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THE VIRGO CLUSTER: GALAXY EVOLUTION IN ACTION

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*Astronomy 233 is offered by the Cornell University Astronomy Department and the College of Arts and Sciences under the John S. Knight Institute Writing in the Majors Program.
Astronomy 233 “The History of Structure in the Universe” was taught during the fall semester of 2007 by Professors Riccardo Giovanelli and Martha Haynes with the always willing and able assistance of Astronomy graduate student Carl Ferkinhoff. Among the topics discussed in the course were the history of the early universe, the cosmic microwave background, evidence for dark energy and dark matter, the relationship between supermassive black holes, active galactic nuclei and their host galaxies, the formation of the first stars and galaxies, and the evolution of galaxies, clusters and superclusters through cosmic time. In addition to providing an overview of the development of structure in the universe, Astronomy 233 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 part of our discussion of cosmic structure, we investigated how galaxy evolution is affected by environmental influences, especially in clusters of galaxies. The Virgo Cluster, the nearest rich cluster to our own Local Group of galaxies, serves as an intriguing laboratory for the study of the environmental mechanisms which drive galaxy evolution. In the context of this symposium, students were placed in the role of summarizing papers selected from the professional literature pertaining to “The Virgo Cluster: Galaxy Evolution in Action.” 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.

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Ithaca, New York
27 November 2007
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1. Diffuse Light in the Virgo Cluster

Jared Feldman

ABSTRACT The paper by Mihos et al. (2005; hereafter M05) presents deep optical imaging of the center of the Virgo Cluster, which was used to search for diffuse Intra Cluster Light (ICL). The imaging revealed a large amount of diffuse ICL, including multiple tidal streamers as well as tidal tails and bridges between galaxies within the cluster. The imaging also revealed the diffuse halo of M 87 and diffuse light around the M 84/M 86 pair. Analysis of the complex substructure of Virgo’s diffuse ICL allows further understanding of the Virgo Cluster’s formation and gives an insight to general cluster formation.

1.1 Introduction

M05 provide evidence that diffuse intra-cluster light (ICL) in galaxy clusters can be successfully applied to determine their structure and history. Intra-cluster light is the light provided by stars that are not bound gravitationally to a galaxy but rather the cluster in which the galaxy resides (Vilchez–Gomez 1999). Originally ICL was discovered through the use of deep broadband imaging in 1951, by Fritz Zwicky. M05s studies show that ICL has been discovered in individual stars and intra-cluster planetary nebulae, a later stage of evolution in large mass stars. Simulations have led to a generally accepted understanding that the formation of ICL is related to tidal stripping during the assembly of the cluster. Tidal stripping occurs when large galaxies pull stars and stellar material from a smaller galaxy (Read et al. 2005). M05 noted that the Virgo Cluster (at an adopted distance of 16 Mpc) is ideal to study ICL, as it appears to be a complex environment perfectly suited for the production of ICL because the cluster contains spatial and kinematic substructure, as well as multiple species of galaxies. This diversity located in a single cluster is useful because the wealth of data available can be applied to the study of cluster formation and structure.

1.2 Imaging Technique

Images of the Virgo cluster used in M05 were obtained in March and April of 2004 using the Burrell Schmidt Telescope at Kitt Peak, Arizona. Seventy-two object images were taken covering nearly 2.25 square degrees of the cluster. Using a complex data processing system, the images were combined to form a large picture of the cluster in lieu of many tiny indistinguishable images. These larger images are more useful for the detection of ICL in the Virgo cluster. According to M05, some errors in measurement could possibly have occurred due to a ring of cirrus surrounding the core of the Virgo cluster that possibly contaminated images to the north and southwest of the field of view. Luckily, the core itself was not obstructed and structures were detected in the ICL. The resulting final image is displayed in Figure 1.1.

1.3 Diffuse Light In Virgo’s Core

M05 declare that a large array of diffuse features can be observed in Virgos ICL. These features vary from extended low surface brightness envelopes, or thin streamers and small scale tidal effects. Low brightness
envelopes are frequently present due to dwarf galaxies in which the baryonic matter is in the form of diffuse light and nearly ninety five percent of the mass is present as non-baryonic dark matter. The goal of M05 is to focus on the morphology of Virgos ICL through a qualitative analysis. Reproduced from M05, Figure 1.2 provides a schematic diagram identifying various ICL features and galaxies located near the cluster center.

Two streamers labelled “A” and “B” in Figure 1.2 seem to be extending to the northwest from M 87, the largest brightest galaxy in the northern Virgo cluster. Streamer “A” passes through a pair of galaxies and then towards a group to the north. The surface brightness of the streamer drops as it enters the halo around the pair of galaxies and fades away. The extent of streamer A was measured to be 178 kpc in length, 16 kpc in width with a luminosity of $10^9 M_\odot$. NGC 4458 and NGC 4461, the two galaxies which streamer “A” passes through, have high velocities relative to each other, leading M05 to argue that the streamer is caused by stripping from one of the galaxies rather than direct interaction between the two.

Streamer “B” appears to begin just to the northwest of M 87 to the northwest and is 130 kpc long and 6 kpc wide. It appears to be “carrying” a low surface brightness dwarf into the halo of M 87, possibly destroying the dwarf in the tidal forces of the cluster. Since this stream is particularly thin, M05 argue that either the dwarf is on a highly radial orbit or is being viewed in the orbital plane. Streamers are not all linear, as streamer “C” appears to be curved and surrounds a low surface brightness dwarf. Besides large streams of ICL, the Virgo cluster also demonstrates tidal features on small scales. The twin galaxies NGC 4435/4438 “D” are in the shape of a “dogleg” as the tidal forces of the two galaxies and the Virgo cluster conspire to alter the shape of the pair of galaxies.

The measurement of the ICL of the Virgo Cluster facilitates the observation of luminous halos around the galaxies in Virgo. An irregular stellar envelope “T” around M 87 has been observed that extends out to around 175 kpc (Weil, Bland-Hawthorn & Malin 1997). It is more difficult to determine halos around M 84 and M 86 and other smaller galaxies because they are closely congregated. Instead, a crown “K” of diffuse light north of M 84/M 86 is visible; in addition a diffuse extension is visible to the south, which eventually blends into the galaxies to the south. Three low surface brightness filaments “L1-L3” are also visible around M 86. An envelope of light “M” is also present around the galaxies south of M 86. A tidal bridge connects NGC 4413 and IC 3363, not shown in diagram. According to M05, an extended HI cloud streaming from NGC 4388, also not shown has been recently discovered which is attributed to ram pressure stripping (Oosterloo & van Gorkom 2005; see also the paper by Jennifer Burt in this volume).
1.4 Discussion

M05's deep imaging of the Virgo cluster revealed a net of tidal features, evidence of the continuous tidal stripping and evolution of galaxies in Virgo. The ICL is not centered around M 87, the center of the cluster; instead M05 discovered the center to be around M 84/M 86. This is evidence the ICL is not growing simply by accretion around a central galaxy, but rather it grows according to the inherent unique structure of the Virgo Cluster. M05, in comparison to the IPNe density study by Feldmeier et al. (2005), provide verification that the density in the core is highly variable and not constant. The deep imaging allows the tracing of the ICL in galaxy clusters.

M05's study of diffuse light assists in the study of low surface brightness dwarf galaxies also known as primarily dark matter galaxies. Increased knowledge of the concentration of dark matter in the Virgo cluster allows for the understanding of the complex substructure of the ICL. This is evidence that there is a hierarchy within the assembly of the Virgo cluster, and it is not simply the product of smooth accretion around a central galaxy.

1.5 References


2. The Metallicity Distribution of Intracluster Stars in Virgo

Kristen Lau

ABSTRACT The Hubble Space Telescope was used to detect and measure about 5300 stars in an intracluster field in the Virgo Cluster. It was then possible to determine the metallicity distribution and the types of stars present in the portion of the Virgo Cluster by performing photometry on these stars. Through analysis, it was then found that most metal-poor stars in the observed field had less structure than that of metal-rich stars. Thus, it was concluded that the intracluster population is not well-mixed.

2.1 Introduction

The interactions and mergers between galaxies are integral in the evolutionary process of galaxies. In such processes, tidal forces often eject stars from their parent galaxies into intergalactic space. As discussed in the paper by Williams et al. (2007: hereafter W07), these stars can provide a “fossil record” of the interactions that took place. As noted by W07, other authors have developed models for the formation and evolution of galaxies by analyzing the chemistry and age distribution of their stellar populations. The chemical abundance (or metallicities) of these ejected stars can provide insight on the galactic origins of the stars. Similarly, according to W07, it is possible to determine the interactions that were involved in these galactic evolutions by analyzing the number and spatial distribution of the stars. The history of a group of cluster can be determined by taking a look at the kinematics and phase-space structure of the stars. From this, the interaction history of a system of galaxies can be studied through observations of red giants, planetary nebulae, and globular clusters (W07).

The intracluster medium provides a suitable environment for the measurement of intergalactic stars. Galaxies that are located in regions of space that are denser tend to be redder and usually have less gas (Dressler 1980). Furthermore, through observed colour shifts, galaxy clusters tend to have evolved much more rapidly than field galaxies (Butcher & Oemler 1978). Explanations for such differences noted by W07 include gravitation interactions and mergers among cluster galaxies, gravitational interactions with the cluster’s gravitational potential, and the loss of gas through interactions with the intracluster medium.

2.2 The Virgo Cluster

The Virgo Cluster is the nearest cluster system (at a distance of about 15 Mpc) that has a significant intracluster population of stars (W07). It is also the best-studied cluster because of its large size. This provides the best example to help further the knowledge of intracluster light; see, for example, the paper by Jared Feldman in this volume. Astronomers have already been able to trace the distribution of intracluster stars through several surveys of the Virgo Cluster’s intracluster planetary nebulae (see references in W07).

