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A Photometric Study of Two Ultra Faint Dwarf Galaxies:

The Connection Between Leo IV and Leo V

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Abstract

In this thesis I investigate if there is a stellar bridge between the two ultrafaint dwarf galaxies Leo IV and Leo V. This is done by processing seven pointings with the MOSAIC imager at the 4m Blanco telescope of the CTIO observatory in Chile. These images were made through V, B and U filters. I-band data from SDSS was added to the photometric catalog. With the use of color-magnitude diagrams, Hess diagrams and color-color plots, a selection of Blue horizontal branch and red giant branch stars was made. Density distributions of these selections between Leo IV and Leo V were analyzed. While the red giant branch star density distribution does not show signs of a bridge of stars between the galaxies, the blue horizontal branch star distrubution indicates that a connection between the two galaxies cannot be totally ruled out.

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Introduction

1.1 Dwarf galaxies: a short history

One of the open questions in astronomy is: how do galaxies form and evolve? The current cosmological paradigm predicts that galaxy formation starts with many small galaxies (e.g., Kauffmann et al., 1993). All these galaxies are believed to merge together over time, forming ever larger galaxies. This process takes a long time to occur, which means the Universe should still contain lots of small galaxies and relatively few large galaxies . Furthermore, the Milky Way itself is still accreting matter, which means this process is still going on today (e.g., Ibata et al., 1994).

The easiest way to look for evidence of the importance of merging in the build up of large galaxies is to look at the most nearby galaxy, our own Milky Way. The remains of the galaxy formation process of our own Milky Way should be seen in the form of satellite galaxies surrounding the Milky Way. We know that the Milky Way has quite a few of these satellites like the LMC and a host of small dwarf galaxies (e.g., Tolstoy et al., 2009; Mateo, 1998; Belokurov et al., 2007; Martin et al., 2008). A few years ago only 11 dwarf galaxy companions of the Milky Way were known. However, models predict there should be as many as 10, or even a few 100 times more of these dwarf galaxies surrounding the Milky Way today. This 'Missing Satellite Problem' predicts that a lot more faint satellites should be found around the Milky Way. As detection technology is improving and telescopes get more sensitive, accurate photometry of ever fainter objects is possible.

In 2000, the Sloan Digital Sky Survey (SDSS) started. SDSS is a major, multifilter imaging and spectroscopic survey using a 2.5-m wide-field optical telescope at Apache Point Observatory in New Mexico, USA. Observations were done in five color bands: u, g, r, i and z. The observations covered 14.555 square degrees on the northern sky, which is about 35% of the full sky. The published SDSS data was scanned for the slightest over densities in stars (see Belokurov et al. (2007) and references therein). This has proven to be a very good way to discover new faint galaxies in and around the MW halo. It is practically the only way to find very small over densities. The new galaxies found in this were investigated in more detail, using larger telescopes. It was concluded that many of these over densities were small galaxies close to the Milky Way, but so faint and extended that they had never been noticed before. Many are almost 100 times fainter than dwarf galaxies known before (e.g., de Jong et al., 2010). Due to the large number of Milky Way foreground stars it is very hard to find these galaxies. One way to distinguish them from the foreground population is by looking at the distribution in a color magnitude diagram (CMD). Most dwarf galaxies are expected to contain populations with a range of ages (e.g., Tolstoy et al., 2009). So fitting isochrones to the CMDs can be very useful to find and distinguish the dwarf galaxy from the Milky Way populations.

The discovered populations of particularly faint and diffuse galaxies are now commonly called Ultra Faint Dwarf Galaxies or Ufds. Since 2005, 14 new satellites have been discovered (see Willman (2010) and references therein). Ufds may be very interesting objects for studying the conditions in the early universe, and the early stages of galaxy formation, because they are so old, small and faint. They may also help to solve the missing satellite problem by removing an important inconsistency between the current models of galaxy formation and observations. However, there remains some uncertainty about the true nature of these systems (e.g, Belokurov et al., 2007; Salvadori and Ferrara, 2009).

1.2 Leo IV and Leo V

Two of the Ufds discovered by SDSS are Leo IV and Leo V. They were discovered by Belokurov et al. (2007, 2008). Leo IV is at a distance of 154 ± 5 kpc, and Leo V at 175 ± 9 kpc, They are located at almost the same distance from the MW (Belokurov et al., 2008; Moretti et al., 2009). Both of them also lie very close together in the sky (about 3° apart). Most research has been done on Leo IV perhaps because it is the brighter of the two. The structural parameters of both are summarized in Table 1.1. Leo IV has a distance modulus of $(m-M)_v = 20.94 \pm 0.07$ and is dominated by an old (14Gyr) metal poor stellar population $\langle Fe/H \rangle =$ -2.85 dex). But there are also signs of a young (~ 2 Gyr) population in the CMD. Leo V has distance modulus of $(m-M)_v = 21.22 \pm 0.10$ and shows a similar stellar population to Leo IV. Belokurov et al. found that the spatial distribution of blue horizontal branch (BHB) stars in Leo V is elongated and they also detected red giant branch (RGB) stars well beyond the estimated tidal radius. Furthermore, they found that the spatial distribution of candidate BHB and RGB stars in the region between the galaxies is not uniform at a $3-\sigma$ level (de Jong et al., 2010; Moretti, 2007). This non-uniform substructure seems to be aligned along the direction connecting the two galaxies. This leads to the question if these galaxies have a connected origin.

