^9 \, M_\odot.
\]

The total stellar mass of the system is at most 108 M, no more than 5

Figure 11.3 is an overlay of the HI contours on top of an optical B-band image from Papaderos et al. (1998). The optical and HI centers of SBS 0335-052W coincide with each other within an accepted error. For SBS 0335-052 the optical and HI centers are offset by 1.6 kpc.

In calculating the total dynamical mass of the system, P01 present two hypotheses. The first is that the HI complex is one cloud with two condensations. The second is that there are two separate systems that are interacting with each other. For the case of one huge cloud, P01 equate the centrifugal and gravitational forces at the edges of the disk to find the total gravitational mass. The lower limit for the dynamical mass is

\[
M_{\text{dyn}} = 5.9 \times 10^9 \, M_\odot.
\]

In the case of two interacting clouds, the masses are

\[
M_{\text{dyn, east}} = 1.6 \times 10^9 \, M_\odot.
\]
11. The Blue Compact Dwarf SBS 0335-052

11.3 Possible Star Formation Triggers

Tidal triggering is the most probable cause for the star formation in the SBS 0335-052 system (P01). The same two hypotheses of one huge cloud and two interacting clouds are considered. In the case of a single self-gravitating HI cloud, the tidal triggering is probably due to the companion massive galaxy NGC 1376 (P01). The distance between the center of the galaxy and SBS 0355-052 system is 150 kpc. Rix & Zaritzky (1995) note that NGC 1376 has three spiral arms; this suggests that the spiral has recently experienced a tidal disturbance. Icke (1985) suggests one mechanism of star formation involving tidal accelerations to supersonic speeds. P01 find that for distances of less than 412 kpc the gas in SBS 0355-052 can be accelerated to supersonic velocities. Thus, for a separation of 150 kpc the required tidal forces can be expected. In the other case, the two separate HI systems interact with each other causing the necessary tidal forces need to trigger star formation. In this case, the Icke (1985) mechanism holds for distances less than 27 kpc. The distance between the two HI concentrations is 22 kpc. The tidal forces in both situations are comparable and it can not be determined which hypothesis is more likely to occur.

\[ M_{\text{dyn,west}} = 2.2 \times 10^9 \, M_\odot, \]

or a total mass (east + west) of

\[ M_{\text{dyn}} = 3.8 \times 10^9 \, M_\odot \, pc^{-2} \]

This is 64% of the value derived from the hypothesis of one giant cloud. These estimates are lower limits since the inclination of the system is unknown and is assumed to be 90° (edge-on). In both cases, there is a large difference between the calculated mass of the gas and the dynamical mass. Therefore, the system requires a large amount of dark matter to make up for this difference.
11.4 Conclusion

Due to its extremely low metallicity, the BCD SBS 0335-052 is most likely a young galaxy currently undergoing its first generation of star formation. This formation was probably triggered by tidal forces caused by interaction with the neighboring massive spiral galaxy NGC 1376, or by interaction between the two HI concentrations within the system.

11.5 References