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2. The Metallicity Distribution of Intracluster Stars in Virgo

2.3 Data Acquisition

A deep Hubble Space Telescope (HST) photometric survey of an intracluster field of the Virgo Cluster was made by W07 in 2005. Figure 2.1 shows the location of the field targeted by the Advanced Camera for Surveys (ACS) superposed on a deep wide field image of the core of the Virgo cluster obtained by the Burrell Schmidt telescope by Mihos et al. (2005); see also the paper by Jared Feldman in this volume. The same field also serves as the basis for the study of intracluster globular clusters reviewed by Samuel Johnson Stoever in this volume. Candidate intracluster stars are indicated by open circles in Figure 2.2 which shows a closeup of a 1′ by 0′8 field near the center of the ACS field.

The ACS images were then used to create a V–I color magnitude diagram of the intracluster stars. These data were then used to determine the age and metallicity of the stellar population. Between May 30, 2005, and June 7, 2005, HST ACS images of a Virgo Cluster intracluster field were obtained as part of project GO 10131. These images were taken with the wide V band and standard I band filters. After the images were taken, they were combined together using a specially designed software pipeline. This program eliminated cosmic-ray events and geometric distortions from the dithered images. The resulting images covered an exposed area of 11.39 square arcminutes in two co-added photometric images.

Through visual examination of these images, astronomers discovered several interesting objects in the Virgo Cluster. The northeast region of the observed field revealed a previously undiscovered dwarf spheroidal galaxy (Durrell et al. 2007). As evident in Figure 2.2, the field also contains a large number of background galaxies, both resolved and unresolved. These background galaxies were then removed from the source catalogue by eliminating the objects with a second numerical fitting routine (W07).
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2.4 Results

As noted by W07, the Virgo Cluster extends considerably along the light of sight; the distances derived for its members range from 15 to 22 Mpc (W07). The strength of the break in the luminosity function of the Virgo Cluster suggests that about 70% of the stars in the observed intracluster field are at a distance of about 16 Mpc away. W07 point out that recently, cosmologists have predicted that although most intracluster stars have their origins in massive galaxies, a sizable fraction of the population comes from the dissolved remains of lower mass objects. The distribution of intracluster stars in the observed field is generally quite homogeneous (W07).

2.5 Age and Metallicity Distribution Analysis

The ability to determine the age of distribution of the Virgo Cluster is limited because the observations made by W07 do not reach the horizontal branch or main sequence turn off point. Younger stars generally populate the red giant branch differently than older objects, as they are usually bluer for the same metallicity. Virgo’s intracluster population is dominated by old, metal-poor stars.

W07 attempt to fit the observed CMD using a number of stellar population evolution models which fit separately for the age and metallicity of the underlying population. Their best-fitting model suggests that between 70% and 80% of the stars in the Virgo Cluster have ages greater than 10 Gyr. These stars have a median metallicity of [M/H]~ −1.3 and a mean metallicity of [M/H] ~ −1.0. The [M/H] ratio is a ratio of the amount of heavier metallic elements to the amount of hydrogen in the object. In addition, there is some evidence for the existence of a younger, metal-rich component. It can be concluded that Virgo’s intracluster population in the field is dominated by low-metallicity stars that are at least 10 Gyr old.

Most evidence suggests that Virgo’s intracluster component is not well mixed, as clumps of stars with similar metallicity properties have been found clustered together. This suggests that the intracluster stars in the Virgo Cluster do not come from a Population III source. In addition, the stars must have been predominantly formed...
inside galaxies and then later ejected out due to galaxy dynamics because the fraction of extremely metal-poor stars is low. Such evidence can be found in the form of ultra-deep surface photometry (Mihos et al. 2005), planetary nebula spectroscopy (Arnaboldi et al. 2004) and the W07 star counts.

2.6 Conclusions

W07 used the HST ACS to obtain deep images (in the V and I bands) of red giant stars in the intracluster space of Virgo about halfway between M86 and M87. They also found that the red giant branch of Virgo is much wider than can be explained by photometric errors through careful evaluation and subtraction of the galaxy background. Measurements indicate that there is a significant number of very metal-poor [M/H] \(< -1.5\) stars in the field. W07 also noticed that although [M/H] \(> -0.5\) stars appeared younger than the rest of the population, the metal-poor stars seemed to exhibit more spatial structure.

W07 found it intriguing that the Virgo Cluster has a dominant low metallicity component. It can then be argued that dwarf galaxies are an important source of intracluster stars. Nevertheless, larger galaxies might also contribute to the intracluster population because stars are expected to be ejected out from the outer, metal-poor regions of galaxies during tidal interactions.

It can be concluded that Virgo’s intracluster stars are not well mixed because of the wide range of metallicities seen in the data collected by W07. This range also suggests that the intracluster stars originate from many different galaxy types. With the results obtained from this survey, W07 hope to facilitate the development of the next generation of models for the dynamical evolution of galaxies in clusters.

2.7 References

3. On the Intracluster Globular Clusters of Virgo

Samuel Johnson Stoever

ABSTRACT In ‘Virgo’s Intracluster Globular Clusters as Seen by the Advanced Camera for Surveys’, Williams et al. (2007a; hereafter W07) report the finding of four possible intracluster globular clusters (IGCs) in a specific deep field view of the Virgo cluster via the Hubble Space Telescope’s Advanced Camera for Surveys (ACS). The ensuing analysis involves identifying metallicity, radial profile, and statistical relevance and comparing against assumptions. This review seeks to communicate the most important results of the analysis and the most interesting methods used in achieving these results.

3.1 Importance and Difficulties

The study of IGCs is essentially the study of the history of the matter of the associated clusters. As clusters evolve, it is thought that tidal interactions between galaxies will cause globular clusters to be expelled from these galaxies, where they then become independently evolving IGCs. These expelled globular clusters then become snapshots of the galaxy at the time and place of expulsion so that they offer great candidates for studies relating to the evolution of the cluster (e.g., matter distribution and tidal interactions). Using the present understanding of globular clusters, one can understand such properties as the chemical composition of the gasses that formed the globular cluster, via a thorough analysis of the globular cluster (W07, and references therein).

However, as useful as analyses of IGCs can be, they are extremely faint and hard to catalog. Because of this difficulty, IGCs have not been extensively been used as mentioned above, and are a great resource waiting to be exploited. The team of Williams et al. focused on a search for IGCs at 16.2 Mpc. At this distance, the IGCs would be resolvable by the ACM (with half-light radii of > 0.005). Additionally, using this distance, it may be possible to analyze individual stars within these Virgo IGCs (which would greatly help in determining such properties as age of the cluster).

3.2 Observations and Data Preparation

The observed intracluster field is located at a position of $\alpha, \delta(J2000) = (12^h28^m10^s80, +12^\circ33'20.0'')$ and at an orientation of 112.58\degree which is about 0.67\degree away from the closest fairly bright galaxy which corresponds to a distance of about 200 kpc at the adopted distance of 16.2 Mpc (W07) The ACS observations were based on F606W (corresponding to wide V-Band) with 26880 seconds of exposure time and F814W (corresponding to the I band) with 63440 seconds of exposure time. An image of this field with respect to the cluster is indicated in Figure 3.1; for a discussion of the deep imaging of central regions of the Virgo cluster by Mihos et al. (2005), see also the paper by Jared Feldman in this volume. For discussion of the analysis of intracluster stars in the the same field, see the contribution herein by Kristen Lau.

The collected data was then passed through a set of software programs that acted like filters (using photometry), first to find the likely most likely IGC candidates. The team used the filters to narrow down the possible IGCs to eight candidates. Four of these were then found to not have properties consistent with IGCs (e.g., three

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The images were then altered to account for extinction (with $E(B-V) = 0.025$), the reddening law of Cardelli, ACS filter transformations, and bolometric correction (with $BC_V \sim -0.5$ so that $BC_V = M_V - M_{bol}$ with an $M_{bol} = +4.74$). The team also used the typical value of $M/L_V = 2.3$ for the mass/luminosity ratio in order to estimate the masses for these clusters. In an attempt to determine if these objects are in fact IGCs, W07 analyzed the stars surrounding each of these objects and found evidence suggesting an abundance of red giants bound to each of these objects, which is indicative of the presence of an IGC. Additionally, the mean density of unresolved point sources surrounding each of the candidate IGCs (of F814W apparent magnitude, $m_{F814W} \leq 28.5$) suggests that, statistically, no more than one of these candidates could be a region with abnormally high stellar density superimposed over a much brighter object.