Table 1.1: Structural Parameters of Leo IV and Leo V. From top to bottom: right ascension (RA), declination (Dec), distance d(kpc), brightness M_V , distance modulus $(m - M)_v$, metallicity [Fe/H] and the half light radius r_h in arcmin and pc.

			_
Parameter	Leo IV	Leo V	
RA	173.24	172.79	-
Dec	-0.53	2.22	References:
d(kpc)	154 ± 5	175 ± 9	Belokurov et al. (2008) ,
M_V	-5.8 ± 0.4	-5.2 ± 0.4	Walker et al. (2009) ,
$(m-M)_v$	20.94 ± 0.07	21.22 ± 0.10	Moretti et al. (2009) ,
[Fe/H]	-2.3 ± 0.1	-2.0 ± 0.2	Simon and Geha (2007) .
$r_h(\operatorname{arcmin})$	4.6 ± 0.8	2.6 ± 0.6	
$r_h(\mathrm{pc})$	206 ± 36	133 ± 31	_

Important questions are: are these galaxies a chance superposition, or are the two galaxies merging? Or are they being ripped apart by some process? Is there evidence for either of these processes? de Jong et al. (2010) tested this hypothesis

for the first time. Some data was lost due to bad weather and they could not investigate this hypothesis fully in the end. Orbit calculations have shown that the two systems are not on the exact same orbit, which makes it unlikely they are remnants of a single disrupted system. Cosmological simulations suggest that the chance of a collision between two small unrelated subhalos is negligible. Another option is that they are a bound "tumbling pair" that fell into the Milky Way (de Jong et al., 2010). These questions about the past history and future fate of Leo IV and Leo V still remain.

1.3 Aim of this project

In this project deep photometric observations of seven fields that connect Leo IV and Leo V are analyzed. An attempt is made to do a full a bridge analysis, including the fields lost by de Jong et al. (2010). This is done by using CMDs and making selections of both BHB and RGB stars. We are looking for evidence that there may be a connection between the two systems. This will give more insight into the true nature of the system as a whole.

CHAPTER 2	
	Data Reduction

In this section it is explained how and when these data were obtained and reduced before the analysis was done. The data were observed at the CTIO observatory in Chile and reduced by T. de Boer.

2.1 Observations

The images used for this project consists of seven seperate pointings covering Leo IV, Leo V and the region in between. The positions of the fields are shown in Figure 2.1. Observations where carried out with the CTIO/MOSAIC instrument, mounted on the 4m Blanco telescope of the CTIO observatory in Chile, over three nights in February 2010. The CTIO MOSAIC II camera has an array of eight 2048 \times 4096 pixel CCDs, with a total field of view of 36' \times 36' arcmin. Optical photometry of the seven fields in the V, B and U band was obtained using the CTIO 4-m MOSAIC II camera.

Deep images of the Leo IV and Leo V field where taken, with the aim to reach the oldest main sequence turn offs. The final images(in the B,V and U filters) were made by stacking several seperate exposures together. Stacking is done because when exposure times are too long, cosmic rays and bright stars will saturate the images. Several images are taken because in total there has to be enough exposure time to be able to detect faint stars.



Figure 2.1: The positions of the seven 36' /times 36' arcmin fields observed in Leo IV, Leo V and the region in between are shown

Additional shorter exposures of both the fields were taken to be sure to sample the bright stars in each field, since the CCDs saturate above $\approx 43\,000$ counts. Besides the deep images in the Leo IV and Leo V fields, shorter exposures were obtained of five fields between both galaxies. For these fields only the B and V bands where measured. The exposure times of these fields were not as long as for the Leo IV and Leo V images. The observing log for all fields is listed in table 2.1.

Image	U (secs)	B (secs)	V (secs)	Seeing	RA(h:m:s)	Dec(d:m:s)
Leo V	3x600, 10, 90	4x600, 10, 90	7x600, 10, 90	1.03 - 1.16	11:31:09.60	+02:13:13.00
brl2	na	2x600, 10, 90	3x600, 10, 120	0.97 - 1.2	11:31:09.60	+01:45:12.24
brs2	na	2x600, 10, 90	3x600, 10, 120	1.49	11:31:45.50	+01:17:12.84
brs3	na	2x600, 10, 90	3x600, 10, 120	1.51	11:32:03.12	+00:50:35.90
brs1	na	2x600, 10, 90	3x600, 10, 120	1.34	11:32:21.10	+00:23:58.90
brl1	na	2x600, 10, 90	3x600, 10, 120	1.17 - 1.25	11:32:57.00	-00:04:00.50
Leo IV	3x600, 10, 90	7x600, 10, 90	7x600, 10, 90	0.92 - 1.24	11:32:57.00	-00:32:00.00

Table 2.1: Overview of all fields with their corresponding exposure time per filter in seconds, the seeing range, right ascension and declination.

2.2 Data Reduction and Photometry

Before the data can be used for analysis, they have to be reduced and photometry is carried out. This was done by T. de Boer, following the approach described by de Boer et al. (2011). IRAF was used, which includes the MSCRED package, especially designed for mosaics of CCD's. The standard data reduction consists of correction for bias and flat field and removing bad pixels. The eight chips of the MOSAIC instrument suffer from electronic cross talk causing ghost images. This was also removed using correction terms provided by NOAO.

Photometry is performed on all the 7 images using DoPHOT (Schechter et al., 1993). DoPHOT is optimized to carry out photometry down to the faintest levels. More details about this process are described by Saha et al. (2010). This resulted in a photometric catalog which was accurately calibrated and can be used for analysis

The measurements were merged together to form 7 single data files. The Leo IV field contains ~ 40000 stars, the Leo V field ~ 60000 stars, and the 5 bridge fields contain a total of ~ 90000 stars.

2.3 The I Filter

To seperate the foreground and background stars from the Leo IV and Leo V populations, color-color plots are made using V,B,U and I filters. In order to do this, extra color bands had to be added to the existing CTIO data. For the fields containing Leo IV and V the I band was added, while for the other five images both the I and U band were added. The data were obtained from the

DR7 database of SDSS. Our own data for the B and V band are observed with Johnson-Cousins (JC) filter. Our U band is observed with an SDSS like filter. But models with which we would like to compare these observations, Besanço Galactic Models (Robin et al., 2003), and the reference isochrone, are made based on a JC filter system . For an overview see Table 2.2. To make color plots, the filters of all bands should be identical. Therefore the U and I band of the Besançon model have to converted to JC filter system. This was done using the formulae from Jordi et al. (2006).

$$u' - g' = 0.750(U - B) + 0.770(B - V) + 0.72$$
(2.1)

And:

$$g' - V = 0.630(B - V) - 0.124 \tag{2.2}$$

Which yields:

$$u' = -0.4V + 0.65B + 0.75U + 0.596 \tag{2.3}$$

In these equation the small letters represent the SDSS filters and the large letters the JC filters. For the I band the same procedure can be done with:

$$g' - i' = 1.481(V - I) - 0.536 \tag{2.4}$$

And 2.2, to obtain a formula for i':

$$i' = -1.851V + 1.481I - 0.63B + 0.654 \tag{2.5}$$

With these formulae the I and U bands of the Besançon models and the reference isochrone can be recalculated with the use of the JC data. Since the SDSS observations do not reach the same depth as our own data, the I and U band could not be added to every single star in our own data. This brings in extra difficulty for finding stars of Leo IV, Leo V and the bridge in between, which will be discussed later.

Table 2.2: Overview of all our data and the filters that have been used for the corresponding data.

Filter	Our Data	SDSS	Besançon models	reference isochrone
V	$_{\rm JC}$	-	$\rm JC$	$\rm JC$
В	$_{\rm JC}$	-	$\rm JC$	$\rm JC$
U	SDSS	SDSS	JC	$\rm JC$
Ι	-	SDSS	JC	$\rm JC$

CHAPTER 3	
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	Metho

In this section we describe the methods used to analyze the photometry of Leo IV and Leo V and the region in between them. We describe what CMDs, isochrones, color-color and Hess diagrams are and how the selection of stars are made using these different ways of analyzing the photometry.

3.1 CMDs

A Color Magnitude Diagram (CMD) is where the difference between the magnitude of a star in two filters (for instance B-V) is plotted against magnitude (see Figure 3.1). At the beginning of the 20th century it was understood that the positions of stars in a CMD represent the evolutionary sequences of stellar populations (e.g., Baade, 1944; Sandage, 1986) All the stars in a galaxy follow a distribution within the CMD, which is determined by the age and metallicity of the stars. CMDs can thus be used to determine the ages and metallicities of individual stars in the stellar populations of a galaxy.



Figure 3.1: The CMD of the single age globular cluster, M55, with all the general features labeled such as the Main Sequence, RGB, Horizontal Branch and Main Sequence Turn Off Point. Source: Australia Telescope Outreach and Education

Some typical features within in the CMD are Main Sequence, Red Giant Branch (RGB), Horizontal Branch (HB) and Main Sequence Turn Off(MSTO), see Figure 3.1.