It is also possible that these candidates are instead elliptical galaxies, as their eccentricities are in fact much higher than a majority of globular clusters. The eccentricity of these objects, however, can be explained in terms of tidal interactions in the Virgo Cluster. Additional data obtained from the SDSS suggests that each of the candidates that appear on the survey are more blue than is expected of elliptical galaxies. Radial luminosity profiles also suggest that these objects are in fact IGCs, using either a radial model called the King model, or the deVaucouleurs’ profile given by the $r^{1/4}$ -law. With this in mind, W07 suggest that the only reasonable alternative classification for the candidate IGCs is that of a rare remnant core of a tidally stripped dwarf galaxy. However, this view also has a problem - the brightest of the candidates is more than a magnitude dimmer than what is taken to be a standard of the cores of tidally stripped dwarf galaxies, $\omega$ Cen. On the other hand, this classification is a tricky one, and these tidally stripped dwarf galaxies seem to very rare, so it’s hard to exclude that the candidates are in fact stripped dwarfs. The team finishes the discussion by pointing out that the fact that these objects appear at the peak of the luminosity profile for globular clusters, the most reasonable and likely situation is that these objects are indeed IGCs.
3.3 Physical Properties of the Candidates and Future Observations

Understanding the metallicity of IGCs can be a great asset to understanding the evolution of the cluster, as was mentioned above. The metallicity of each candidate was found by plotting the F606W–F814W color-magnitude diagram for the point-like sources within each candidate. IGC-4 was found to be the most metal rich of the four while still being relatively metal poor with comparison to other globular clusters. Both IGC-2 and IGC-3 were also found to be very metal poor. The team’s analysis of IGC-1 indicated an overabundance of background objects providing an error for its metallicity, and is still suspected to be somewhat metal poor. The team, however, uncovered an inconsistency (regarding reddening) between the integrated colors of IGC-1 and IGC-2 and their colors for their respective red giant star systems. One answer that the team suggested is that these two are in fact of intermediate metallicity - the inconsistency can then be explained by any number of effects, including the presence of a few relatively bright stars disrupting the analysis.

The team also suggests that, because these IGCs are bluer than one would expect, either the population of IGCs in the observed field are fundamentally different from those a great deal closer to the brightest galaxy clusters, or the four candidates chosen are simply not representative of standard IGCs in Virgo as a whole. The latter of these suggestions implies that a larger survey for IGCs is necessary. W07 proceeded to try to ascertain if the candidates were in fact possibly representative of IGC populations in Virgo. Although their analysis suggested that these four candidates likely represent the Virgo IGC population well, their analysis provided two warnings: that these clusters could possibly have been formed by a preferential stripping of GCs from their host galaxies, which would imply that those IGCs that were ejected from galaxies were in fact done so based on metallicity which could impact how much we can learn about Virgo from IGCs. The other caveat involves the way that certain types of globular clusters may not survive well outside of galaxies, which could influence the population in one way or another, again limiting what we can learn about Virgo from their IGCs.

Another important physical property to understand about these clusters is the radial profiles. The team suggests that the candidates exhibit similar profiles to those globular clusters in the Milky Way with large distances from the galactic center, confirming that the structure of globular clusters is greatly affected by the tidal forces,
which are stronger near galactic centers. The team also used the radial profile analysis to suggest the time since these clusters were ejected from their host galaxies. The premise is a simple one: given a cluster that was ejected and highly shaped by tidal forces, there is a minimum amount of time after which the cluster recovers and such tidal influences are not visible. W07 suggest that each of these IGC candidates have been free from their parent galaxies for a few Gyr.

W07, as was mentioned above, suggests that a wider area survey would be of great importance for this study. Not only would it help ascertain the statistical relevance of these candidates, but perhaps uncover stronger data to help understand the evolution of the Virgo Cluster.

3.4 References


Ian Waters¹

ABSTRACT In their investigation, van Zee, Skillman, & Haynes (2004; hereafter vZSH04) have found rotationally supported dwarf elliptical galaxies in the Virgo Cluster. Typical velocity dispersions for surveyed galaxies in Virgo are $44 \pm 5$ km s$^{-1}$, which indicates that rotation can be a large part of the dynamics of dwarf elliptical galaxies (dEs) in the Virgo cluster (vZSH04). The authors also note that the rotation of dEs is comparable to the rotation of similar brightness dwarf irregular galaxies (dIs), and through this relationship, propose that some, if not most, dEs are formed when dIs are stripped of their gas in a high density environment.

4.1 Introduction

Even though they are the most plentiful structure in the local universe, the evolution and formation of dEs is still a relative mystery. Despite sharing their morphology with giant elliptical galaxies, due to their light distribution, vZSH04 state that it is clear that they are not simply low mass elliptical galaxies as hypothesized by others. Due to the tendency of dEs to be found in high density regions, vZSH04 suggest that the environment has some effect on the evolution of these structures. Their paper seeks to explain the relationship between dEs and dIs established in the literature (see references in vZSH04), and in so doing, link the formation of dEs to the conditions inside dense cluster regions and near large galaxies. The authors claim that ram pressure stripping by the intergalactic medium (IGM) or intra-cluster medium (ICM) would explain the evolution of a dE from a dI. However, vZSH04 point out that previous studies found no kinematic link between dEs and dIs, a fact that would be essential to proving this progression. The new observations of vZSH04 suggest that some dEs do have a rotational component of motion, much like their irregular cousins. This new evidence supports an evolutionary link between the two types of dwarf galaxies.

4.2 Observations

For their survey, vZSH04 chose 16 dEs within the Virgo cluster at a distance of approximately 16.1 Mpc. To choose the samples, they went to the Virgo Cluster Catalog (VCC, Binggeli et al. 1985) and selected galaxies based on their apparent magnitude ($m_b < 15.5$), morphological classification (dE) and on their apparent ellipticity ($\epsilon > 0.25$). To obtain the high resolution spectral images for the survey, the Double Spectrograph on the 5m Palomar telescope was used, with each galaxy observed with multiple 1200s exposures (vZSH04).

To obtain kinematic data for the sample galaxies, multiple techniques were used. Both Gaussian fits, used to provide a rough base line, and Fourier analysis were used to obtain velocity measurements, and find rotation profiles. A set of the the rotation curves and velocity dispersion profiles is illustrated in Figure 4.1. The analysis yielded rotation curves with a radius of about 1.56 kpc, and upon finding these curves, it was found that of the 16 dEs selected, 7 showed evidence of a velocity gradient.

Five of the galaxies surveyed were also surveyed in Geha et al. (2003), but vZSH04 found rotational velocities greater than those reported by those authors. However, this can be explained by the larger radii of rotation that were traced in vZSH04 compared to Geha et al. (2003). Table 4.1 provides the kinematic information

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for the observed galaxies including: rotational velocities $V_{\text{rot}}$, derived from the rotation curves, $\sigma_0$, the velocity dispersion of the central 2\arcsec of the galaxy, and $\sigma_m$, the average velocity dispersion of each galaxy.

vZSH04 have determined that five of the dEs in the Virgo cluster have significant rotational components. They point out that while this contradicts studies of the past, it is consistent with several more recent studies (see references in vZSH04) which found dEs with a rotational component to their motion. This isn’t entirely unexpected; unlike their larger cousins, which retain a morphological distinction when stripped of their gas by the ICM, dwarf galaxies are characterized by their appearance, which is in turn characterized by their star formation. If a dwarf galaxy has had its gas stripped and is no longer producing stars, it is far more likely to be classified as a dE (vZSH04).

One issue that arose in their analysis was that the dEs analyzed had only stellar rotation curves, whereas the dIs they were being compared to had large gaseous components, and it cannot be assumed that the two are coupled (vZSH04). To convert from stellar to neutral gas rotation widths, the authors went back to the observations dIs of van Zee et al. (1997) and van Zee (2001). By comparing the maximum velocity, and the slope of the rotation curve, as listed in Table 4.1, the authors were able to derive rotation curves out to 2.45 scale lengths, far greater than the observed 1–1.5 scale lengths (vZSH04). The scale length is a component of the exponential function describing the brightness of a galaxy. It is defined as the distance over which the brightness of an object decreases by a factor of 1/e. The resulting figure illustrated in Figure 4.2 indicates that the observed stellar rotation curves underestimate the actual kinematics of the galaxies (vZSH04); the velocities fit better on the standard Tully-Fisher relation when the rotation curves are extrapolated out to the larger radius.
One of the questions that astronomers are seeking to answer about dwarf galaxy evolution is why dEs and dIs are so similar. When looking at the two side by side, the stellar content and morphology are almost identical; the only significant differences are gas content and current star formation (vZSH04). Until these new observations into the Virgo cluster will be stripped of their gas. Due to the presence of dark matter, this stripping would relationship of dEs, the vZSH04 suggest that the environment plays a role in the development of dEs in the form of ram pressure stripping. They point out that the literature has shown that nearly all low mass dIs falling the possible evolutionary tracks of these galaxies were restricted by the lack of a kinematic link. But, this new work reopens the possibility that at least some dEs evolved from dIs.

As discussed by vZSH04, one of the two evolutionary scenarios that have been proposed is that the progenitor dI galaxy lacked the mass necessary to retain its gas during a star formation episode. As they note, supernovae are cited as the cause of the loss of gas in this scenario. However, they also point out that recent studies of several dwarf spheroid galaxies suggest that low mass galaxies are able to retain gas through multiple star burst periods. In another proposed scenario, ram pressure stripping is the culprit. Due to the morphology-density relationship of dEs, the vZSH04 suggest that the environment plays a role in the development of dEs in the form of this ram pressure stripping. They point out that the literature has shown that nearly all low mass dIs falling into the Virgo cluster will be stripped of their gas. Due to the presence of dark matter, this stripping would have a minimal effect on the kinematics of the dI. The resulting object would then most likely be classified as a dE. Tidal effects are then stated as a possible reason for the presence of non-rotating dEs, showing that the presence of non-rotating dEs is not detrimental to this evolutionary model (vZSH04).

### 4.3 Evolution Scenarios

One of the two evolutionary scenarios that have been proposed is that the progenitor dI galaxy lacked the mass necessary to retain its gas during a star formation episode. As they note, supernovae are cited as the cause of the loss of gas in this scenario. However, they also point out that recent studies of several dwarf spheroid galaxies suggest that low mass galaxies are able to retain gas through multiple star burst periods. In another proposed scenario, ram pressure stripping is the culprit. Due to the morphology-density relationship of dEs, the vZSH04 suggest that the environment plays a role in the development of dEs in the form of this ram pressure stripping. They point out that the literature has shown that nearly all low mass dIs falling into the Virgo cluster will be stripped of their gas. Due to the presence of dark matter, this stripping would have a minimal effect on the kinematics of the dI. The resulting object would then most likely be classified as a dE. Tidal effects are then stated as a possible reason for the presence of non-rotating dEs, showing that the presence of non-rotating dEs is not detrimental to this evolutionary model (vZSH04).