3.2 Isochrones

The greek word 'iso' stands for 'same' and 'chronos' for 'time'. An isochrone is a line which connects points that correspond to the same time within a CMD. That means that the line connects stars that were all born at the same time and are the same age. It is well known that globular clusters are systems with effectively a single population. From globular clusters one can make models of isochrones of a single age population. A very well known example of an ancient metal poor globjular cluster in the Milky Way is M15, in the constellation of Pegasus. Generally, Milky Way globular clusters have a very old population of about 13 Gyr old. From the CMD of M15, the isochrone of an ancient metal poor system can be inferred (Durrell and Harris, 1993). Isochrones like this can then be used in more complex stellar-system like galaxies to select populations of the same age and metallicity. In previous investigations of Leo IV and Leo V the CMD of M15 has proven to be a good match to the populations of both of them. In this project a isochrone with an age of 15 Gyr and a metallicity of -2.31 is used as a reference isochrone to select stars of Leo IV and Leo V, as well as the possible stars belonging to the bridge.

3.3 Hess Diagrams

A Hess diagrams is a density plot of the stars in a CMD. The stars in the CMD are divided into bins. In this project bin sizes of 0.1 for magnitude and 0.1 for color are used. When one plots the density of every bin as a function of color, one can achieve more contrast in highly populated regions of the CMD. This means one can for instance better see the structure of the RGB, BHB or MSTO. It is also possible to make difference Hess diagrams. This is done by the use of equation 3.1. In this formula the 'numbers of stars inside' is the number of stars in the CMD of the field inside a chosen region. The 'number of stars outside' is the number of stars in the CMD outside this chosen region. When one divides these two numbers and multiply it by the outside, the outside field gets scaled down to the inside field. The Hess diagram of the field inside a chosen region is then subtracted by the scaled down outside field, making a difference Hess diagram.

$$X = Inside - \left(\frac{number \, of \, stars \, inside}{number \, of \, stars \, outside}\right) \times Outside \tag{3.1}$$

In this way one can obtain an even higher contrast within the CMD than by just using a single Hess diagram. Relative density differences will tell what part of a CMD is more likely from the system you want to investigate and what part is more likely to be foreground or background. This approach is used in this project.

3.4 Color-Color Diagrams

In color-color diagrams the magnitude difference of two different filters is plotted against the magnitude difference in two others. For instance B-I against V-R. In this way of plotting the stars also follow a typical sequence, which depends on the age, metallicity and the types of stars that are observed.



Figure 3.2: Example of a color-color diagram. The color give the place for certain types of stars as proposed by the SEGUE (Sloan Extension for Galactic Understanding and Exploration) project. Source: SEGUE

Figure 3.2 is an example of a color-color diagram. Stars are distributed in a typical stretched Z-shaped pattern. The colors highlight regions where certain types of stars dominate. For instance, Blue Horizontal Branch stars (A/BHB) and RGB stars (K or M) are located in a specific place in the color-color diagram. Generally, background objects (mainly unresolved galaxies) are located on the upper right side of the Z-shaped sequence. This is because background galaxies have been typically redshifted.. Thus a color-color diagram is a useful way to distinguish background and foreground populations and can be used to make better selections of stars in the galaxy being studied. More about the concept of colorcolor diagrams is discussed by Bono et al. (2010). Color-color diagrams are used in this project to make better selections of stars belonging to Leo IV and Leo V.

3.5 Milky Way Foreground

Because Leo IV and Leo V are at low galactic latitude there is a lot of contamination of MW stars. We need to distinguish these stars in both the CMDs and the color-color diagrams. Extensive modeling of the stellar population of the Milky Way has been carried by Robin et al. (2003). These models are known as the Besançcon models and predict numbers, colors and magnitudes of MW stars expected at any direction in the sky. For this project predictions we make use of these predictions. As an example the Besançon model prediction for the Leo V field is shown in Figure 3.3. We see that there are two distinct regions where the MW stars are concentrated around a B-V of 0.5 and 1.5. Also in the region between B-V 0.5 and 1.5 there is some concentration of stars, but less dense. Important is to notice that there is no distinct BHB seen. In Figure 3.4 the color-color diagram of the Besancon prediction of the Leo V field is shown. We also identify the region where background contamination is expected, mainly from unresolved galaxies. We use this distribution to constrain the selection of stars for the analysis of stars belonging to Leo IV and Leo V and to try to identify the bridge in between them.



Figure 3.3: Predicted CMD from the Besançon model of the Galactic stellar population in the Leo V field we observed.



Figure 3.4: Predicted Color-color diagram from the Besançcon model of the Galactic stellar population in the Leo V field we observed.

3.6 Coordinate Transformations

For the Leo IV/V bridge analysis we needed to do coordinate transformations from RA and Decs to plain field coordinates. Also a rotation was applied to align Leo IV and Leo V. The galaxies need to be in a straight line to make easier analysis of the properties of the stellar bridge. RA en Dec are converted to xi and xn coordinates, which are plain field coordinates for X and Y, with the center of Leo IV at (0,0). The xi and xn coordinates are shown in several plots within this thesis.

CHAPTER 4.

Results

In this section the CMDs, Hess diagrams and color-color diagrams of the Leo IV and Leo V fields are presented. Along with the CMDs of the connecting fields we consider the possible connection between Leo IV and Leo V galaxies.

4.1 Leo IV

CMDs

Because of the extensive Galactic foreground contamination it is hard to distinguish the stellar population of Leo IV. For the analysis of the CMD a similar approach to Sand et al. (2010) is used. They calculated the half light radius of Leo IV using an exponential profile fit to the surface density profile and found a value of $r_h = 2.85$ arcmin. In Figure 4.1 the (B,B-V) CMD of the central 2.85 arcmin of Leo IV is plotted. This looks quite similar to the CMDs made by Sand et al.. For instance, a population of BHB stars is clearly present, as described by Sand et al. There is still Galactic contamination on the right side and in the middle of the CMD. There are also signs of a 'blue plume'. With this CMD we can establish a selection box for the BHB. Additionally a selection box for the RGB is also shown. This is established by using the reference isochrone, which is also plotted. The lower limit of the RGB box is chosen at magnitude B=23.5. At fainter magnitudes the scatter increases strongly. Only stars brighter than B=23.5 are used for all analysis, because photometric errors up to that magnitude limit are acceptably small.

In Figure 4.2 the CMD of the region outside 12 arcmin of the central region of

Leo IV is plotted. This 12 arcmin radius is also used by Sand et al. This CMD is very different from Figure 4.1 because it includes predominantly foreground MW stars and little from Leo IV. Comparing this to the Besançon models, we predict a large number of foreground stars, especially at B-V = 0.5 and 1.5. The MSTO of Leo IV is obscured due to the large photometric scatter at faint magnitudes. The BHB is less prominent, but there still seem to be some BHB stars in this region.

Figure 4.3 shows the CMD of the entire 36×36 arcmin Leo IV image. A selection box for BHB stars is shown. In blue, a selection of stars around the reference isochrone is shown. The selected stars are all those with acceptable the photometric error (0.05 in color). We do not only want to look at stars from Leo IV, but also at stars from the bridge between Leo IV and Leo V. Stars within the selection boxes will be used for the bridge analysis.



Figure 4.1: B-V versus B CMD of the Leo IV field within the central 2.85 arcmin of of Leo IV, which is the half-light radius of the exponential profile fit made by Sand et al. (2010). Overplotted is our reference isochrone and the selection boxes for the BHB and RGB region.



CMD of LeoIV outside 12 armin with M15 isochrone

Figure 4.2: B-V versus B CMD of the Leo IV field 12 arcmin outside of the central region of Leo IV. Overplotted is our reference isochrone and the selection boxes for the BHB and RGB region.



Figure 4.3: B-V versus B CMD of the entire 36×36 arcmin Leo IV field. Overplotted is our reference isochrone and the selection boxes for the BHB and RGB region. The blue dots are a selection of stars around the isochrone. The stars within the box (B < 23.5) are used for further analysis.

Hess Diagrams

In Figure 4.4 the Hess diagram of the central Leo IV field within 2.85 arcmin of the center is shown. The properties of the Hess diagram are comparable to the CMD and confirms the results described in the previous section. The BHB clearly pops out. It is clear that the reference isochrone is consistent with the overdense points, which is expected. A faint blue plume is also clearly visible and is not well matched by the reference isochrone.

In Figure 4.5 the Hess diagram of the Leo IV field 12 arcmin beyond the central region of Leo IV is shown. Not much detail is seen in this picture. There is a lot of scatter at faint magnitudes, which causes a huge over density. This is the big white spot at the bottom of the plot. On the red side and in the middle again there are lots of foreground stars and unresolved background galaxies.

In Figure 4.6 a scaled background-subtracted Hess diagram of the same, central half-light radius region is shown. This diagram is made by subtracting an inside and an outside field from each other. This is done using equation 3.1, as described in the previous section. The background subtracted Hess diagrams enhance the contrast within the CMD. Lighter regions in Figure 4.6 are in this case more likely to be from Leo IV, while darker regions are more likely to be from foreground or background contamination. This Figure confirms the existence of a BHB associated to Leo IV and the reference isochrone seems to be consistent. At the MSTO level there is also a clear over density seen, which supports the fact that the reference isochrone is a good choice. A tiny overdensity is visible at (B-V = 0.35, B = 24.5), which could be caused by a blue plume population, suggested by Sand et al. (2010) and de Jong et al. (2010).