### 4.4 Conclusions

In their investigation, VZSH04 have given new life to the possibility that dEs may be the result of dIs encountering a dense region of space and being stripped of their gas. As evidence, they point to the morphological similarities presented in the literature, and observed kinematic similarities. The rotational velocities, observed
in several Virgo Cluster dEs, suggest that dEs evolved from dIs through ram pressure stripping of their gaseous component.

4.5 References


5. Internal Properties and the Nature of Virgo Ultracompact Dwarf Galaxies

Min Kang

ABSTRACT Recently, a new class of small, high surface brightness stellar systems have been found in the Fornax and Virgo clusters. Evstigneeva et al. (2007; hereafter E07) use different models and examine the internal properties of a subset of these “ultracompact dwarfs” (UCDs) to determine their true nature as galaxies or star clusters. Even though UCDs have characters that lie between both globular clusters (GCs) and dwarf ellipticals, E07 argue that UCDs may be brighter GCs at the end of their evolution. Determining the nature of UCDs may provide a more definite picture of GC evolution and formation.

5.1 Introduction

A new class of stellar system has been discovered recently in the Fornax and Virgo galaxy clusters. Ultracompact dwarf galaxies (UCDs) have some characteristics of both large globular clusters and small elliptical dwarf galaxies. Astronomers have come up with formation hypotheses that give them their intermediate nature. In a recent paper, E07 take a look at the six brightest UCDs in the Virgo cluster. E07 compare their observations of UCDs to various fitting models and analyze their mass, metallicity, and velocity dispersion. Also the UCDs are compared to already known stars and other structures in the cluster to determine their internal properties. The authors propose a possible solution to the “Missing Satellite Problem” as well as a possible explanation of what UCDs could actually be.

5.2 Discovery and Formation Hypotheses

Figure 5.1, from E07, shows that GCs and dwarf galaxies are morphologically different from UCDs. In Figure 5.1, E07 plot the absolute magnitude (luminosity) versus central velocity dispersion $σ_0$ for globular clusters, dwarf elliptical galaxies and UCDs, identifying each type of object by different symbols in the diagram. Both Fornax and Virgo UCDs are more luminous than GCs yet much dimmer than dwarf ellipticals. UCDs were first discovered in the Fornax cluster in 2003 during an all-object survey designed to gather more data on dwarf galaxies. Having absolute magnitudes of $-14$ to $-11$, Fornax UCDs were originally thought to be galaxies. Due to their intermediate nature, most UCD formation hypotheses pertain to GCs and dwarf galaxies (Drinkwater et al. 2003). According to E07, UCDs could be super-massive and highly luminous GCs or highly compact and low-luminosity dwarf elliptical galaxies. They are also believed to have formed by merging of galaxies or primordial objects or by the tidal disruption of nucleated dwarf elliptical galaxies. E07 examine the possibility of UCDs being GCs or dwarf ellipticals.

5.3 Observational Tests for the Formation Hypotheses: Data Fitting

It is nearly impossible to test the formation hypotheses separately – neither does the UCDs all give separate results nor gives enough information. E07 mainly concentrate on UCDs internal properties, such as their

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5. Internal Properties and the Nature of Virgo Ultracompact Dwarf Galaxies

5.4 Interpretation of the Data-fitted Values

As is shown in Table 5.3, the correlation between the adopted simple models and the actual radial light profiles obtained from the images is very weak. This reflects the difficulty faced when detecting this new class of dwarfs. Many UCDs are hard to detect due to their low luminosity. Even the brightest UCDs are shrouded by the uncertain boundaries among different classes of stellar systems. Even though the deep-field imaging of the Fornax and Virgo clusters and the use of GALFIT model show that UCDs are not just dwarf galaxies with
TABLE 5.1. Structural Parameters Derived from the Light Profiles for Seven Virgo UCDs.

<table>
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<tr>
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<th>VUCD 3</th>
<th>VUCD 4</th>
<th>VUCD 5</th>
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<th>VUCD 7 Halo</th>
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</table>

The first line of each entry represents the goodness-of-fit ($\chi^2$) for the models and the images. All parameters are the mean of the two passbands, V and I. From Table 8 of E07.

their outer part gravitationally torn away, the lack of definite evidence makes it hard to determine their unique nature.
5.5 Mass/Luminosity Ratio and Metallicity

Still with the possibility of UCDs being very young GCs, the mass/luminosity (M/L) ratio could tell a great deal about their internal structure. In particular, the M/L ratio gives a possible inkling of existence of dark matter. E07 claim that theories regarding UCDs origin may be tested with this ratio. For instance, if a UCD had been formed in a dark matter halo, it would still have some dark matter. However, it is not as simple as it sounds: high M/L ratio, resulting from existence of dark matter, can also be caused by tidally disturbed systems. This uncertainty in the M/L values reflects the age and metallicity ranges of UCDs. As E07 show, the Virgo UCDs have relatively low metallicity ranges, resulting in low M/L ratios. Consequently, this proves that the Virgo UCDs do not require dark matter in their central regions, but this does not prove that dark matter does not exist further out.

5.6 Interpretation of M/L Ratio and the Dark Matter The Missing Satellite Problem

By questioning the existence of dark matter in the UCDs, E07 provide a possible solution to the Missing Satellite Problem. The problem describes the discrepancy between the number of extremely small galaxies predicted to be around the Milky Way and the number actually observed. The observation only explains less than ten percent of the predicted value. Although the Virgo UCDs do not require dark matter, the existence of dark matter in UCDs has become one of the possible solutions to the problem (along with changing the character of inflation and changing the character of the dark matter itself).

5.7 UCDs Internal Properties and Their Importance

According to their metallicity ranges and the red absorption line spectra, the Virgo UCDs are very old (shown by their low metallicity) (Jones et al. 2006). Also the determination of their real masses of about $(2 - 9) \times 10^7 \, M_\odot$ shows that it is highly possible that they are indeed very young globular clusters. In other words, the measurements of the internal UCD properties, such as the age, metallicity, the abundance of UCDs, and the outer properties, such as the surface brightness, are very similar to those of the brighter GCs. The evolutionary path of young GCs can be the key to determining the properties of UCDs. If the Virgo UCDs are indeed GCs, the young GCs will obtain the UCDs’ parameters and masses as they grow old. If so, it may be possible to deduce the formation epoch and history of GCs by more closely examining the UCDs according to E07.

5.8 Summary and Conclusion

E07 explain their method of analyzing and interpreting the observed data of newly discovered UCDs. The GALFIT model is used to take the images apart and to attempt to understand the internal properties and the make-up of the Virgo UCDs. They conclude that UCDs are morphologically closer to GCs than elliptical dwarf galaxies. Many of the UCDs properties – age, metallicity, mass – indicate they are similar to the brightest GCs. Furthermore, M/L ratios predict that there need not be any dark matter in the UCDs. However, with the possibility of there being dark matter, UCDs are considered a possible alternate solution to the Missing Satellite Problem.
5.9 References


6. VCC 2062 and the Case for Tidal Dwarf Galaxies in the Virgo Cluster

Stephen Demjanenko

ABSTRACT While numerical simulations predict the existence of old Tidal Dwarf Galaxies (TDGs) which have survived long after their creation, finding old galaxies with a tidal origin is challenging. As shown by Duc et al. (2007; hereafter D07), VCC 2062 is a prime candidate for being an old TDG which managed to survive in a tidally active environment. Specifically, VCC 2062 has many indicators suggesting that it is recycled such as a strong CO emission, high metallicity and a high oxygen abundance which support the old TDG theory. Competing theories such as an origin as a low-surface brightness spiral or a pre-existing dwarf bring up serious contradictions in observations. D07 argue that VCC 2062 was probably formed in a pre-enriched HI tail expelled from NGC 4694 during a tidal interaction. Since the parents have already merged, if this scenario is correct, VCC 2062 is an old TDG.

6.1 Introduction

According to standard cosmological models significantly more satellite galaxies are predicted than observed for the Andromeda and Milky Way Galaxies. According to Bournaud & Duc (2006), current cosmological models do not account for second generation (recycled) galaxies which are formed during galactic collisions. According to their numerical simulations, a significant proportion of Tidal Dwarf Galaxies (TDGs), which form from tidally expelled material during galaxy mergers, survive to contribute to the satellite populations around massive galaxies.

While the formation of tidal tails between gravitationally interacting objects is well known, only young TDGs have been identified due to the presence of tidal arms bridging to the parent galaxies. Over a period of 0.5–1 Gyr these bridges disappear making identification of old TDGs difficult. In general, TDGs have a high metallicity inherited from a parent galaxy and an absence of dark matter. These observations can only be made for nearby galaxies, such as those in the Virgo Cluster.

While there are several candidate TDGs such as the Antennae system (NGC 4038/39) as studied by Mirabel et al. (1992), VCC 2062 in the Virgo Cluster will be the main subject of the discussion. Overall, the Virgo Cluster does not contain many tidally interacting systems. While several systems of molecular clouds, HII regions and HI clouds have been observed, none have had the time to form significant stellar populations and were not included in the Virgo Cluster Catalog (VCC) by Binggeli et al. 1985. One exception is VCC 2062 which has properties that suggest it is composed of recycled material. The rest of this paper will provide additional data, such as metallicity and CO emission, to prove its origin.

6.2 Observations, Data Reduction and Analysis

The Very Large Array (VLA) was used to image the region around NGC 4694 and VCC 2062 in the 21 cm HI line as part of the VLA Imaging of Virgo galaxies in Atomic gas (VIVA) survey (Chung et al. 2007). For their analysis, D07 retrieved the VIVA survey VLA map from the NRAO database archive and reprocessed it. The HI distribution is shown in blue in Figure 6.1 superposed on an optical image. The far-ultraviolet (FUV)
emission obtained from the GALEX satellite is superposed in red; FUV emission maps regions of recent star formation. The HI distribution shows a clear connection between NGC 4694 and VCC 2062 (the “bridge”); the HI associated with VCC 2062 also appears to be extended in the direction away from NGC 4694 (the “tail”).

FIGURE 6.1. VLA map of NGC 4694 (left) and VCC 2062 (right). The HI gas is shown in blue and is superimposed on the optical image. A GALEX-FUV emission is overlaid in red to track recent star formation. The overall field of view is $9' \times 6'$. From D07.

FIGURE 6.2. Selected spectra of CO(1-0) (red lines) and HI (cyan lines) along the main body of the HI (blue image) associated with VCC 2062 and HI/SW. The CO emission suggests a high metallicity for the tail shown here. In particular, the highest metallicity is determined to be in the upper left portion of this view, where VCC 2062 is located. From D07.
The metal abundance is indicated by the derived abundance of oxygen relative to hydrogen. VCC 2062 is indicated by the red square (top right), which appears to have a significantly higher metallicity for its luminosity than predicted by the mean relation defined by nearby dwarf irregular galaxies (dashed line). These data suggest that VCC 2062 inherited its high metallicity from a more luminous parent galaxy, such as NGC 4694. From D07.

CO(1-0) and CO(2-1) molecular lines were detected with the IRAM 30 m telescope in the densest regions in the HI tail including the gaseous condensation to the South-West of VCC 2062 given the name HI/SW. Figure 6.2 shows a comparison of the HI and CO(1-0) spectra obtained at selected positions along the body of the HI. The CO map showed a strong signal from VCC 2062 which suggests a high metallicity. The CO intensity trends toward $1 \text{ K km s}^{-1}$ which is typical for normal late-type galaxies in Virgo and unexpectedly strong for an early type dwarf.

Optical spectroscopy of HII regions also suggests a high metallicity in the tail containing VCC 2062. Observations of nearby dwarf galaxies have shown that there is a relatively well defined relationship between optical luminosity (absolute magnitude) and metallicity (as indicated by the abundance of oxygen relative to hydrogen): lower luminosity galaxies have lower oxygen abundances. As illustrated in Figure 6.3, VCC 2062 appears to deviate from this relationship; it has a higher metallicity for its luminosity. This suggests that the material in VCC 2062 also has a high metallicity, an observation which suggests it is a TDG and not a dwarf irregular galaxy which are generally metal-poor. Based on theory, the higher metallicity came from material once part of a massive parent galaxy out of which VCC 2062 formed.

6.3 Results

VCC 2062 is in the outskirts of the Virgo Cluster, 4° (1.1 Mpc) to the east of the M87 core. Lying at the same redshift (1175 km s$^{-1}$), NGC 4694 appears to connect to VCC 2062 by an HI bridge, as evident in 6.1). At the Virgo distance, the bridge measures 38 kpc in length. In the HI/SW region of the tail, however, VCC 2062 has no significant optical counterpart, as seen in Figure 6.4. That figure illustrates the location of sites of active massive star formation as traced by H$\alpha$ and the distribution of HI gas relative to the optical object. While an absolute blue magnitude of $-13.0$ puts VCC 2062 in the dwarf category, it also suggests a slow but active star formation. In general, dwarf ellipticals have rates indicating low/no star formation.

The HI spectral data can also be used to trace the kinematics of the gas in and around the tail. As evident in the position-velocity diagram shown in Figure 6.5, VCC 2062 has significantly unique rotational velocities in
the tail which suggests it is gravitationally bound.

Measurements of the mass of VCC 2062 derived from the HI spectra had previously led to a wide range of mass estimates. D07 only include the gravitationally bound HI, a mass which shows a velocity gradient of 42 km s\(^{-1}\) over 4.2 kpc. The total luminous mass accounts for one half to one third of the mass of VCC 2062. Compared to normal dwarf galaxies, VCC 2062 has a low \(M_{\text{dyn}}/M_{\text{vis}}\) where \(M_{\text{dyn}}\) is the total mass and \(M_{\text{vis}}\) is the visible mass. The low abundance of dark matter is one of the theoretical properties of TDGs.

6.4 Discussion

VCC 2062 is an outsider in the dwarf galaxy population in the Virgo Cluster. It has a complex HI structure, a high metallicity and a low proportion of dark matter when compared to the average dwarf galaxy in the Virgo Cluster. D07 examine whether VCC 2062 was a pre-existing dwarf galaxy, a low surface brightness galaxy which underwent tidal disruption or a recycled galaxy.

If VCC 2062 was a pre-existing dwarf, its HI content is unlikely to have been there when it formed. The mass of VCC 2062 would not have been able to steal gas from larger galaxies. The mass-to-light ratio is also much too low to support this theory. The oxygen abundance in VCC 2062 is significantly higher than dwarfs of similar luminosity. It is unlikely that VCC 2062 is a pre-existing dwarf galaxy.

Could VCC 2062 have been the remnant of a massive, metal rich object, like a spiral galaxy, which underwent severe tidal disruptions? There are examples of the formation of large tails. In this case, for VCC 2062 to have low luminosity it must be a low-surface brightness spiral. However, the dynamical mass calculated from the rotational curves of VCC 2062 is much too low for this scenario. The dark matter does not readily separate from a galaxy which suggests VCC 2062 started with very little. The lack of dark matter contradicts the theory that VCC 2062 is a remnant of a large galaxy.

D07 argue that since all of the above models have serious flaws, the case for VCC 2062 as a recycled galaxy is the most obvious origin. In this model NGC 4694 would be the parent since it is linked to VCC 2062 by a HI bridge which may have formed from ram pressure of tidal interactions in a previous merger. Once in the
intracluster medium, the matter in the tail could collapse to form dwarf galaxies. While ram pressure could have caused the tail, D07 argue that the Intra-Cluster Medium (ICM) is not dense enough to form such a large tail. The structure of the tail from NGC 4694 does not suggest it was formed by ram pressure stripping.

Thus arises the argument by D07 for a tidal origin for the tail, and the formation of VCC 2062. While high-speed collisions and mergers create signs of severe galaxy harassment, D07 argue NGC 4694’s tail was created by a slow merger. Since there are no major galaxies near NGC 4694, it must be an old merger. Signs of disturbance within the galaxy support this model. A merger of NGC 4694 and a galaxy one-fifth its mass would be at the limit for creating the tail and leaving NGC 4694’s disk structure intact. The merger might have been an accretion of the smaller galaxy, instead of a direct collision. Either way, according to D07, a tidal origin for the tail, and hence the formation of VCC 2062, is the most acceptable solution.

6.5 Conclusion

D07 presented an analysis of the ICM near NGC 4694 which shows a HI tail containing VCC 2062. VCC 2062 is considered separate from the tail since it is kinematically detached. Through careful observation, it has been determined that VCC 2062 differs significantly from other dwarf irregular galaxies in the Virgo Cluster. VCC 2062 has a high metallicity and a strong CO signal which suggest VCC 2062 was pre-enriched, rather than enriched because of its low mass, with material from a larger galaxy. D07 argue the best hypothesis of the formation of VCC 2062 is that the galaxy is a recycled object formed after the gravitational collapse to ejected matter, expelled as a result of tidal interaction. While most TDGs can only be detected in their infancy, VCC 2062 is several hundred million years old since the parent galaxies have already merged. Compared to other candidate TDGs, VCC 2062 is ancient and yet close enough to make accurate observations for this class of object.

6.6 References

6. VCC 2062 and the Case for Tidal Dwarf Galaxies in the Virgo Cluster


7. The Globular Cluster System of the Virgo Dwarf Elliptical Galaxy VCC 1087

Jae Hwan Kang

ABSTRACT Beasley et al. (2006; B06) explored the evolution of a dwarf elliptical galaxy in a cluster environment by analyzing photometric and spectroscopic data of the globular cluster (GC) system of the dwarf elliptical galaxy VCC 1087 in the Virgo Cluster. They estimate the total population of 77 ± 19 GCs belonging to VCC 1087, which gives the specific frequency (S_N) of 5.8 ± 1.4 for this galaxy. Through spectroscopy of 12 GCs, they examine several traits of this GC system such as rotation, velocity dispersion, age, metallicity, and mass to light ratio. This GC system's significant rotation implies that the progenitor of VCC 1087 was a spiral galaxy. Finally, in the context of galaxy harassment scenario, B06 conclude that this galaxy might have come from a Sc spiral galaxy that has been faded and tidally perturbed in the cluster environment. The S_N and the significant rotation of the system serve as the two main clues to their reasoning.

7.1 Introduction

In their paper, B06 examine the GC system of the Virgo Cluster dE galaxy VCC 1087 by photometric and spectroscopic analysis. Dwarf elliptical (dE) galaxies constitute the dominant galaxy population in galaxy clusters (Binggeli et al. 1988). They subdivide into those with nuclei (dE,N) and those without nuclei (dE,noN) and also into rotating and non-rotating ones. VCC 1087 is a rotating dE,N. According to Conselice (2004), there are three observational constraints that formation scenarios for dEs must satisfy. First, dEs are found mostly in the highest density regions. Second, while some dEs are dominated by random stellar motions, some show significant rotation; for a discussion of rotational velocities in Virgo dEs, see the paper by Ian Waters in this volume. Lastly, dEs exhibit a range of stellar population mixes, harboring old, metal-poor stars, or young, metal-rich stars, or both. As discussed by B06, there are currently supported two possible models of dE formation. First, dEs could have been formed initially in cluster regions with their further growth halted by reionization. Second, dEs could have been formed be originally as spiral or irregular galaxies and then morphologically transformed by interactions in the cluster environment.