Figure 4.4: B-V versus B Hess diagram of the Leo IV field inside 2.85 arcmin of the center of Leo IV. Overplotted in red is the reference isochrone and the BHB selection box.



Figure 4.5: B-V versus B Hess diagram of the Leo IV field outside 12 arcmin of the center of Leo IV. Overplotted in red is the reference isochrone and the BHB selection box.



Figure 4.6: B-V versus B difference Hess diagram of the Leo IV field. The outer field is scaled and subtracted from the inside field. Overplotted in red is the reference isochrone and the BHB selection box.

Color-Color Diagrams

Figure 4.7 shows the color-color diagram of the entire 36×36 arcmin Leo IV field. In red are the points that correspond to the RGB selection previously discussed. The blue points correspond to BHB stars within the selection box in Figure 4.3. The expected Z-shaped pattern is pretty clear. Some background contamination can be seen in the upper right side of the diagram.

Figure 4.8 shows the color-color diagram of the region of the Leo IV field within 2.85 arcmin from the center. The number of stars drops dramatically. This is mainly because many of the stars do not have an I band magnitude, which was obtained from SDSS. Still a Z-shape can be seen. A small clump of BHB stars can be seen on the left side of the Z-shape, which again confirms the existence of a BHB belonging to Leo IV it this distance. There is very little background contamination on the right side.

Figure 4.9 shows the region of the Leo IV field outside 12 arcmin of the center of Leo IV. While the Z-shape pops out clearly, there is also a lot more background contamination. Also the BHB clump contains fewer stars.



Figure 4.7: B-I vs U-V color-color diagram of the entire 36×36 arcmin Leo IV field. Red dots are the RGB stars and blue dots are the BHB stars from the selection boxes in Figure 4.3.



Figure 4.8: B-I vs U-V color-color diagram of the region 2.35 arcmin from the center of Leo IV



Figure 4.9: B-I vs U-V color-color diagram for the region 12 arcmin beyond the center of Leo V

4.2 Leo V

CMDs

Because there is also extensive foreground contamination of the Leo V galaxy, the same problems with the analysis of Leo IV also apply to Leo V. In Figure 4.10 the (B,B-V) CMD of the central 2.85 arcmin of Leo V is plotted. Because Leo V is the fainter and smaller of the two galaxies, it can be seen that we have much fewer stars within this CMD. The BHB box hardly contains any stars. Also there are many fewer RGB stars. The MSTO is not clearly visible.

In Figure 4.11 the CMD of the region 12 arcmin beyond the central region of Leo V is plotted. The foreground contamination in the middle and on the right can be clearly seen. There are some stars in the BHB region, but not many. In Figure 4.12 the CMD of the entire 36×36 arcmin Leo V field is shown. Again the blue stars are a selection of stars around the reference isochrone and within the photometric error. The results are similar to the Leo IV CMD, however the number of stars is much less and perhaps as a result the features are less clear.



Figure 4.10: B-V versus B CMD of the Leo V field within 2.85 arcmin of the center of Leo V. Overplotted is the reference isochrone and the selection boxes for the BHB and RGB regions.



Figure 4.11: B-V versus B CMD of the Leo V field 12 arcmin beyond the center of Leo V. Overplotted is the reference isochrone and the selection boxes for the BHB and RGB regions.



Figure 4.12: B-V versus B CMD of the entire 36×36 arcmin Leo V field. Overplotted are the reference isochrone and the selection boxes for the BHB and RGB regions. The blue dots are a selection of RGB stars around the isochrone of magnitude < 23.5. These stars are used for further analysis of Leo V.

Hess Diagrams

In Figure 4.13 the Hess diagram of the field within 2.85 arcmin of the of Leo V is shown. The result is comparable to the CMD and confirms the results described in the previous section. The BHB is slightly better visible and seems to fit within the selection box. Also the RGB seems to be consistent with the reference isochrone

In Figure 4.14 the Hess diagram of the Leo V field beyond 12 arcmin from the central region of Leo V is shown. The Figure does not show much detail and is comparable to the Hess diagram of the same region of Leo IV.

In Figure 4.15 a scaled background-subtracted Hess diagram of the same, central half-light radius region is shown. Lighter regions in Figure 4.15 are more likely to be from Leo V, while darker regions are more likely to be from foreground or background contamination. This Figure confirms the existence of a BHB associated to Leo V and the reference isochrone seems to be consistent. At the MSTO there is also a small over density seen.



Figure 4.13: B-V versus B Hess diagram of the Leo V field within 2.85 arcmin radius of the center of Leo IV. Overplotted in red is the reference isochrone and the BHB selection box.



Hess diagram of Leo V with M15 isochrone outside 12 arcmin

Figure 4.14: B-V versus B Hess diagram of the Leo V field beyond 12 arcmin from the center of Leo IV. Overplotted in red is the reference isochrone and the BHB selection box.