B06 note that because GCs normally consist of the oldest stellar populations, they are bound tightly to their parent galaxies and therefore should resist strongly against tidal effects. In addition, GCs are easily separated from the galaxy background thanks to their great luminosity and compact nature. Also, the number of GCs in the system gives a useful parameter. The specific frequency (S_N) is the standard measure used to characterize the globular cluster population. Since large (more luminous) galaxies would be expected to have more globular clusters simply by scaling laws, the S_N metric attempts a normalization of the GC count by parent galaxy luminosity; S_N then is defined as the number of GCs in a galaxy per unit luminosity. The standard absolute magnitude for the normalization is M_V = -15 in the visual band. If N_t is the total number of globular clusters in a galaxy and L_V is the galaxy’s luminosity, then the S_N is given by:

\[ S_N = N_t \frac{L_{15}}{L_V} = N_t 10^{0.4(M_v+15)} \]  (7.1)

Observations have shown that the average value of SN is larger for earlier type galaxies. For Sc galaxies S_N is in the range of 0.5 ± 0.2. For Sa and Sb galaxies, it is 1.2 ± 0.2 (Carroll & Ostlie 1996). For ellipticals, S_N, it is typically higher.

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FIGURE 7.1. HST ACS $g_{475}$ image of VCC 1087. GC candidates are indicated by small circles, and those we have spectra are double circled. The bright nucleus of the galaxy can be seen in the center of VCC 1087. From B06.

7.2 The Data

7.2.1 Imaging

B06 obtained images of VCC 1087 and its GC system from Sloan-type g-band ($g_{475}$) and z-band ($z_{850}$) wide-field images taken with the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) as part of the ACS Virgo Cluster Survey (Cote et al. 2004). They processed those images through the standard ACS pipeline. On the ACS images, they identified GCs as round, compact objects by distinguishing them from other objects using shape, color, and size information. Candidate GCs are shown in the Figure 7.1 by small blue circles. B06 originally detected 68 GCs. However, faint GCs are hard to detect, and the field used by B06 does not cover an exhaustive region. After considering the uncertainties in the number of GCs caused by background galaxies, they derive a final number of $77 \pm 19$ GCs. Adopting the absolute magnitude of -17.8 for VCC 1087 (Jerjen et al. 2004), they obtain a specific frequency $S_N$ of $5.8 \pm 1.4$.

7.2.2 Spectroscopy

B06 obtained optical spectra for 12 GC candidates identified from the $g_{475}$ and $z_{850}$ HST ACS images during April 24-25 2004, using the Keck I telescope. Those GCs that were analyzed through spectroscopy are circled as red (or double circled) in Figure 7.1. All science images went through the standard image processing before they were analyzed.
7. The Globular Cluster System of the Virgo Dwarf Elliptical Galaxy VCC 1087

7.3 Analysis

7.3.1 Photometric Properties of the GC System

As evident in Figure 7.1, the GCs are distributed mainly toward the center of the galaxy and elongated in the northeast-southwest direction. B06 found that the envelope of the galaxy is not very much redder than its nucleus. In the color-magnitude distribution for the confirmed and candidate GCs, there is a blue peak and a tail of red. The blue peak indicates metal-poor clusters (MPCs), and the tail of red indicates metal-rich clusters (MRCs). This shows that the GC system of VCC 1087 consists mostly of MPCs, not unlike the Milky Way.

7.3.2 Kinematics

B06 obtain the velocity for the GC system of $686 \pm 24$ km s$^{-1}$, consistent with the observed systemic recessional velocity of the galaxy itself of $646 \pm 30$ km s$^{-1}$; the identified GC candidates shown in Figure 7.1 really are globular clusters in VCC 1087. They have found that the GCs show the most significant rotation at the position angle (P.A., measured east through north) of $127^\circ \pm 8^\circ$. The outermost GC at this P.A. has the velocity of $104 \pm 35$ km s$^{-1}$.

A useful measure of the importance of rotational motion to the dynamical state of a system of particles is the ratio of the rotational velocity $V$ to the velocity dispersion $\sigma$ due to random motions, $V/\sigma$. Simple dynamical models can predict how much a spheroid will be be flatted to ellipticity $\epsilon$ by rotation. Figure 7.2 compares the value of $V/\sigma$ measured by B06 for the GC system of VCC 1087 to values measured for GC systems in other galaxies. As evident in the Figure, VCC 1087 has a higher value for its ellipticity than other GC systems. In the GC systems of other elliptical and S0 galaxies, velocity dispersion dominates rotation. In contrast, for the two dE galaxies located on the upper-half of the plot, rotation becomes important. From observations we know that random motion is dominant in elliptical galaxies, and that rotational motion is dominant in spiral galaxies.
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7.3.3 Ages and Abundances

From analysis of the spectral properties of the GCs, B06 conclude that the GCs in VCC 1087 are generally old (\(\sim 10\) Gyr) MPCs and about the same ages. However, the galaxy star light is more metal-rich and appears to be younger (\(\sim 4\) Gyr). The scenario of the history of VCC 1087 in the Virgo Cluster must account for these traits.

7.4 Discussion

B06 note that for an adopted absolute magnitude of VCC 1087 is \(-17.8\), VCC 1087 falls into the bright end of the luminosity function for dEs. Since this one object cannot necessarily be generalized to a class, B06 discuss its properties in the context of dE galaxy formation. As discussed by B06 (see references therein), previous authors have have showed via numerical simulations that spiral galaxies can be transformed into spheroidal galaxies in the cluster environment. This process by which a galaxy is deformed in a galaxy cluster by gravitational interactions is called galaxy harassment.

B06 obtain two significant traits of VCC 1087 that support the galaxy harassment scenario. First, B06 estimate 77 ± 19 GCs in VCC 1087, giving a globular cluster specific frequency \(S_N = 5.8 \pm 1.4\). This value of the specific frequency is much higher than the typical value of \(S_N \sim 1\) for late type spiral galaxies (Carroll & Ostlie 1996). From Equation 7.1, we can see that in order to carry \(\sim 80\) GCs with \(S_N = 1\), the absolute magnitude in the visible band should be \(M_V \sim -19.8\). Hence, if the progenitor of VCC 1087 was a spiral galaxy, it must have lost some of its luminosity. This loss of luminosity can be achieved through interactions of the galaxy with the cluster environment. If a spiral galaxy fell into the Virgo Cluster, and lost its gas through ram pressure stripping or its stars were dispersed through galaxy harassment as in the simulations of Moore et al. (1998), it could fade by 1–2 mag in the visible band. Because GCs might also be stripped also, therefore lowering the \(S_N\), a faded but once very bright Sc spiral galaxy could have the \(S_N\) of VCC 1087 today. In addition, to be strongly affected by galaxy harassment so that the fading in luminosity was significant, the parent galaxy would have had to be a pure disk system (Moore et al. 1998), because dense spiral bulges are less susceptible to harassment. Second, B06 measured the dominant rotational motion in the GC system of VCC 1087. Since normal elliptical galaxies show random motions with low ratios (\(V/\sigma\), the large rotational component seen in the GC system of VCC 1087 supports the idea that its progenitor might be a spiral galaxy.

Consequently, B06 constructed a plausible evolutionary scenario for VCC 1087 as follows. Five Gyr ago, a Sc spiral with \(M_V \sim -20\) carrying about 100 GCs fell into the Virgo Cluster. Ram pressure stripped a great amount of gas from the galaxy, preventing further star formation. Subsequently the galaxy faded by \(\sim 1.5\) mag. Interacting with cluster members, its disk was disrupted. The galaxy lost some field stars and GCs during this period. Some gas staying in the galaxy would lose angular momentum and fall onto central regions creating stars and a solar metallicity nucleus of \(\sim 4\) Gyr old. This event resulted in the appearance of VCC 1087 as we see it today.

7.5 References


8. A Large HI Cloud near the Center of the Virgo Cluster

Jennifer Burt

ABSTRACT Oosterloo & Van Gorkom (2005; OVG05) discuss their analysis of a large (110 × 25 kpc in size and containing $3.4 \times 10^8 M_\odot$ of HI) HI cloud in the central region of the Virgo Cluster. By examining the morphology and kinematics of the cloud, they deduce that the cloud was most likely formed from gas removed from the nearby NGC 4388 galaxy by ram pressure stripping. This ram pressure stripping is most likely due to the ISM (Interstellar Medium) of NGC 4388 reacting with the hot halo of galaxy group M 86 as opposed to its interaction with the ICM (Intra-cluster Medium) centered on galaxy M 87 as previously thought. Analysis of the size and density of the cloud lead to the hypotheses that gas stripped from galaxies in a cluster can remain neutral for up to $10^8$ years. The existence of this HI cloud implies that ram pressure stripping of infalling spiral galaxies contributes to the enrichment of the ICM.

8.1 Introduction

It is a well-recognized fact that the high galaxy density of clusters forms a hostile environment for galaxies because it leads to frequent interactions that result in strong affects and transformations. In addition, because cluster galaxies travel at high speeds through the ICM, they experience ram pressure stripping (OVG05). That is, as they orbit the center of the cluster the gas within the galaxy interacts with the hot x-ray emitting gas of the ICM and the galaxy’s gas is stripped away in a process that can dramatically alter the evolutionary history of the galaxy. One very obvious demonstration of this is seen in the fact that many cluster spirals contain less neutral hydrogen than expected for their type and luminosity (see references in OVG05). Using H I imaging it has been discovered that the H I disks of such galaxies often cut off well inside the optical disk (see references in OVG05).