Figure 4.15: B-V versus B difference Hess diagram of the Leo V field. The outer field is scaled and subtracted from the inside field. Overplotted in red is the reference isochrone and the BHB selection box.

Color-Color Diagrams

Figure 4.16 shows the color-color diagram of the entire 36×36 arcmin Leo V field. The red points are stars of the RGB selection by comparison to the reference isochrone. The blue points are the blue horizontal branch stars within the selection box in the CMD. Background contamination is much less compared to the Leo IV color-color plot (see Figure 4.7).

Figure 4.17 shows the color-color plot within 2.85 arcmin from the center of Leo V. The number of stars in this plot is very low. This is mainly caused by the fact that many of the stars are lost because they do not have an I band magnitude, which was obtained from SDSS. The Z-shaped pattern can hardly be seen.

Figure 4.18 shows the region beyond 12 arcmin from the center of Leo V. The Z-shape is now clearly visible, but mainly consists of foreground contamination. There is not much background contamination.



Figure 4.16: B-I vs U-V color-color diagram of the entire 36×36 arcmin Leo V field. Red dots are the RGB stars and blue dots are the BHB stars from the selection boxes in Figure 4.12.



Figure 4.17: B-I vs U-V color-color diagram of the region within 2.35 arcmin of the center of Leo V.



Figure 4.18: B-I vs U-V color-color diagram for the region 12 arcmin beyond the center of Leo V.

CHAPTER 5_

The Connection Between Leo IV and Leo V.

To determine if there is a connection between Leo IV and Leo V we need do the full analysis the data of all fields between the two galaxies. In Figure 5.1 a spatial plot of all these fields is shown (see Figure 2.1). A coordinate transformation has been done in order to have Leo IV and Leo V aligned in a straight line. This is useful for analyzing the stellar distribution in between the dwarfs. A box is plotted within which we will do the density analysis of the BHB and RGB star selections. The dotted lines represent lines along which the density will be analyzed.



The fields with the Leos cut out of it

Figure 5.1: Spatial plot of all the fields around and in between Leo IV and Leo V. The area of both galaxies within 5 half light radii has been cut out. Lines are plotted along which the density distributions of RGB and BHB stars will be analysed.

5.1 CMDs

In Figure 4.20-4.24 the CMDs of all the different fields connecting Leo IV to Leo V are plotted. It can be noticed that because the fields are less 'deep', the scatter becomes already visible at the magnitude of the BHB. This is especially the case within the three innermost fields (Figures 5.3-5.5). The fact that these data are less it more difficult to do the analysis than was the case for Leo IV and V.



Figure 5.2: B vs B-V CMD of the brl1 field. The reference isochrone and BHB selection box are also shown.



Figure 5.3: B vs B-V CMD of the brs1 field. The reference isochrone and BHB selection box are also shown.



Figure 5.4: B vs B-V CMD of the brs3 field. The reference isochrone and BHB selection box are also shown.

CMD of the brs2 field with a M15 isochrone മ 0.5 1.5 B-V

Figure 5.5: B vs B-V CMD of the brs2 field. The reference isochrone and BHB selection box are also shown.



Figure 5.6: B vs B-V CMD of the brl2 field. The reference isochrone and BHB selection box are also shown.

To make a selection of the BHB and RGB which are likely to be associated to Leo IV or Leo V, first a CMD containing all the fields is made. This is shown in Figure 5.7. All stars within the BHB box are used for the analysis of the BHB star distribution. The selection of the RGB stars has been done using isochrones with the two different distances of Leo IV and Leo V. This means there are two isochrones used, with only a different distance modulus, as shown in Figure 5.7. The blue stars in the CMD are the stars selected around both isochrones and within the photometric errors. These stars are used for the RGB star distribution analysis. In Figure 5.8 the selection of stars we need is plotted in a CMD, with our selection boxes shown. In Figure 5.9 the selection of stars is shown in a color-color plot.



Figure 5.7: CMD of all fields around and between Leo IV and V. Overplotted are the two isochrones used to select stars in each field at the distances of Leo IV and Leo V. The blue dots are stars selected around both isochrones. Also the RGB and BHB selection boxes are shown.



Figure 5.8: CMD of the final selection of stars from the central fields which will be used for the bridge analysis.



Figure 5.9: Color-color plot of the selection of stars in Figure 5.8 used for the bridge analysis

5.2 Bridge Analysis

RGB

We first take a look at the RGB stars. After the selections from the isochrones are refined with the use of color-color plots a final selection of RGB stars has been made. The spatial distribution of these stars has been plotted in Figure 5.10. The stars are plotted inside the same box used in Figure 5.1. In Figure 5.11 a histogram the same RGB stars as in Figure 5.10 is shown. The bin size in the histogram is 0.05 degrees and centered on the line connecting the centers of Leo IV and Leo V. Looking at the histogram there is no significant overdensity along a particular line. But since the bridge doesn't have to be necessarily along a line it is also useful to look at the stellar distribution by eye. Looking at Figure 5.10, there is no clear bridge-like structure visible. The distribution looks very uniform.