OVG05 note that, despite studies, both theoretical and observational, of the events that cause this removal of gases (i.e. ram pressure stripping and tidal forces), there are many unanswered questions about the process. Unknown factors, such as the galaxy’s exact path through the cluster, mean astronomers have to guess when and where during the galaxy’s existence the stripping occurred. Even more hypothetical is the fate of the gas once it is pulled out of the galaxy. A prime candidate for study, in an attempt to answer these questions, is the NGC 4388 spiral galaxy in Virgo, which, is moving at a rate of at least 1500 km s$^{-1}$ and has lost approximately 85% of its H I. Previous studies of this galaxy are summarized in detail in OVG05 to which the reader is referred. The galaxy has an HI disk truncated to well within its optical range and a large plume of ionised gas, visible in Hα, extending 35 kpc off the galactic plane to the NE. Taken together with the fact that there are observable soft X-ray emissions out to 16 kpc and evidence for neutral gas out to at least 20 kpc NE of NGC 4388 with an HI mass of $6 \times 10^7 M_\odot$. OVG05 point out that these observations indicate that NGC 4388 is strongly affected by its movement through the cluster. The cause of this gas plume is unknown; suggestions include ram pressure stripping, nuclear outflow related to the Seyfert AGN in NGC 4388 and accretion of a small companion (see references in OVG05).

OVG05 present new observations that prove the HI disk extends further than previously thought. Their work gives substantial support to the ram pressure stripping theory of the cloud’s evolution and determines that it is most likely the halo of M 86 that is causing the stripping, not the ICM of the cluster itself. Also, they hypothesize that stripped gas can remain neutral for up to $10^8$ years and that local column density may be high enough to promote star formation.

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8.2 The detection of a large HI plume NE of NGC 4388

On February 26 2005 a region to the northeast of NGC 4388 was observed using the Westerbork Synthesis Radio Telescope (WSRT) for 12 hours on a 20 MHz bandwidth. Observations were centered on a 1500 km s\(^{-1}\) heliocentric velocity.

8.2.1 Properties of the Plume

Figure 8.1 shows the image of the integrated HI emission superimposed over a visual picture of the region taken from the Digital Sky Survey (OVG05). This figure shows that the authors detect a large, linear plume of HI, starting to the east of NGC 4388 and expanding towards the NorthEast direction. The velocity of the plume is roughly between 2000–2550 km s\(^{-1}\) which is close to the velocity of NGC 4388 itself: 2524 km s\(^{-1}\) (OVG05). That the plume connects to NGC 4388 not only visually on the observed plane of the sky but also in the velocity shows that the gas is physically related to the galaxy. The HI plume appears to be the neutral extension of the plume of ionized gas first detected by Yoshida et al. (2002) and Iwasawa et al. (2003). The ionized and the neutral filaments, which are integrated together in the figure and indicated by the contour lines, are easily seen to be parts of the same overall structure as evident in the Figure 8.1 (OVG05).

OVG05 find that the plume of gas extends approximately 110 x 25 kpc and the mass of HI is \(3.4 \times 10^8 M_\odot\). The peak of the HI emission is located close to M 86, instead of close to NGC 4388 as expected, which is \(\sim 10\) kpc to the SouthSouthEast of the Galaxy. At this point, the observed column densities reach values just above \(10^{20}\) cm\(^{-2}\). Because of the large beam used for the observations, the column density will locally exceed this value by a significant factor. OVG05 report that the plume also reaches its maximum width near M 86 with a diameter of 25 kpc. As the observation is moved out from M 86 towards NGC 4388 the column densities decrease slowly until, near NGC 4388, the plume is almost undetectable with a column density of \(10^{19}\) cm\(^{-2}\). The distance between this maximum and NGC 4388 is approximately 70 kpc and the plume extends for another 40 kpc to the NE from the location of the maximum.
In Figure 8.2, the position-velocity plot shows that the velocity of the plume slowly decreases from $2550 \text{ km s}^{-1}$ (the velocity of the eastern side of NGC 4388) to about $2000 \text{ km s}^{-1}$ at the far end of the plume. The velocity width is about $100 \text{ km s}^{-1}$, except in the region near the maximum where the velocity width is about $200 \text{ km s}^{-1}$.

8.3 Discussion

8.3.1 Origin

The gas plume’s morphology and kinematics clearly demonstrate that the plume is made of gas pulled from NGC 4388, either by tidal forces or ram pressure stripping (OVG05). Because the relative velocities of galaxies within the Virgo cluster are high, tidal interactions between them are frequent but last for short times. The long, single filament form of the plume would be a highly improbable result from many short duration interactions. The main argument against the tidal origin of the gas plume is the distinct lack of a stellar component in the deep optical image from Phillips & Malin (1982). Because HI disks generally extend much farther than their associated optical disk they are more susceptible to tidal distortion, but the HI disk of NGC 4388 is truncated to well within the radius of its optical counterpart. Thus it would be expected to see some stellar distortion corresponding to what the authors observed at the same radii in the HI range. While the deep optical image of NGC 4388 does show some small distortion in the stellar disk, which suggests tidal interactions in the past, these tidal effects could not have caused the plume. The authors suggest that they may however have shaken the ICM of the galaxy so that effects such as ram pressure could have a more pronounced effect.

The above details argue in favor of a ram pressure origin for the gas plume associated with NGC 4388 and it is often cited as a good example of a galaxy undergoing ram pressure stripping (see references in OVG05). While it has been considered in the past that the stripping is centered on the halo of hot gas surrounding M 87, there is also the possibility that that the HI plume is due to stripping by the halo of M 86 (OVG07). The authors cite the following reasons for their belief in this option: the plume appears to be much closer to M 86 (10 kpc projected distance) than to M 87 (350 kpc projected distance); the density distribution along the HI plume is what one would expect from an interaction with M 86; and the vicinity of the maximum density near M 86. The main argument for the M 86 case is the fact that NGC 4388 has a negative velocity with respect to M 86, while its velocity with respect to the ICM currently assumed to do the stripping is positive. The negative velocity relation would allow for the proper gas kinematics for a gas plume to form. OVG05 report that previous authors have suggested that the halo of M 86 can provide the same ram pressure as the halo of M 87, so a passage of NGC 4388 close to M 86 will have similar effects (see references in OVG05).
8.3.2 Fate of the Gas

OVG05 and others cited in their paper, refer to different predictions for the gas’ fate. The copious amount of HI gas implies that it can survive for a long time. By estimating that NGC 4388 is moving at a rate of 500 km s\(^{-1}\) in the sky’s plane, the plume’s length implies an age on the order of 10\(^8\) years. OVG05 cite previous results which suggest that absorption into the ICM is slow, possibly due to a saturated heat flow or a complicated magnetic field that impedes heat flow into the plume. Assuming this long evaporation time span, areas of higher density may occur in the plume and some of the gas may become molecular. Citing previous works, OVG05 predict that in such a scenario only 10% of the total gas mass may be in the form of neutral hydrogen. In such a case, the total mass of gas in the plume would be \(\sim 3.4 \times 10^9\, M_\odot\).

Citing other works, OVG05 claim that in normal spiral galaxies if column density in any local region exceeds a few times 10\(^{20}\) cm\(^{-2}\), star formation almost always occurs. In the gas plume, column densities in various areas likely exceed this threshold, in particular near M 86. Thus, the authors conclude that star formation could occur locally in the plume if the processes that dictate star formation in the ICM are close enough to those that regulate it in regular spiral galaxies.

The last question addressed by the authors is how common neutral gas clouds such as the one associated with NGC 4388 are in clusters. If the neutral gas can exist for 10\(^8\) years as predicted by OVG05, then many more plumes should be observed, but many Virgo spirals have been imaged in HI and no large plumes have been reported. However the OVG05 research suggests that new deeper optical observations may reveal plumes in places where they are not currently thought to exist.

8.4 References


Sarah Tyree

ABSTRACT Gerhard, Arnaboldi, Freeman & Okamura (2002: G02) discovered an isolated compact region of HII gas in the Virgo Cluster’s intracluster medium. After identifying the HII region in a deep image obtained with the Subaru Telescope, the team used the ESO-VLT to obtain a spectrum which showed strong nebular emission lines. G02 found the region to be relatively high in metallicity and ionized by nearby OB stars, making it a critical location candidate for on-going star formation.

9.1 Introduction

The current understanding of star formation is that it typically occurs well inside galaxies. The halos of galaxies are not dense enough with baryonic matter to support massive star formation in that region. Because of this, the star formation that occurs in galaxies is not even close to occurring on the outskirts of these galaxies.

Stars form from collapsing clouds of gas and dust, which were put into motion and pressurized by a fluctuation caused by some disturbance in the galaxy. Some of the phenomena that could create such a disturbance are passing massive bodies, such as a large comet or even a star (Hermans-Killarn 2007). In radio galaxies, star formation is triggered by high-energy particles and magnetic field flowing in a jet-like beam out of the active galactic nucleus.

Using the Suprime-Cam of the Subaru Telescope in Japan, Arnaboldi et al. (2003) have discovered an isolated compact region of HII gas in the Virgo cluster that does not exist within the bounds of any galactic halo. According to this new find, large amounts of star formation can take place outside the typical galactic star-forming regions. This is because the HII gas in the region is high in baryonic density.

9.2 Observations

Arnaboldi et al. (2003) used the Suprime-Cam of the Subaru Telescope in Hawaii to obtain deep observations of several intracluster fields in the Virgo cluster for the purpose of trying to find intracluster planetary nebulae. In one of those fields, shown in Figure 9.1, they identified a compact HII region; this object, denoted by the blue circle in Figure 9.1 then became the target of further observations with the ESO Very Large Telescope (VLT) by G02.

Using the Arnaboldi et al. (2003) observations, G02 found the compact HII region in question to be located at (R.A., Dec.) = (12h23m31.9s, +12°43′47.7″). This location is remarkably close to that of NGC 4388, one of Virgo’s galaxies. (Interestingly, the NASA/IPAC Extragalactic Database does not have any object on file corresponding to the location of the HII region.) The HII region is not only close to NGC 4388 in location; it is close in velocity and has similar emission line peaks, indicating that the region could have broken off of the galaxy somehow.

When the clump of HII entered the intracluster medium (ICM), star formation was triggered in the region.

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During the lifetime of its most massive stars, the region has moved around 500 pc in relation to the Virgo cluster, which is over 1630 light years. This means that the star formation is taking place well outside the star-forming region of the galaxy. This fact still stands regardless of whether or not the HII region was ever a part of NGC 4388, as G02 have hypothesized.

Evidence further shows that the star-forming activity in the compressed HII region is not even caused by NGC 4388. There is a small cluster of OB stars near the HII region which are causing stars to form there. OB stars are large, hot, and short-lived stars that exist in small communities or associations of other OB stars. OB stars give off ultraviolet radiation, which in turn blows away electrons of nearby gas and dust clouds. By this process hydrogen can be ionized into HII. The photometry produced by the G02 observations shows that the emission lines of the compact HII region are similar to that seen in NGC 4388. An example of the emission lines detected in the nuclear region of NGC 4388 is illustrated in Figure 9.2 from Ho, Filippenko & Sargent (1995). However, the compact HII region has underlying continuum emission (the emission other than the large line peaks), showing that the ionization of HII is caused by the cluster, and not by the stars of NGC 4388.

9.3 Analysis

Figure 9.3 shows the spectrum of the compact HII region obtained by G02 with the UT4 of the Very Large Telescope. The major emission line peaks can be matched up with those seen in the spectrum of NGC 4388, but the underlying continuum emission from about 4500 to 7000 cannot. The emission lines observed by G02 indicate a significant presence of metals in the compact HII region. High metallicity corresponds to population I stars, which are young. This description more generally fits the stars that are within galaxies, as the roaming OB stars are also young. The discovery of metallicity in the ICM is therefore something notable, since it further indicates the independence of the HII region from NGC 4388.

9.4 Ramifications

In addition to the object studied spectroscopically and confirmed to be an HII region, G02 have identified 16 other intrachannel HII region candidates within the field of the Arnaboldi et al. (2003) image. Assuming a semi-uniform density of these regions throughout Virgo, G02 suggest that Virgo has $10^3$ star-forming HII regions that are not contained within the normal star-forming region of any particular galaxy. Also, if HII regions generally exist on the outskirts of galaxies, G02 propose that the outskirts of galaxies are a new place to study when searching for major birthplaces of stars.

The aforementioned OB stars that are ionizing the HII regions explode as Type II supernovae and enrich the Virgo ICM with metals. In this scenario, G02 propose that the presence of metals in the ICM combined with the newly discovered star formation in the ICM lets stars form outside galaxies that contain a large variation of elements.

The discovery of 17 compact HII regions in the ICM within one field of view of Subaru implies heavy changes in the way we study star formation. It is therefore crucial to our study of the development of the Virgo cluster.

9.5 References


10. Virgo Galaxies with Long One-Sided HI Tails

Jessie DeGrado

ABSTRACT In the paper “Virgo Galaxies with Long One-Sided HI Tails,” Chung et al. (2007, henceforth C07) provide the results of a new HI imaging survey of Virgo galaxies. They find seven spiral galaxies in lower-density regions (0.6–1 Mpc in projection from M87) with long HI tails. The tails all point roughly away from M87, suggesting that a single mechanism may have caused the HI loss. C07 conclude that the tails are likely a result of ram pressure stripping as the galaxies fall towards the center of the cluster.

10.1 Introduction

It has been known for some time that galaxies in high density regions of a cluster may be affected by a number of factors: tidal distortions, harassment, starvation, and ram pressure stripping. Each of these factors affects the morphology of a galaxy in a specific way. Tidal distortions – perhaps the grandest of all – occur due to the cluster potential and galaxy-galaxy interactions. Through a second process, harassment, far off galaxies may exert a gravitational pull on a specific galaxy and disturb its outer layers. The final two factors affecting galaxy morphology pertain to the fate of HI within the galaxy. Through the process of starvation, increased rates of star production may cause a galaxy to use up the vast majority of its HI, essentially starving itself to death. Finally, the entire galaxy cluster is filled with hot gas, called the inter-cluster medium (ICM). Each specific galaxy is also filled with cool gas that is held in by a gravitational restoring force. Ram pressure is the force exerted on a galaxy as it is accelerated through the ICM. When the ram pressure overcomes the gravitational restoring force, a galaxy can literally leave its (HI) guts behind. This is called ram pressure stripping.

C07 investigate the morphological changes taking place in galaxies in the lower density outskirts of the Virgo cluster. The majority of these galaxies appear undisturbed in the optical; however, C07 identify seven galaxies located at an intermediate distance from M87 with long HI tails pointing roughly away from the center of the cluster (see Figure 10.1). C07 conclude that these galaxies are recent additions to the cluster which have begun to lose their neutral hydrogen gas due to ram stripping and tidal interactions with their neighbors.

10.2 Observations

The VLA (Very Large Array) Imaging of Virgo Galaxies in Atomic gas (VIVA) survey collected HI data on 53 galaxies in the Virgo cluster. C07 focus their research on seven spiral galaxies with long HI tails. They find that the HI tails in all seven galaxies are distinct from tidal bridges – i.e., they do not connect the galaxies to another object. Further, all seven tails are pointed roughly away from M87. The galaxies lie between 0.6 and 1 Mpc in projection from M87 – hence all seven are in low- to intermediate-density regions. The galaxies show a wide range of HI gas deficiency, and the HI mass in the tail varies from 10% to 40% of the total HI mass (C07).

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10.3 Discussion

The fact that all of the HI tails point roughly away from the cluster center suggests that a single mechanism such as the gravitational cluster potential or ram pressure due to motion through the ICM may be responsible for the tails. C07 calculate the tidal acceleration due to the cluster potential \( \left( \frac{2GMR}{d^3} \right) \), where \( M \) is the mass of the cluster within a radius of \( d \), \( R \) is the radius of the galaxy) and find that it is on average three orders of magnitude less than the gravitational acceleration of the galaxy \( \left( \frac{V_{\text{rot}}^2}{R} \right) \). Consequently, tidal acceleration alone cannot account for the existence of the HI tails.

C07 consider alternatively the affect of ram pressure on the galaxies. In the case that the ram pressure (the...
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FIGURE 10.2. The range of ram pressure and the restoring force per unit area for galaxies with tails. The possible range of ram pressure is indicated in black; the restoring force is indicated in gray. From C07.

pressure exerted by motion through the ICM) exceeds the restoring force of the galaxy, one expects to see ram pressure stripping. Figure 10.2 compares the estimated ram pressure with the restoring force per unit area. Observe that the ram pressure is equal to $p_{\text{ICM}}v_{\text{gal}}^2$, where $p_{\text{ICM}}$ is the ICM density, and $v_{\text{gal}}$ is the galaxy’s velocity with respect to the ICM. Additionally, the restoring force per unit area is equal to $\Sigma_{\text{ISM}}v_{\text{rot}}^2/R$, where $\Sigma_{\text{ISM}}$ is the surface density of the ISM. The range in the restoring force reflects an uncertainty in the surface density of the ISM at the time of stripping.

Figure 10.2 indicates that for five out of the seven galaxies, the ram pressure may exceed the restoring force. C07 also make observations of the galaxies’ velocities with respect to the cluster mean velocity. For two of the galaxies, C07 find that the galaxies’ velocities are close to the cluster mean velocity – i.e., the galaxies move mainly in the plain of the sky. This, combined with the fact that the tails are pointed away from the cluster, leads C07 to conclude that the two galaxies are falling into the cluster along highly radial orbits. In the case of a third galaxy, C07 find that it is highly blue shifted with respect to the cluster mean, suggesting that the galaxy may be falling in towards the center of the cluster from the back.

10.4 Conclusion

Previous research has focused on HI deficiency in high density regions of galactic clusters. For example, Solanes et al. (2001) found that galaxies within the dense cluster interior suffer depletion of neutral hydrogen; however, as one moves out from the center of the cluster, they found that the degree of hydrogen depletion gradually decreases. This suggests that galaxies are already affected by the cluster environment, long before they reach the dense cluster core; C07 call this preprocessing.

C07 provide a concrete example of preprocessing in the Virgo Cluster. Their research suggest that newcomers to the Virgo Cluster are indeed influenced by cluster dynamics, even in relatively low-density regions. C07 investigate how galaxies in these low-density regions begin to lose their HI. They find that seven of 16 imaged galaxies between 0.6 and 1 Mpc from M87 have HI tails and conclude that at least 26% of galaxies in this region of Virgo are recent arrivals to the cluster being stripped of gas by ram pressure and tidal forces as they fall towards the center of the cluster. This suggests that HI loss begins in galaxies in lower density regions long before the galaxies show any signs of perturbation in the stellar component visible in optical images.
10.5 References