Figure 5.10: Spatial plot of the final selection of RGB stars



Figure 5.11: Histogram of the final selection of RGB stars. Bin size is 0.05 degrees and centered on the line connecting the center of Leo IV and Leo V

BHB

Now we take a look at the stars selected from the BHB box in the CMD. Again the selection has been refined with the use of color-color plots. After the selection procedure only 24 BHB stars are left. In Figure 5.12 the spatial distribution of these stars is shown. In Figure 5.13 a histogram of these stars is shown. Within the histogram there is no line along which the stars are significantly concentrated. But when we look at Figure 5.13, there seems to be more structure. There may be concentration along a line that goes from the lower left to the upper right corners, as plotted in Figure 5.14.



Figure 5.12: Spatial plot of the final selection of BHB stars



Figure 5.13: Histogram of the final selection of BHB stars. Bin size is 0.05 degrees and centered on the line connecting the center of Leo IV and Leo V



Figure 5.14: Spatial plot of all the stars and the BHB selection. Overplotted is a line along which the BHB stars appear more concentrated and thus could possibly form a bridge.

Contour Plots

We also take a look at the RGB star distrubutions around Leo IV and Leo V using contour plots, which indicate the density of RGB stars. They are shown in Figures 5.15 and 5.16. In Figure 5.15 there is a clear concentration of RGB at the central region of Leo IV. Beyond the central region there is also a small extension to the lower left corner, where there is an over density of RGB stars. Leo V lies in the upper direction. No bridge like features seem to be visible in the direction of Leo V.

In Figure 5.16 the contour plot of RGB stars around the central position of Leo V is shown. In the central region and in the upper left corner there are concentrations of RGB stars. Leo IV lies in the downward direction. Again we conclude that there is no clear bridge-like structure to be seen in the direction of Leo IV.



Figure 5.15: Contour plot of RGB stars around the central position of Leo IV.



Figure 5.16: Contour plot of RGB stars around the central position of Leo V.

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Conclusion and Discussion

In this work I have investigated the existence of a bridge of stars between Leo IV and Leo V. This was done by using data of seven images in three color bands (V, B and U) taken at the CTIO observatory in Chile. I-band data from SDSS was coupled to our existing data to expand the analysis to allow color-color selections. With the use of CMDs, Hess diagrams and color-color plots a selection of stars was made to include predominantly those that belong to the Leo IV and Leo V galaxies and the region in between.

de Jong et al. (2010) previously studied this problem and concluded that signs of a bridge are present, but because they lost their central pointing uncertainties remained. In this thesis images of the fields covering the region between Leo IV and Leo V were obtained in V,B and U filters. Based on these data we still see tentative signs of a bridge between both dwarfs, using BHB stars, but the statistics remain poor. It is still very hard to make good selections of stars. This is partly because our images of the bridge region are not that deep. We were also limited because we had to add less deep data from SDSS to our data, before we could use color-color plots to do the analysis.

We conclude that based on our selection of RGB stars is no evidence for a stellar bridge between Leo IV and Leo V. But based on the BHB stars we selected, it cannot be ruled out that there is a bridge between Leo IV and Leo V. Blue horizontal branch stars seem to be concentrated in a way that could represent a bridge, which is visible in Figure 5.10. However the number of stars is low and thus prone to large statistical uncertainties. A better analysis of the bridge between Leo IV and Leo V would require deeper photometry, down to magnitude 27, in four colors bands, before any decisive conclusion can be taken about the true nature of the bridge. BHB stars seem to be the best candidate stars for investigating the bridge in our data. Since their distance is given and they are bright enough for us to detect.

Recent findings by Jin et al. (2012) suggest that the connection between Leo IV and Leo V might not be there and that the region in between both galaxies is better matched by a foreground stellar stream, possibly associated with the Virgo overdensity. They did not use BHB stars at all for their analysis and only used two color bands (r,g) instead of the four we used for the analysis. They could not use color-color plots for further refining their selections and base their results only on the CMDs they have. In our data there is a hint of a connection, but clearly this problem is still an open one. By obtaining deeper, multi-color observations of Leo IV and V and the region in between, it will be possible to unambiguously determine if there really is a connection between both systems.

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Cheers

Casper Blokzijl

APPENDIX A	
	Additional CMDs

Because four color bands are present in our data, also CMDs of other bands than B-V,V can be made. In this appendix some extra CMDs are plotted of the fields. The different CMDs are not used in any analysis, but can be interesting to study.

Leo IV



Figure A.1: Different CMDs of the Leo IV field.

Leo V



Figure A.2: Different CMDs of the Leo V field.

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